CHEMICAL ENGINEERING

May 2011

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Harnessing the Power of Cyclones

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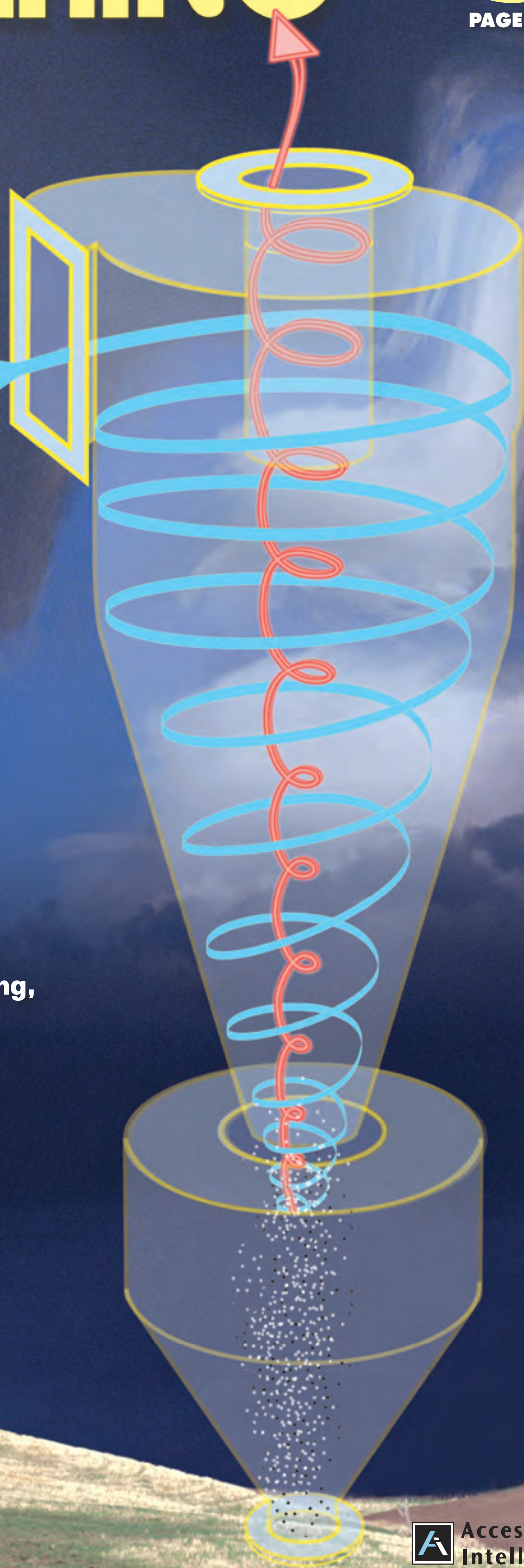

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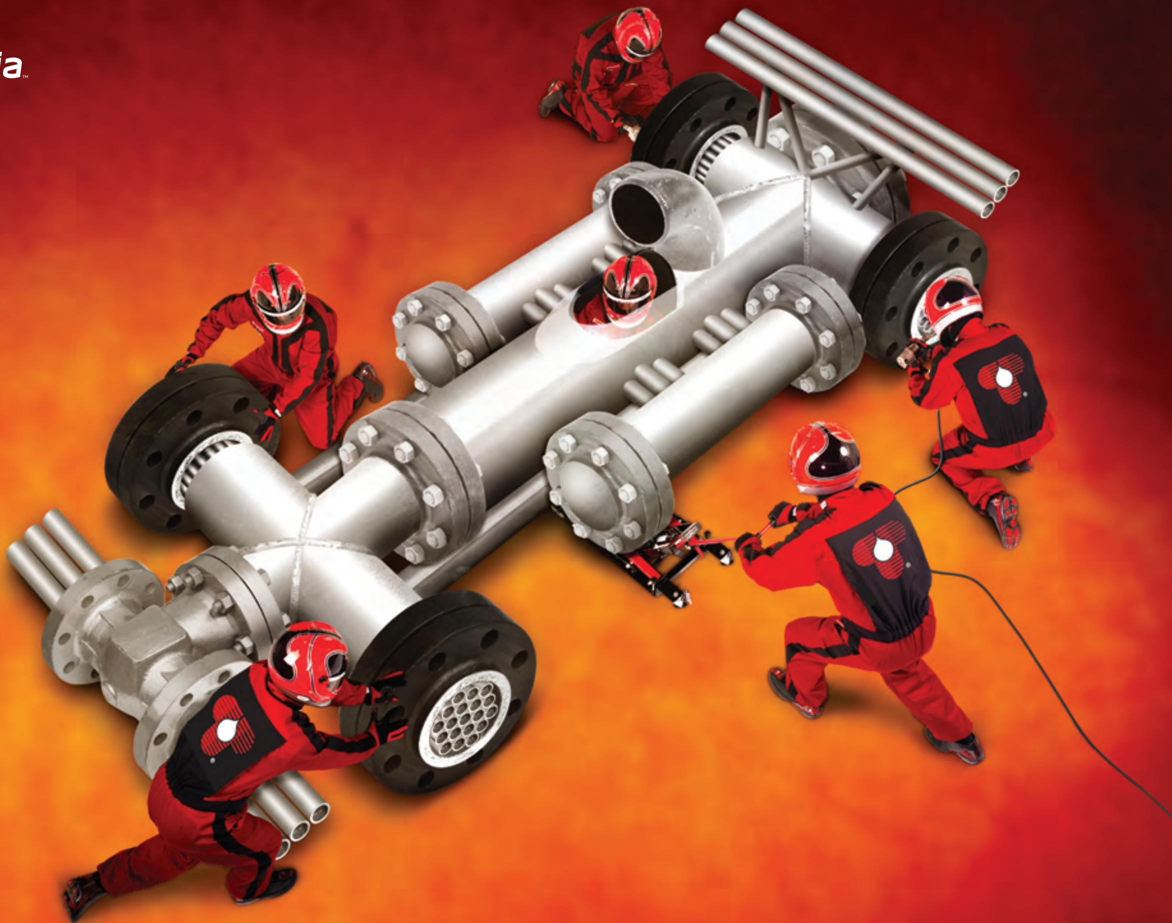

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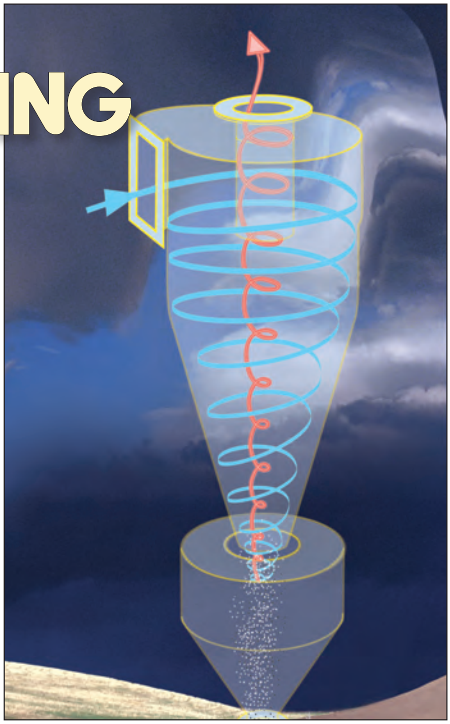

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Published since 1902
An Access Intelligence Publication

PUBLISHER

MIKE O'ROURKE
Publisher
morourke@che.com

EDITORS

REBEKKAH J. MARSHALL
Editor in Chief
rmarshall@che.com

DOROTHY LOZOWSKI
Managing Editor
dlozowski@che.com

GERALD ONDREY (Frankfurt)
Senior Editor
gondrey@che.com

SCOTT JENKINS
Associate Editor
sjenkins@che.com

CONTRIBUTING EDITORS

SUZANNE A. SHELLEY
sshelley@che.com

CHARLES BUTCHER (U.K.)
cbutcher@che.com

PAUL S. GRAD (Australia)
pgrad@che.com

TETSUO SATOH (Japan)
tsatoh@che.com

JOY LEPREE (New Jersey)
jlepree@che.com

GERALD PARKINSON
(California) gparkinson@che.com

ART & DESIGN

DAVID WHITCHER
Art Director/
Editorial Production Manager
dwhitcher@che.com

PRODUCTION

MICHAEL D. KRAUS
VP of Production & Manufacturing
mkraus@accessintel.com

STEVE OLSON
Director of Production &
Manufacturing
solson@accessintel.com

JOHN BLAYLOCK-COOKE
Ad Production Manager
jcooke@accessintel.com

MARKETING

JAMIE REESBY
Marketing Director
TradeFair Group, Inc.
jreesby@che.com

JENNIFER BRADY
Marketing Coordinator
TradeFair Group, Inc.
jbrady@che.com

AUDIENCE DEVELOPMENT

SYLVIA SIERRA
Senior Vice President,
Corporate Audience Development
ssierra@accessintel.com

SARAH GARWOOD
Audience Marketing Director
sgarwood@Accessintel.com

GEORGE SEVERINE
Fulfillment Manager
gseverine@accessintel.com

JEN FELLING
List Sales, Statlistics (203) 778-8700
j.felling@statlistics.com

INFORMATION SERVICES

ROBERT PACIOREK
Senior VP & Chief Information Officer
rpaciorek@accessintel.com

CHARLES SANDS
Senior Developer
Web/business Applications Architect
csands@accessintel.com

CORPORATE

STEVE BARBER
VP, Financial Planning & Internal Audit
sbarber@accessintel.com

BRIAN NESSEN
Group Publisher
bnessen@accessintel.com

HEADQUARTERS

88 Pine Street, 5th Floor, New York, NY 10005, U.S.
Tel: 212-621-4900 Fax: 212-621-4694

EUROPEAN EDITORIAL OFFICES

Zeilweg 44, D-60439 Frankfurt am Main, Germany
Tel: 49-69-9573-8296 Fax: 49-69-5700-2484

CIRCULATION REQUESTS:

Tel: 847-564-9290 Fax: 847-564-9453
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Editor's Page

A New Online Face for *CE*

As the calendar flips to May, spring is finally beginning to push a tough winter out of the way in the Northeastern part of the U.S. With the change of season, many companies in the chemical process industries (CPI) are renewing a push to invest in longterm growth. A recent report from the American Chemistry Council (ACC; Washington, D.C.; www.americanchemistry.com) suggests that ethane supplies from shale formations in North America could help boost investment and chemical manufacturing in the U.S. This is one of several good signs for the CPI.

CPI companies are not alone in investing to improve their products. Here at *Chemical Engineering*, we continue to invest in our products as well, the latest example being a comprehensive redesign of our Website (www.che.com). You may have noticed the change already if you have visited the Website since its launch at the end of April.

Begun in Fall 2010, the ChE.com redesign was a process in which we examined the experience from the perspective of our loyal readers. While it was a painful process at times, it was ultimately rewarding, and I hope you will appreciate the enhanced features and enjoy the new "look and feel."

The main goal of the redesign was to create an improved user experience for our readers. The first thing most visitors will notice on ChE.com is a completely refreshed homepage. The clean new look is intended to draw users' eyes to everything that *Chemical Engineering* has to offer. We have substantially increased our online offerings and have made it easier to locate the type of information you have come to expect from the magazine, including our quintessential, practical how-to articles.

Among the new items that you will find on the redesigned Website is an area labeled "Only on ChE.com". This section highlights our growing collection of Web-exclusive feature articles and provides a convenient place to retrieve online extras for articles that have been published recently in the magazine. You will also find our new searchable and browseable New Products section, which will be updated daily with the latest technologies being launched for the CPI.

Another new offering is a "My che.com" area. From this section, registered users will be able to customize RSS feeds on the topics that interest them the most and manage their accounts and the level of access they have to our various products. Visitors with the most-basic registration, for instance, can upgrade their accounts to the Gold level to gain access to our archives and Facts at Your Fingertips. Meanwhile, visitors who upgrade to the Platinum level will receive online access to the full *Chemical Engineering* Plant Cost Index (CEPCI) database.

The new Website also features access to our newly launched discussion groups. Through our new presence on LinkedIn, we are launching a general discussion forum and three topical subgroups: Process Automation, Water Treatment and Reuse, and Solids Processing. We encourage you to join these online communities through the links on our site and begin to interact with us and other ChEs who have faced or are facing similar challenges in their jobs. In the coming weeks, we will begin to offer experts on a variety of topics to help moderate the lessons to be shared there.

Other tools to help you in your everyday work include quick access to a searchable buyer's guide. The bottom of the page contains links to everything that *Chemical Engineering* has to offer, including our expanding selection of eNewsletters. It also provides contact information for our staff. I sincerely hope you like the investment we have made in www.che.com. Please take a look. Your feedback is welcome (morourke@che.com). ■

Mike O'Rourke, Publisher

Letters

Missing a major CTC player?

February, Coal-to-Chemicals, pp. 16–20: I find it quite interesting that no mention of one of the largest coal-to-chemicals (CTC) practitioners is made in the article. The company is of course South Africa's Sasol. Any reason for ignoring them? They are, after all, round about number 30 on the list of the world's largest chemicals companies...

P. Julius Pretorius, senior research scientist
Saskatchewan Research Council, Saskatoon, Canada

Yes, Sasol is a major player in coal-to-chemicals technology, as this magazine has pointed out on numerous occasions, including: A primer on coal-to-liquids (January 2009, pp. 23–27); A new surge in coal gasification (February 2007, pp. 18–21); and Gas-to-liquids projects get the green light (May 2004, pp. 23–27). That said, the oversite was unintentional. —Ed.

LEAN Chemical Manufacturing

There has been a great deal of new activity around so-called lean thinking or the lean enterprise lately, even though the practical application has been going on since the early 1900s. It was started by Henry Ford, and followed on by Edwards Deming and Taiichi Ohno. These three were relentless foes against waste.

If the chemical process industries (CPI) were to implement lean to the fullest extent, one vision might look like this:

Reaction kinetics would not go away, but there would be a profound diminishing of all other unit operations. Why? Because we would control our reactions at the molecular level, and by this I mean one molecule at a time, just as the lean approach proposes that the most efficient and fast work process is one-piece-flow. Instead of large batches of chemical molecules going into large reactors in chemical plants, usually far removed from their customers, we would react one molecule with another in micro-chemical plants to produce exactly the new molecule that each customer needs for its operation.

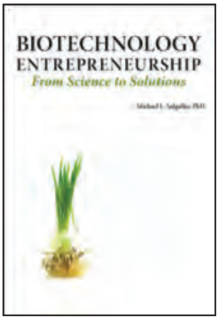
Why is this important? First, there would be little, if any waste from these micro-operations. The unit operation of waste management or minimization could literally go away. Think of the thousands of overhead manhours we spend associated with this activity that brings no value.

If you consider what our CPI plants consist of today, over 90% of the physical plant is there for no other reason than to separate the good stuff from the not-so-good stuff: distillation, extraction, adsorption, leaching, decanting, sublimation, gaseous diffusion, dialysis and so on.

Even storage would be minimized as we would move our micro-plants onto the customers' sites, just as we do Oxygen (vacuum swing adsorption) VSA plants. Since the separation unit operations would diminish, then all of the associated piping, controls, power and other ancillary operations would also be minimized.

Seems impossible, you say? So did putting man on the moon and so many other far-reaching visions. Take the first step: embrace this vision as a company initiative.

Ed Anderson
President, Lean Implementation Services of Florida



Biotechnology Entrepreneurship: From Science to Solutions. By Michael Salgaller. Logos Press. 3909 Witmer Rd., #416, Niagra Falls, NY 14305. Web: logos-press.com. 2010. 216 pages. $64.95.

Reviewed by Kris Mani, NSR Technologies Inc., Decatur, Illinois

Many books have been aimed at would-be entrepreneurs interested in starting companies. All address the myriad of complex issues that aspiring entrepreneurs must address to transform a promising idea into a full-fledged business. The contents of this book provide a sobering overview of the biotechnology business for any aspiring biotech entrepreneur

While all new businesses must address the same core issues — finding investors, building a team, and so on — there are notable differences among different business segments. Starting a science- or technology-based business, for example, is considerably more complicated than starting a restaurant, for example, if only because larger financial resources are required and the timespan needed to reach positive cash flow and profitability is longer.

Starting a biotechnology business is certainly among the most challenging for an entrepreneur. Society's need for medications is large and continues to grow. The range of products to meet those needs includes active pharmaceutical ingredients, targeted therapies, medical devices and delivery vehicles. This demand creates significant opportunities for entrepreneurs with the right combination of technical and managerial skills, as well as the vision to start a biotechnology businesses. However, the regulatory and product-filing requirements, in addition to competitive factors, can vary significantly for a given targeted product, making the biotechnology field particularly challenging.

With help from a number of industry insiders with specialized knowledge in various business-development areas, Salgaller has authored and assembled a comprehensive overview of the critical issues that entrepreneurs face during both company startup and the transition to an established entity. After an initial chapter that reviews the common reasons for starting a biotechnology company — including favorable societal impact, altruism and the desire for wealth — the book provides details on company formation, team-building, intellectual-property protection and financing. These topics are of general applicability, not only for starting a biotechnology business, but also to business startups in other areas. Later chapters dealing with exiting the business venture and effective networking are also widely applicable.

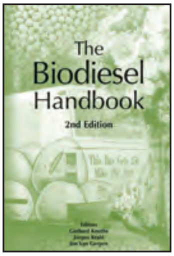
The middle section of the book addresses issues specific to the business of biotechnology. Any aspiring biotech-oriented entrepreneur would be well advised to master them. Specific topics addressed include: partnering with industry; licensing and technology transfer from universities and federal laboratories; regulatory affairs; and obtaining

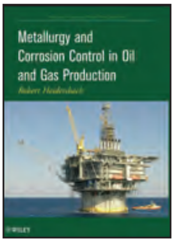
Bookshelf

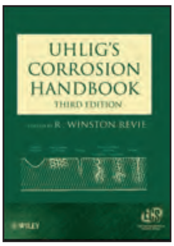
satisfactory reimbursement from health insurers for the anticipated end-product. The material in these chapters is described well and in great detail. The reader is left with a clear understanding of the effort needed to meet the market challenges for any medical product or device.

The long period for moving a product to market, high development cost for new drugs, and clinical trial risks mean that an entrepreneur must have not only excellent technical skills but also the ability to secure sustained funding by demonstrating progress at each product-development stage.

Structure and Properties of Crosslinked Polymers. By Gasan Magomedov, Georgii Koslov and Gennady Zaikov. iSmithers Rapra Publishing, Shawbury, Shrewsbury, Shropshire, SY4 4NR U.K. Web: ismithers.net. 2011. 492 pages. $205.00.







Ashford's Dictionary of Industrial Chemicals. 3rd ed. By Robert D. Ashford. Wavelength Publications, Kamakura, Botus Fleming, Cornwall, PL12 6NJ U.K. Web: industrialchemistry.info. 2011. 10,449 pages. $300.00 (eBook).

Handbook of Flavors and Fragrances. Compiled by Michael and Irene Ash. Synapse Information Resources Inc., 1247 Taft Ave., Endicott, NY 13760. Web: synapseinfo.com. 2011. 980 pages. $375.00.

Practical Guide to Smoke and Combustion Products from Burning Polymers: Generation, Assessment and Control. By Sergei Levchik, Marcelo Hirschler and Edward Weil. iSmithers Rapra Publishing, Shawbury, Shrewsbury, Shropshire, SY4 4NR, U.K. Web: ismithers.net. 2011. 252 pages. $130.00.

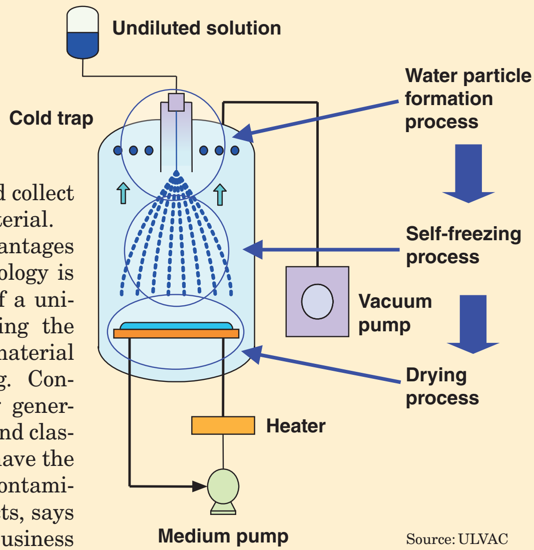
The Biodiesel Handbook, 2nd ed., Edited by Gerhard Knothe and Jon Van Gerpen. AOCS Publishing, 2710 S. Boulder Ave., Urbana, Ill. 61802. Web: aocs.org. 2010. 516 pages. $129.95

Metallurgy and Corrosion Control in Oil and Gas Production. By Bob Heidersbach. John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030. Web: wiley.com. 296 pages. $110.00.

Uhlig's Corrosion Handbook, 3rd ed., Edited by R. Winston Revie. John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030. Web: wiley.com. 1,288 pages, $195.00 ■

Scott Jenkins

Freeze-drying based on fine-spray produces uniform microspheres



Source: ULVAC

A freeze-drying system recently commercialized by ULVAC, Inc. (Chigasaki, Japan; www.ulvac.co.jp) produces spherical particles by spraying a solution into a vacuum chamber. The approach has numerous advantages over conventional freeze-drying, and can be used for generating dry powders in the pharmaceutical, food and electronics industries.

The system works by spraying a solution through a specialized nozzle into a vacuum chamber (diagram) with pressures in the range of 5–30 Pa. As the raw material enters the chamber, it disperses to form droplets of uniform size, since air resistance is virtually zero inside the vacuum chamber. As water evaporates from the droplets, latent heat is removed, and the particles self-freeze into a powder whose size can be controlled within the range of 100–400 µm. The frozen particles settle onto a heated shelf, where the remaining water is removed and product collected. The patented vacuum chamber and heated collection apparatus is designed to reduce drying times and collect over 95% of the dry material.

Among the major advantages of the fine-spray technology is the direct production of a uniform powder, eliminating the need to crush dried material before final packaging. Conventional freeze-drying generally requires crushing and classification steps, which have the potential to introduce contamination to sterile products, says David Mount, ULVAC business development manager. In addition, the particle size distribution is narrower with the fine-spray approach, and the resulting particles are porous, allowing excellent solubility when the product is reconstituted, adds ULVAC's Ryoshin Imai.

The system is available in two sizes — a laboratory size, with a capacity of up to 5 L of process solution, and a production size (up to 150 L).

CNT-enhanced membranes show promise for desalination method

By immobilizing carbon nanotubes (CNTs) within polymer membrane pores, scientists at the New Jersey Institute of Technology (NJIT; Newark, N.J.; www.njit.edu) were able to significantly improve the efficiency of desalination via a membrane distillation process. Somenath Mitra and colleagues at NJIT used a vacuum to force a dispersion of CNTs into the pore network of commercially available polymer membranes. The result is a uniform distribution of 0.5-wt.% multiwalled CNTs in the membrane. The scientists found that, compared to the membrane alone, flux doubled and salt reduction was five times higher with the CNT-infused membrane. The result could allow the use of membrane distillation for purifying brackish and seawater as a lower-energy alternative to reverse osmosis and other thermal and chemical desalination methods.

In testing the CNT-infused membranes with solutions of salt water from 10 to 34,000 mg/L, the NJIT team observed "significantly higher flux and salt reductions at all feed flowrates" and mass transfer coefficients that were two to six times higher in the presence of CNTs.

In a recent paper, Mitra and the other NJIT scientists proposed that the CNTs alter the water-membrane interactions such that a higher transport of pure vapor can occur across the membrane. The CNTs help the membrane maintain high hydrophobicity, which can prevent clogging, and also may facilitate the transport of water through the membrane by adsorption to the CNT surface or by travel along the CNT surface.

The NJIT team hopes to find a commercial partner to help develop the technology at larger scale.

Wastewater reuse

Aqua-Chem Inc. (Knoxville, Tenn.; www.aqua-chem.com) has developed a filtration-based process for purifying wastewater from large-scale carpet manufacturing. The process effectively removes dyes and other additives from wastewater to reduce concentrations from around 800 ppm to less than 30 ppm. A recent pilot with a U.S.-based carpet manufacturer demonstrated that 70% of wastewater effluent in dyeing operations can be reused in manufacturing. The company says with optimizations planned for the full-scale system, the process will be able to recover 90% of wastewater.

A cleaner route to MEK

Within the next two to three years, Idemitsu Kosan Co. (Idemitsu; Tokyo; www.idemitsu.com) plans to install 80,000–100,000-ton/yr production capacity for methyl ethyl ketone (MEK) in Asia. The new production facility will utilize a new process that the company has developed and demonstrated in a 400,000-ton/yr plant at its Tokuyama Factory. The process involves a direct hy-

(*Continues on p. 10*)

Note: For more information, circle the 3-digit number on p. 78, or use the website designation.

(Continued from p. 9)

dration using a hetero-poly acid instead of the indirect hydration by sulfuric acid. Elimination of the H_2SO_4 removes the need for corrosion-resistant equipment and the waste associated with the liquid acid.

Replacement for indium

Researchers at Eindhoven University of Technology (the Netherlands; www.tue.nl) have developed a replacement for indium tin oxide (ITO) — an important material used in the manufacturing of displays. Available supplies of the rare element are expected to be exhausted within as little as ten years, according to the University. The replacement is a transparent, conducting film produced in water, and based on electrically conductive carbon nanotubes and plastic nanoparticles.

The research team was able to achieve higher conductivity by combining low concentrations of CNTs and conducting latex in

(Continues on p. 13)

A step closer to commercial production of spider silk

Spider silk has many unique properties that make it suitable for applications such as coatings and medical products. As a protein, the silk is remarkably stable and is only destroyed physically or digested and recycled by the spider. However, an industrially viable synthetic route to spider silk has eluded researchers over the last 25 years, says Axel Leimer, managing director at AMSilk GmbH (Planegg/Martinsreid, Germany; www.amsilk.com). "There have been many patents, but no products."

AMSilk may have the answer, having developed a fermentation process capable of producing kilogram quantities of material, which is sufficient for product development and testing, says Leimer. The process relies on *E. Coli* bacteria in which the protein sequence — solved by the Technical University of Munich — has been expressed for high production yields. The company has also developed a process to extract the synthetic silk from the bacteria, and aims to produce the silk proteins at the 100-kg scale in the near future.

The company is targeting both medical and technical film applications for the new material. For example, silk beads have been shown to be good carriers for drugs, having a high (30–60%) drug-loading efficiency, with a good "release curve," while the silk itself is biocompatible. The synthetic silk can also be made into a 10-µm thick film that feels like Cellophane, has the same or better toughness and yet is completely clear — properties suitable for optical coatings, explains Leimer. Another potential product is nonwovens for filtration applications in the medical and biotechnology sector or technical films that can be functionalized.

In March, the company received €5 million in Series B financing to further commercialize the technology. First products are expected to be ready for marketing later this year.

'One-pot' ammonia-borane recharging could boost fuel-cell vehicles

Ammonia borane's (AB) capacity to contain and easily release large amounts of hydrogen has made it an attractive candidate to store the gas for onboard fuel-cell powered vehicles. A major technological hurdle that remains is how to reintroduce hydrogen to spent AB in an energy-efficient way. Now, a team comprised of researchers from Los Alamos National Laboratory (Los Alamos, N.M.; www.lanl.gov) and the University of Alabama (Tuscaloosa, Ala.; www.ua.edu), has published a single-vessel method to recycle the material left when H_2 is released. The method could significantly reduce the expense and complexity of ammonia borane recycling, and represents a step toward the practical use of H_2 for powering automobiles.

The scientists developed a regeneration process in which the spent fuel material (polyborazylene) is reacted at 40°C with hydrazine and liquid ammonia in a sealed pressure reactor to yield recharged AB. The researchers envision the use of removable tanks containing AB that would be interchanged with a fresh AB container when the H_2 is released. "By recharging the AB off-board, you can access more thermodynamically reasonable chemistry than what would be required for direct onboard regeneration of AB," explains LANL scientist John Gordon.

One caveat for the widespread use of this method is the need for hydrazine, production of which would have to increase for large-scale AB recycling. It is envisioned that hydrazine production could occur in situ at a possible, future AB-regeneration facility.

A new high-temperature alloy

Last month, Carpenter Technology Corp. (Wyomissing, Pa.; www.cartech.com) licensed an alumina-forming austenitic stainless-steel alloy developed at the U.S. Dept. of Energy's Oak Ridge National Laboratory (ORNL; Tenn.; www.ornl.gov). The new alloy is said to be unique in that the composition allows for alumina scales to form on the exterior of steel, which provides significant oxidation resistance. The alloy displays "excellent" creep strength at high (700–800°C) temperatures, and can be produced at a lower price than existing alloys that require high amounts of nickel, says ORNL.

Potential applications include recuperators and heat exchangers, downhole drilling and chemical processing equipment and materials — applications in which high-temperature or corrosive environments are encountered, says ORNL.

Coal slurry as a substitute for diesel fuel

An Australian team including CSIRO (Melbourne; www.csiro.au) and the University of Newcastle (www.newcastle.edu.au) has developed an alternative pathway for producing ultra-low-ash coal that, the team believes, can be used to fuel diesel engines, thus providing the opportunity for diesel engines to replace steam engines for large-scale base-load power generation. The method involves slurrying and micronizing the coal to a size less than 30 µm to liberate the mineral matter, then using ultra-fine flotation to remove the coal from the mineral matter. The micronized raw coal slurry has the appearance of crude oil, and is called micronized refined coal (MRC).

The team has studied a range of Australian coals, and verified that if coal is ground finely enough, flotation will yield a consistent low-ash product with significantly higher coal recovery than the product of earlier studies. In laboratory tests, the team used an Isamill for ultrafine coal milling. For the laboratory Isamill, the energy for micronizing the coal was about 65 kWh/ton of coal. The laboratory Essa flotation cell and Universal Flotation tests yielded 2–3% ash for all coals at a combustibles recovery of 85–93 wt.%. Tests in a larger pilot J-cell produced a lower concentrate ash of 1–2%.

A few small-scale demonstration projects have been proposed in Australia. These involve mostly a two-stage program starting with pilot testing of fuel production at about 1–3 ton/d for use in large test engines, and engineering for larger demonstration plants. This would be followed by a 10,000-h demonstration plant with a 7–10-MW power plant.

CSIRO and partners are now considering two New South Wales sites for pilot plant development, but Norman anticipates that the catalysts will be available for commercial use by the end of 2011.

(*Continued from p. 10*)

an inexpensive polystyrene film. Although the conductivity of the film is still 100 times lower than that of ITO, the scientists believe the use of metallic nanotubes can quickly close the gap.

Automated pyrolysis

Researchers at the Fraunhofer Institute for Solar Energy Systems (ISE; Freiburg, Germany; www.ise.fraunhofer.de) have developed a fully automated pyrolysis system for producing hydrogen from fuels. The system can be used with gaseous and liquid fuels, such as natural gas, biogas or diesel, and produces more than 80 vol.% H_2.

The system features two reactors, which alternate between pyrolyzing the fuel and burning off the carbon deposits that form on the catalyst. The researchers developed a non-precious-metal catalyst capable of withstanding the high temperatures (over 950°C) used for the decoking step. A prototype of the two-

(*Continues on p. 14*)

A renewable, 'green' oxidation catalyst

Scientists from the National Institute of Advanced Industrial Science and Technology (AIST; Tsukuba, Japan; www.aist.go.jp), in collaboration with Tokyo University of Science and Panchakot Mahavidyalaya University, have demonstrated that a nickel-complex-type organic nanotube (Ni-ONT), developed by AIST, can catalyze oxidation reactions for producing industrial chemicals. For example, the researchers have demonstrated that Ni-ONT dispersed in aqueous hydrogen peroxide catalyzes oxidation reactions at room temperature, producing 2,3,6-trimethylphenol (TMP); trimethylquinone (TMQ; an intermediate for making vitamin E); benzophenone (an ultraviolet absorbing agent); tetralone (an agrochemical intermediate); and epoxides (for photo-curing of resins). A selectivity of more than 90% was achieved for TMQ, and a 55–60% selectivity for TMP. The Ni-ONT did not lose its activity after at least five cycles with recycled catalysts.

Unlike traditional oxidation reactions, which use heavy metal catalysts, organic peroxides or high temperatures, those carried out with Ni-ONT occur at room temperature with hydrogen peroxide, without producing hazardous or halogenated wastes. Ni-ONT is also a solid in aqueous solutions, so it can be simply filtered for reuse. As a result, the scientists believe the new catalyst will be more economical and environmentally friendly than alternatives.

Ni-ONT is synthesized by simply mixing an aqueous solution of a nickel salt into an alcohol solution of peptide lipids — amphiphilic molecules composed of glycylglycine and aliphatic acids. The resulting structure is a cylindrical nanotube with all of the Ni ions exposed on the inner and outer surfaces (see *CE*, January 2009, p. 16).

(*Continued from p. 13*)

reactor system was on display at the Hannover Trade Fair (April 4–8). ISE has also developed a one-reactor pyrolysis system that alternates between recharging with fuel and regeneration. The small units deliver a continuous supply of H_2 with very low CO content for use in a fuel cell.

Renewable acrylic acid

The Dow Chemical Co. (Midland, Mich; www.dow.com) and OPX Biotechnologies, Inc. (OPXBio; Boulder, Col.; www.opxbio.com) are collaborating on the development of an industrial-scale process to make bio-based acrylic acid from a fermentable sugar (corn or sugar cane) feedstock. OPXBio has developed its EDGE (efficiency directed genome engineering) technology to engineer microbes and bioprocesses faster than conventional genetic engineering methods, and has already demonstrated the ability to produce bioacrylic acid in an

(*Continues on p. 16*)

Commercial production for a self-cleaning coating

Last month, PJI Contract Pte Ltd. (Singapore; www.pji-con.com.sg) opened a production facility for the manufacture of titanium dioxide solution — a self-cleaning, nanocoating material developed at Singapore Institute of Manufacturing Technology (SIMTech; www.simtech.a-star.edu.sg), a research institute of the Agency for Science, Technology and Research (A*Star; Singapore; www.a-star.edu.sg). PJI Contract has licensed the patented TiO_2 manufacturing process from A*Star, and has already applied the self-cleaning coating on the facades of several commercial buildings.

The self-cleaning properties of the TiO_2 coating technology are derived from the oxidative and hydrophilic nature of the coating. When exposed to sunlight, TiO_2 catalyzes the oxidation of organic compounds and microbes. Water is repelled by the hydrophilic coating, and thus washes away dust and dirt. The coating has been recognized by Singapore's Building and Construction Authority's Green Mark Scheme.

In addition to using the technology for self-cleaning coatings for buildings, PJI Contract plans to make the coating available in a spray can for the consumer market. The company anticipates the TiO_2 coating will become one of its top-ten revenue generators.

Solar cells made of carbon nanotubes

A solar cell made of carbon nanotube (CNT) fiber has been demonstrated by researchers from Fudan University (Shanghai; www.fudan.edu.cn). University professor Huisheng Peng says, "For the fibers we use, the carbon nanotubes exhibit a high degree of alignment with much improved mechanical and electrical properties. Therefore those fibers greatly enhance the short current density, open voltage, and the energy conversion efficiency of solar cells." Also, the fibers are ultralight and flexible, and may see applications not possible with conventional solar cells.

The researchers used polydiacetylene-CNT-composite fibers. Peng says high-resolution transmission electron microscopy indicated a multiwalled structure for the building nanotubes with a diameter of about 8.5 nm. "Our nanotube fibers exhibit much higher specific strength and specific stiffness than current engineering fibers. For example, the specific strength of a nanotube fiber is 2.9 times that of T1000 — the strongest commercial fiber — and the specific stiffness is 3.9 times that of M70J — the stiffest commercial fiber," he says.

The reseachers found that the properties of CNT fibers are strongly dependent on the lengths of the nanotubes. The spinnable nanotubes they are now using are shorter than 1 mm. They will now try to make longer nanotubes.

Peng says the solar cells could see application in aerospace as in foldable solar panels or in photovoltaic skins, since they could be easily woven into clothes.

Desalination without pressure or membranes

After a nine-month field demonstration at BTX, Inc.'s Sleepy well site in Indiana, Pa., Altela Inc.'s (Albuquerque, N.M.; www.altelainc.com) AltelaRain 4000 water desalination system has been shown to turn Marcellus Shale wastewater into distilled water. The demonstration, funded by the U.S. Dept. Of Energy's National Energy Technology Laboratory (NETL; Pittsburgh, Pa.; www.netl.doe.gov), showed that 77% of the water stream can be treated onsite, and the average treated water cost per barrel was approximately 20% lower compared to previous total conventional disposal costs at the site. The system also significantly reduced the need for trucking wastewater from the site.

The AltelaRain system is based on thermal distillation, which desalinates and decontaminates brackish and polluted water by mimicking nature's way to make rain water. The system consists of a tower containing chambers separated by a thermally conductive, water-impermeable plastic sheet. On one side of the sheet, brackish water falls through the chamber and is evaporated by a cross flow of air. The water from the saturated air then condenses on the other side of the plastic, with the energy of condensation transferred across the plastic to heat the evaporation chamber. The system operates on low-grade waste heat, and requires no pressure, high temperatures, filters or membranes as used in alternative reverse-osmosis or mechanical vacuum-compression systems.

Based on the field data generated by the NETL demonstration, Altela increased the efficiency of its technology by more than 30%. The company also designed larger towers for the system and four AltelaRain 600 modules were sold and installed in Williamsport, Pa., to treat 100,000 gal/d of produced and flowback water from hydraulic fracturing. The commercial installation is a 50-fold increase in capacity over the demonstration unit, and is said to be the first of many planned facilities for the Marcellus Shale Basin and similar shale-gas basins throughout the U.S. ■

(Continued from p. 14)

18-month pilot-scale program (*CE*, March 2010, p. 12). An independent lifecycle analysis concluded that OPXBio's process has the potential to reduce greenhouse gas emissions by 70% compared to petroleum-based acrylic acid production.

The companies anticipate that a commercial bio-based acrylic acid could be on the market in three to five years.

Less TiO_2 for paint

Last month, Dow Coating Materials (DCM), a business unit of Dow (see above), introduced Evoque Pre-Composite Polymer technology — an additive that improves the particle distribution and light-scattering efficiency of TiO_2, thereby improving the "hiding" efficiency and allowing up to 20% less TiO_2 used in the formulation. Additional benefits include improved barrier properties, such as stain and corrosion resistance, says DCM. ❑

PETROLEUM REFINING IN THE SPOTLIGHT

Faced with increasing competition from abroad and more environmental regulations at home, U.S. refiners look to new process technology to remain relevant

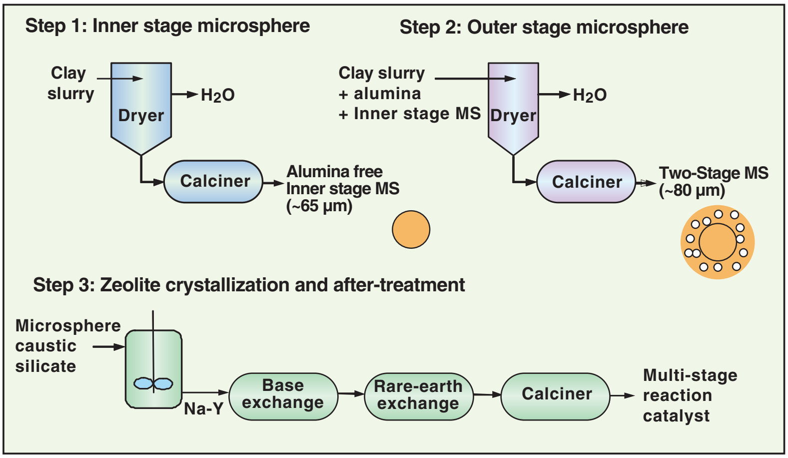


FIGURE 1. BASF has developed a three-step manufacturing process to produce its staged catalysts (MS = microsphere)

Motorists filling up at U.S. gasoline stations these days may think that petroleum refiners are making good profits, but it depends on where the station gets its fuel. The industry is plagued by overcapacity and is concerned about government regulations that call for greater use of renewable fuels and tougher pollution control. The National Petrochemical & Refiners Assn. (NPRA, Washington, D.C.; www.npra.org) is lobbying strongly in Washington against pollution-control regulations it claims are unfair and impede refiners' ability to produce fuels economically (see box, p. 18).

Profit margins improved somewhat in 2010 from a depressed 2009, but refinery utilizations "continue to hover in the mid-70s," says Alan Gelder, a consultant with Wood Mackenzie (Houston; www.woodmac.com). Gross refining margins in the first quarter of this year ranged from a "super normal" $12/bbl in the U.S. Gulf Coast for refiners that have access to low-cost crude, to only $0.08/bbl in Europe.

The combined North American-European market has excess capacity of about 3 million bbl/d, says Gelder, and even if most of this gap was closed, excess would remain until at least 2015, as previously deferred new capacity comes online. The U.S. Gulf Coast and northwestern Europe, where most of those continents' refining capacities are located, each has crude distillation capacity of about 8.9 million bbl/d (the two markets are intertwined, with the U.S. importing gasoline from Europe and exporting diesel fuel). Another problem for U.S. refiners is a growing shortage of heavy crude from Mexico and Venezuela — this after refiners had invested heavily in heavy-crude-upgrading equipment in recent years.

Meanwhile, the potential recovery of the U.S. refining industry may be derailed by lower-cost imports from large new refineries that are being built or are planned in Asia and the Middle East, says Rich Thomas, senior consultant with Baker & O'Brien, Inc. (Houston; www.bakerobrien.com). By 2015, the Middle East and India will have about 5 million bbl/d of export capacity. This includes several refineries in Saudi Arabia and the Reliance refinery in Jamnagar, India. The latter is "the single largest grassroots refinery ever built," with more than 1 million bbl/d of combined capacity, says Thomas.

Thomas and Gelder spoke at the recent NPRA annual meeting in San Antonio, Tex. Most meeting sessions focused on refinery operations and technology. Several companies offered new technologies for fluid catalytic cracking (FCC), alkylation and distillation.

New FCC technology

Staged reactions normally take place over fixed catalyst beds, but BASF Corp. (Houston; www.catalysts.basf.com) has developed multistage reaction catalysts for FCC. In this case, the catalyst itself contains multiple stages (Figure 1), each of which has a specific catalytic function, explains Alexis Shackleford, a BASF technical service engineer. BASF's initial offering is Fortress, a two-stage catalyst designed for residual feeds that contain traces of nickel, which is detrimental to catalyst performance. The catalyst's two functions are to crack the resid and passivate the nickel.

As in conventional catalysis, a specialty alumina in the catalyst traps the nickel and forms nickel aluminate.

However, Shackleford notes that nickel accumulates mainly on the catalyst surface, so BASF concentrates the alumina within 8 µm of the surface of an 80-µm microsphere, in contrast with the conventional method of distributing it evenly throughout the particle.

In a commercial trial in a refinery, Fortress reduced hydrogen yield by 0.05 wt.% (an indication of improved metals passivation) and coke yield by 0.7 wt.% (17%), compared with a conventional catalyst. This resulted in a 0.7 wt.% increase in yields of gasoline and liquid petroleum gas (LPG), says Shackleford.

In the catalyst manufacturing process, kaolin precursor microspheres are formed in a slurry, added to a second

NPRA EYES EPA REGS

The U.S. needs to develop "a real energy program" that includes petroleum as well as other sources of energy, said Charles Drevna, president of the NPRA, at the association's recent annual meeting in San Antonio, Tex. Consumers and policymakers should realize that "we are part of the solution instead of a problem," he said. "There's room enough for all sources of energy, but we want a level playing field."

In particular the association is concerned about measures taken by the U.S. Environmental Protection Agency (EPA; Washington, D.C.) to regulate emissions of greenhouse gases (GHGs) and to increase the amount of ethanol that must be mixed with gasoline.

In the case of ethanol, refiners typically sell gasoline that contains 10% ethanol (E10), a safe level of ethanol that does not affect vehicle performance. This is within the current requirements of EPA's Renewable Fuels Standard (RFS), which calls for the industry to use increasing amounts of ethanol (13.8 billion gal this year, rising to 36 billion gal by 2025). Refiners are faced with hitting the "blendwall" within the next two years or so, when the total volume of ethanol required will push the average ethanol content of gasoline above the 10% level.

However, EPA has made decisions that already permit the use of 15% ethanol (E15) in cars and light trucks for model years 2001 and later. NPRA and other organizations have challenged the decisions in federal court, contending that EPA violated the Clean Air Act (CAA) by issuing partial waivers that allow the use of E15 in some engines, but not others. "EPA's decision to allow E15 in the marketplace before adequate testing has been conducted disregards the safety of consumers," says Drevna.

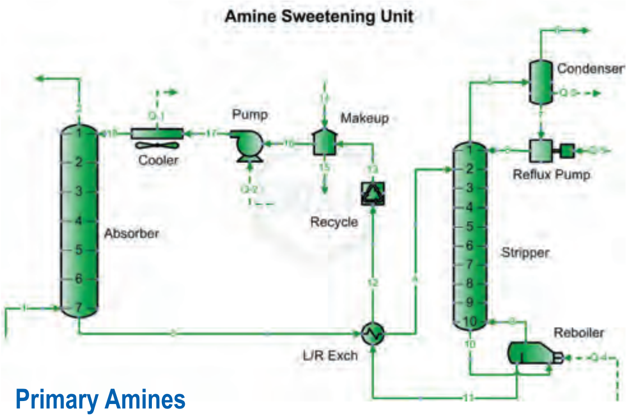
In the case of GHGs, NPRA has been supporting legislation that would transfer the authority to regulate GHGs from the EPA to Congress. A bill that would do this was recently approved by the House of Representatives and similar legislation was pending in the Senate at press time.

Gregory Scott, NPRA's executive vice-president and general counsel, notes that in 2008 the Supreme Court ruled that EPA could regulate GHGs under the Clean Air Act. As a result, last year EPA ruled that industry (including petroleum refiners) would have to develop a Best Available Control Technology (BACT) standard for major refinery additions, and to show that the additions would not cause "significant deterioration." Also, next December EPA is scheduled to propose a New Source Performance Standard (NSPS) for GHGs, to be finalized next year. ❐

PROCESS INSIGHT

Selecting the Best Solvent for Gas Treating

Selecting the best amine/solvent for gas treating is not a trivial task. There are a number of amines available to remove contaminants such as CO_2, H_2S and organic sulfur compounds from sour gas streams. The most commonly used amines are methanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA). Other amines include diglycolamine® (DGA), diisopropanolamine (DIPA), and triethanolamine (TEA). Mixtures of amines can also be used to customize or optimize the acid gas recovery. Temperature, pressure, sour gas composition, and purity requirements for the treated gas must all be considered when choosing the most appropriate amine for a given application.



Primary Amines

The primary amine MEA removes both CO_2 and H_2S from sour gas and is effective at low pressure. Depending on the conditions, MEA can remove H_2S to less than 4 ppmv while removing CO_2 to less than 100 ppmv. MEA systems generally require a reclaimer to remove degraded products from circulation. Typical solution strength ranges from 10 to 20 weight % with a maximum rich loading of 0.35 mole acid gas/mole MEA. DGA® is another primary amine that removes CO_2, H_2S, COS, and mercaptans. Typical solution strengths are 50-60 weight %, which result in lower circulation rates and less energy required for stripping as compared with MEA. DGA also requires reclaiming to remove the degradation products.

Secondary Amines

The secondary amine DEA removes both CO_2 and H_2S but generally requires higher pressure than MEA to meet overhead specifications. Because DEA is a weaker amine than MEA, it requires less energy for stripping. Typical solution strength ranges from 25 to 35 weight % with a maximum rich loading of 0.35 mole/mole. DIPA is a secondary amine that exhibits some selectivity for H_2S although it is not as pronounced as for tertiary amines. DIPA also removes COS. Solutions are low in corrosion and require relatively low energy for regeneration. The most common applications for DIPA are in the ADIP® and SULFINOL® processes.

Tertiary Amines

A tertiary amine such as MDEA is often used to selectively remove H_2S, especially for cases with a high CO_2 to H_2S ratio in the sour gas. One benefit of selective absorption of H_2S is a Claus feed rich in H_2S. MDEA can remove H_2S to 4 ppm while maintaining 2% or less CO_2 in the treated gas using relatively less energy for regeneration than that for DEA. Higher weight percent amine and less CO_2 absorbed results in lower circulation rates as well. Typical solution strengths are 40-50 weight % with a maximum rich loading of 0.55 mole/mole. Because MDEA is not prone to degradation, corrosion is low and a reclaimer is unnecessary. Operating pressure can range from atmospheric, typical of tail gas treating units, to over 1,000 psia.

Mixed Solvents

In certain situations, the solvent can be "customized" to optimize the sweetening process. For example, adding a primary or secondary amine to MDEA can increase the rate of CO_2 absorption without compromising the advantages of MDEA. Another less obvious application is adding MDEA to an existing DEA unit to increase the effective weight % amine to absorb more acid gas without increasing circulation rate or reboiler duty. Many plants utilize a mixture of amine with physical solvents. SULFINOL is a licensed product from Shell Oil Products that combines an amine with a physical solvent. Advantages of this solvent are increased mercaptan pickup, lower regeneration energy, and selectivity to H_2S.

Choosing the Best Alternative

Given the wide variety of gas treating options, a process simulator that can accurately predict sweetening results is a necessity when attempting to determine the best option. ProMax® has been proven to accurately predict results for numerous process schemes. Additionally, ProMax can utilize a scenario tool to perform feasibility studies. The scenario tool may be used to systematically vary selected parameters in an effort to determine the optimum operating conditions and the appropriate solvent. These studies can determine rich loading, reboiler duty, acid gas content of the sweet gas, amine losses, required circulation rate, type of amine or physical solvent, weight percent of amine, and other parameters. ProMax can model virtually any flow process or configuration including multiple columns, liquid hydrocarbon treating, and split flow processes. In addition, ProMax can accurately model caustic treating applications as well as physical solvent sweetening with solvents such as Coastal AGR®, methanol, and NMP. For more information about ProMax and its ability to determine the appropriate solvent for a given set of conditions, contact Bryan Research & Engineering.

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Bryan Research & Engineering, Inc.
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979-776-5220 • www.bre.com • sales@bre.com
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slurry that has a high concentration of specialty alumina, then spray-dried to obtain a two-stage microsphere of the desired size. The catalyst structure is completed in a crystallizer, in which zeolite is grown from the kaolin and binds each particle together.

Commercial trials of a second multistage catalyst, called HALO, are scheduled to start shortly. HALO is designed to provide high attrition resistance for gas-oil feeds where attrition is a concern.

Gasoline yield has been improved by 6% and coke production reduced by 15% in pilot tests of a new zeolite FCC catalyst developed by Rive Technology, Inc. (Monmouth Junction, N.J.; www.rivetechnology.com). Rive is working with Grace Davison (Columbia, Md.; www.grace.com) to further develop and commercialize the technology, says Barry Speronello, a research fellow with Rive. The catalysts differ from conventional zeolite catalysts in that they contain a small percentage of mesopores with a pore diameter of about 40 Å. These mesopores are integrated to form "molecular highways" throughout the zeolite crystals, the bulk of which consist of conventional micropores of <10 Å.

Speronello says that while standard zeolite catalysts are very efficient at cracking smaller FCC feed molecules that can enter the micropores, many feed molecules are too large to enter and must first pre-crack less selectively, either thermally or outside the zeolite. Similarly, larger product molecules, of gasoline or light cycle oil, fit tightly in the micropores, so they can stay longer and be overcracked to less valuable gases and coke. The molecular highways largely avoid these problems, he says.

Rive produces the zeolite by a proprietary process in which surfactant micelles are used to create the mesopores. Rive and Grace plan to begin refinery trials in late spring and expect to commercialize the technology in 2012.

Integrated & Proven Catalyst Technologies Corp. (Inprocat; Houston; www.inprocat.com) has developed a process to remove undesired catalyst fractions that limit FCC-unit productivity. In the process, called Quanta, catalyst is taken out of the FCC unit, treated to remove the unwanted particles, then returned to service.

Augusto Quinones, president of Inprocat, declines to describe the process, but says its steps take advantage of the different physical properties of the catalyst particles and in pilot tests on resid feed, the method improved gasoline yield by 2 wt.% and lowered coke production by 5 wt.%. Inprocat is forming a joint venture with Porocel International LLC (Houston) to commercialize the technology.

Organic peroxides are used to remove sulfur from sour crudes in an oxydesulfurization process being developed by Auterra Inc. (Malta, N.Y.; www.auterrainc.com). In the FlexDS continuous process, crude is fed to a fixed-bed reactor, where 99+% of its

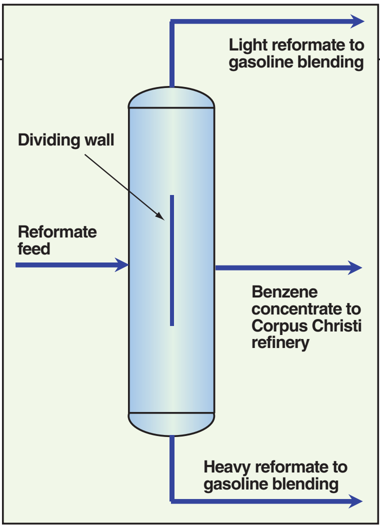


FIGURE 2. Valero Energy uses dividing-wall columns to obtain a concentrated benzene stream from reformate

sulfur content is converted to sulfones over a proprietary catalyst. In the last step, the sulfones are separated from the crude by a caustic medium and recovered as sulfur dioxide or gypsum.

Eric Burnett, president, says the process also lowers nickel, iron and vanadium contaminants, which are removed in the last step of the process. Auterra has been operating a small pilot plant and is building a larger, 2-bbl/d unit. Burnett estimates that the capital cost of a commercial plant would be one-third that of an equivalent hydrotreating installation, with "significantly lower" operating costs.

'Solid' alkylation

In recent years, a number of companies have developed solid-acid alkylation catalysts to substitute for the conventional sulfuric acid and hydrogen fluoride processes, which are environmentally hazardous. However, no commercial units have been built that use these technologies, says James Nehlsen, process development manager for Exelus, Inc. (Livingston, N.J.; www.exelusinc.com). "The biggest stumbling block is that refiners are reluctant to try something new," he says.

Nehlsen believes Exelus has a better answer with its ExSact process, which has been licensed by AB Mazeikiu Nafta (Mazeikiai, Lithuana). ExSact uses a specially designed zeolite catalyst in a dual swing-bed reactor at 75°C and about 300 psig. Acceptable feeds range from ethylene to butenes, says Nehlsen.

The catalyst triples the life of other solid acid catalysts, he claims. Also, the reactor is carbon steel, so the capital cost is expected to be 60% below that of a sulfuric acid alkylation plant, says Nehlsen, and the operating cost 5% lower.

Benzene and the dividing wall

A new regulation that requires the benzene content of gasoline to be reduced to 0.62 vol.%, from the previous requirement of 1.0 vol.%, went into effect January 1. The requirement is part of the second phase of the Mobile Source Air Toxics (MSAT II) regulation from the U.S. Environmental Protection Agency (EPA: Washington, D.C.; www.epa.gov).

Most refiners have already developed an approach to meet the regulation, says Bryan Glover, a senior business leader for naphtha and gasoline technology with Honeywell's UOP LLC (Des Plaines, Ill.; www.uop.com). Smaller refineries, for which the cost is more burdensome, have been granted extensions to 2015.

Valero Energy Corp. (San Antonio, Tex.; www.valero.com) came up with a novel and less expensive way to meet the benzene rule. Instead of building a costly new benzene extraction plant, Valero opted to produce benzene concentrate by distillation at four of its refineries and ship the concentrate to its existing aromatics recovery plant in Corpus Christi, Tex.

The company chose dividing-wall distillation columns (DWCs) to produce the concentrate from reformate and started up three DWCs at the end of 2010. A fourth is scheduled to start up in 2011.

A DWC's advantage is that it separates three-component mixtures, a fractionation that would otherwise require two columns in series. "Compared with a two-column system, a DWC saves capital costs, uses less energy and has a smaller footprint," says Daryl Hanson, Valero's technical fractionation adviser.

In Valero's process, reformate is fed to the middle of the column, on one side of the vertical wall. The lighter fraction flows upward and exits the top of the column, while heavier material is recovered from the bottom. A third fraction, a benzene-rich stream, flows around the top and bottom ends of the wall and is recovered midway up the column on the opposite side of the dividing wall (Figure 2).

A DWC recovers essentially all benzene in the feedstream while maximizing benzene purity in the concentrate, says Javier Quintana, Valero's technical reforming and aromatics adviser. "With conventional fractionation in a single column, you would achieve only one-third to one-half of the concentration, so it would cost two to three times as much to transport the material."

The DWCs "are meeting our expectations for performance," says Quintana, adding that a DWC typically costs 30–40% less than a two-column system and uses about 30% less energy.

The Valero installations are a significant step forward for DWC technology and mark the first use of DWCs in the Western Hemisphere, says William Townsend, manager of KBR's London Technology Center. DWCs were first commercialized in the 1980s, but acceptance has been slow. "People still have reservations about operability and control," says Townsend. Today there are only a few dozen DWCs in the world, he says, with most in BASF plants.

UOP includes a DWC in its Pacol Enhanced Process (PEP), part of a linear alkyl benzene (LAB) complex that selectively removes aromatics in the olefin/paraffin feed. The DWC separates a mixed stream into light paraffin, aromatics and benzene, which is then used to obtain LAB. So far, UOP has designed five PEP units that include a DWC, three of which are in operation today. ■

Gerald Parkinson

GETTING A REACTION

Continuous flow and specialty batch reactors with built-in flexibility allow processors to get more reactions with less equipment

De Dietrich Process Systems

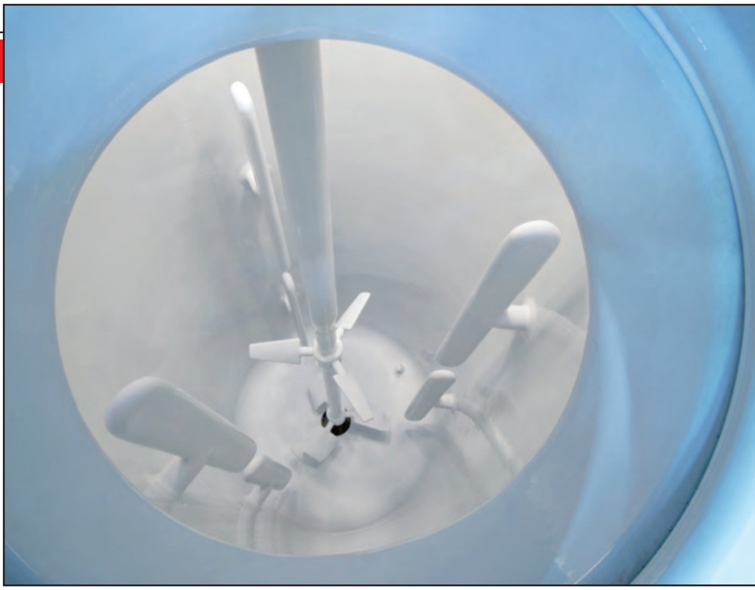


FIGURE 1. The newly designed OptiMix HE models use the thermal fluid contained in the half coil to create a circulation through the baffles, which results in an increased heat transfer area that shortens cycle times

As chemical processors continue their quest to process more with less equipment, they are seeking reactors capable of helping with this endeavor. For this reason, many are turning to continuous flow reactors because they provide scaleability and flexibility. However, vendors of specialty batch reactors are making every effort to provide these same characteristics in their models, as well. As a result, there are a lot of new technologies to choose from, making the hardest part finding the reactor that will supply the most benefits to a particular process.

"There are two key issues in the chemical process industries (CPI) when it comes to reactors: scaleability and flexibility," says Robert Ashe, president of AM Technology (Cheshire, U.K.). He says scaleup has been a major factor for years in the CPI, which has often been solved via the use of batch or microreactors. "However, these are effectively scale limited, so when processors try to increase the scale, they often run into problems."

Ashe explains by saying that an ideal batch reactor performs in the same way as an ideal flow reactor, but with batch, as the system gets larger, it moves away from the idealology quickly because of the mixing and heat transfer constraints, moving the process away from true batch and closer to fed batch. As a result, many processors have started looking at microreactors, which allow them to vary the parameters under ranging conditions to help accelerate the development cycle, and engineers have been finding that in some processes, there are substantial improvements in yield, quality and cycle time. But, they're still left scratching their heads as to how they can exploit those capabilities at higher throughputs (for more on microreactors, see *CE*, April, pp. 17–20).

Ashe continues to say, "Once you mess around with the scale of microreactors, the capabilities you see tend to suffer the same [as] they do in batch reactors — meaning you lose a lot of them."

Recently, processors have realized that flow reactions allow them to make the larger volumes they want while still permitting variations of parameters. Flow chemistry also allows them to get a stream of data from one experiment, showing how the system will perform under ranging conditions, which can help accelerate the development cycle and accurately demonstrate how it will work out on the larger scale, he says.

AM Technology

FIGURE 2. A reactant is being added to the fourth stage of a 10-stage Coflore ACR reactor

Flexibility, too, is becoming increasingly important. Continuous reactors have been used in the CPI for years, but usually for dedicated purposes. Ashe says he is now seeing, especially in pharmaceuticals and fine chemicals, that there is a wide variety of reaction types or a single product being synthesized in a series of steps. "The idea that processors have a single reactor doing a dedicated job is a big obstacle for them, given the fact that they are often processing more than one product or varying the steps of a single product."

Martin Jonsson, sales and marketing manager with Alfa Laval's reactor technology group (Lund, Sweden) agrees that flexibility is a growing issue and adds that batch reactors were previously the go-to choice when flexibility was needed in a process. He says many chemical processors come from an environment of batch reactors because it is possible to run different types of chemistry while using the same reactor, but because the benefits of flow technology are garnering a lot of attention, more processors are beginning to inquire about flow chemistry. "They want to know, 'Can we perform a fast reaction in the same reactor as a slower reaction?'" he says. "They are looking for flow reactors that enable them to do both types of reactions in the same equipment."

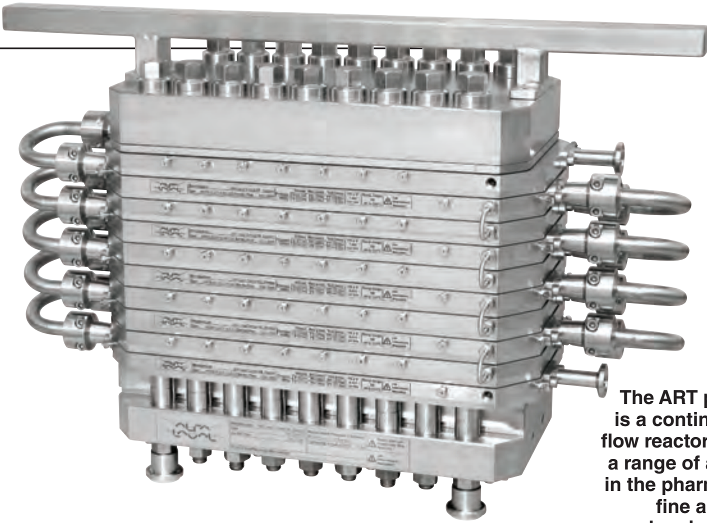
And, several vendors — including Alfa Laval, AM Technology, Corning S.A.S. (Avon, France) and Buss Chem Tech (Pratteln, Switzerland) — are delivering options that can.

Alfa Laval's ART plate reactors are continuous, multi-purpose flow reactors for a wide range of applications within the fields of pharmaceuticals, fine and specialty chemicals. The reactor consists of a series of cassettes. The core of each of these is a specially designed process channel plate, into which the process and utility channels are machined. These are designed to promote optimum mixing and heat-transfer performance.

Different numbers of these cassettes can be stacked vertically and held together in a frame. Each cassette has one process inlet and one process outlet port. Secondary ports make it possible to add specific reactants or to insert measuring and monitoring devices that are positioned along the length of the plate to provide access to the main process channel. The process channels are connected in series to ensure the required residence time. The utility channels can be connected in series or in parallel and each is fitted with two thermocouple ports.

The reactor frame holds the plates together in compression, thus sealing the fluid channels. This frame is spring loaded to ensure that the correct sealing force is maintained at all times, even when extreme temperatures are involved.

Jonsson says because the modular arrangement makes it multi-purpose, the ART plate reactor can help convert



Alfa Laval

FIGURE 3. The ART plate reactor is a continuous, multi-flow reactor suitable for a range of applications in the pharmaceuticals, fine and specialty chemical industries

batch processes to continuous ones.

In a similar vein, Buss's BCT Loop Reactor can help processors make the transition from batch to continuous. The reactor is being used increasingly as a continuous reactor system due to its ability to intensify the reaction and to shorten the reaction time in new and existing plants.

In the BCT, the raw material is dosed into the reactor system near the reaction mixer. In the reaction mixer, gas is dispersed into fine bubbles and reacts efficiently with the liquid raw material. The heat exchanger ensures stable operation conditions, and final product can be discharged from the self cleaning, in-line filter which keeps all catalyst in the reactor system.

Under the constant reaction conditions achieved by this design, catalyst lifetime increases, and the consumption of catalyst is lower than that of batch reactors. Catalyst is replaced periodically using an automatic dosing and discharging system.

Meanwhile, AM Technology offers its Coflore flow reactors, which are multi-stage flow reactors designed to deliver good plug flow and mixing over a range of operating conditions. Available in sizes from laboratory to industrial scale, the Coflore design employs a patented mixing technique where free moving agitators within each reaction stage promote mixing when the reactor body is subjected to lateral shaking. This generates intense mixing without the need for rotating shafts, mixing baffles or mechanical seals. Problems of centrifugal separation (when two phases are present) are also eliminated.

Continuous flow benefits

Aside from the improved catalyst and solvent use, experts say continuous flow offers a host of other potential benefits. A major advantage for many processors is time savings. "The batch reaction itself may take only five minutes, but before you can run that reaction, you have to go through a whole sequence of operations," says Ashe. "You have to inert the vessel, load it with solvent and heat it to the right temperature before you can start the reaction. At the end of the reaction, you have to cool it down, so that a five minute reaction may actually require a five or six hour cycle time."

He says in a flow reactor, those different operations are working in parallel, meaning the process is heating up and feeding at the same time that it is reacting and cooling down, substantially compressing the total operating time.

Other opportunities relate to the way flow reactors perform. Using a flow reactor, processors can operate closer to the ideal process control conditions under which the particular chemistry will benefit. For example, an unstable product can be reacted to cool down quickly before impurities build up. The effects of back mixing could also be reduced, further reducing the chance of impurities in product. The tighter control — especially the ability to start the second reaction at the optimum point, improved heat transfer capabilities and ability to stop a reaction at any point during the process — permits reactions that normally would be unsafe to run in batch processors to be performed in flow reactors.

REACTOR PROVIDERS

Alfa Laval	www.alfalaval.com
AM Technology	www.amtechuk.com
Buss ChemTech	www.buss-ct.com
Corning	www.corning.com
De Dietrich Process Systems	www.dedietrichddz.com
Parr Instrument	www.parrinst.com
Pfaudler	www.pfaudler.com

"Typically if you perform a reaction under good flow conditions, you get a substantial uplift in yield, faster reaction time, lower levels of impurities, and improved safety, and if the reaction is going faster as it often will in a flow reactor, the size of the equipment can come down substantially," notes Ashe.

These benefits can be enhanced, especially on smaller scale, using continuous flow reactors as part of a turnkey system, says Steve Ciucci, chief operating officer with Parr Instrument (Moline, Ill.), which provides the 5400 continuous flow tubular reactor for development and research purposes. "If you are doing research, you have to know how you're going to handle feedstocks and under what temperature, pressure, pH and other conditions you will run your reaction to reap the optimum amount of benefits. Turnkey systems are the best way to achieve that," he says. A turnkey system would include not only the tubular reactor, but mass flow controllers, automation controller, automated valves, backpressure regulators, as well as probes and detectors used to measure the conditions during the research process.

Specialty batch reactors

While the benefits associated with continuous flow reactors may sound intriguing, even flow reactor vendors urge users not to count out batch reactors. "While there are clearly a number of benefits associated with continuous flow reactors, there is still chemistry that works well in batch reactors and will receive only limited benefits using flow technology," says Jonsson.

And for these applications, specialty batch reactor vendors are upping their game in order to provide the same level of benefits, efficiency and service

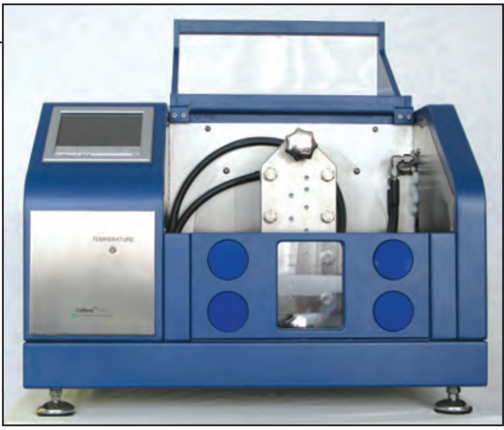


FIGURE 4. This Coflore ACR platform has an attached reactor block. This is a laboratory scale flow reactor with ten mixed reaction stages

as continuous flow. For example, Tom Adams, director of technical sales with De Dietrich Process Systems (Union, N.J.), says his company, which provides glass lined batch reactors, has tried to focus on improving process efficiency within the reactor in the areas of mixing and heat transfer and in terms of how and where users add different materials. The company has also made strides to improve associated operations like cleaning, maintenance and contamination issues to increase the speed and efficiency of cycle times.

"All different aspects of improving the process, making the reaction more efficient, taking less time between batches — whether on the process side or the steps that happen between batches — have been improved," he says.

Further, flexibility is also an option. "Glass lined reactors offer flexibility over a range of temperature and materials," he says. "Some alloys work well in some chemistries, but not others, whereas a glass lined reactor has a very broad corrosion resistance across the whole spectrum, and allows temperatures and pressures across a wide range, as well."

This flexibility is important in today's economy, says Adams, as many companies are making the move toward contract or flexible manufacturing operations in which they will be running a different product each week or month.

Efficiency is also important for batch reactors, which led De Dietrich to introduce the OptiMix HE (heat exchange) for process intensification. The newest design uses the thermal fluid contained in the half-coil in order to create a circulation through the baffles. This results in an increased heat transfer area up to 25%, enabling a more homogeneous, faster thermal management, which helps shorten cycle times.

So how to decide whether an improved specialty batch reactor or a continuous flow reactor will be right for a specific process? In most cases the decision will be based on what type of chemistry is running and which reactor will work best for that chemistry. However, where there are safety concerns or where the chemistry has been changed to work with a continuous process, a flow reactor will likely be the best option. "When you run a reactor at cold temperature to minimize the heat release that would definitely be another area where a flow reactor would work best because it can remove heat much more efficiently," says Jonsson. "I also think when it comes to mixing sensitive reactions that there could be advantages with flow over batch."

Before making the switch from batch to continuous, Ashe cautions processors to educate themselves. "The chemical industry has been using batch reactors for a long time and the know-how in terms of how to scale up and use them is well established," he says. "There is a lot of ground to be covered before the same level of knowledge is out there in terms of flow processes."

With that in mind, he says processors need to manage their expectations for flow. "The idea that they can have a continuous process from start to finish using flow methods is nice in principle, but in practice it's different because there are many processes that are difficult to operate in flow by nature of the products they are handling."

That said, all parties agree it is best to closely study the chemistry that will be occurring in the reactor and speak to providers of both flow and batch reactors to see which will best handle the process while providing the highest level of efficiency. ■

Joy LePree

Fractionation Column

Low cost bidding

Mike Resetarits is the technical director at FRI (Stillwater, Okla.; www.fri.org), a distillation research consortium. Each month, Mike shares his first-hand experience with *CE* readers

Raise your hand if you ever regretted going with the low cost bidder. Keep your hand raised if the low cost bidder ever yielded you the highest cost result. If your officemate is staring at you quizzically, pretend to be working out the shoulder kink that originated two evenings ago when you played racket ball with the vice president of human resources at the gym.

Distillation columns at Fractionation Research Inc. (FRI) are driven by steam, which originates in a boiler. Oklahoma State University (Stillwater, Okla.; www.okstate.edu) owns the boiler, and the university personnel assist with controls, maintenance, inspections and environmental compliance. Repairs are undertaken at FRI's expense. For many years, almost every year, the repair bills were high. Nevertheless, it passed every annual state inspection.

The subject boiler is cylindrical with a diameter of 8 ft and a length of 22 ft. It is rated at 600 hp. It is comprised of a natural gas combustion chamber, four tube passes for hot gases and a shell wherein water is vaporized. The water/steam chamber typically functions at 200 psig.

During March of 2009, an alert operator pointed out that steam was issuing from two small, hot gas vent holes. The boiler was shut down immediately — and opened. As always, cracks were found in the tube sheet and many tube welds. Until that time, the university had usually recommended a low-cost boiler repair company, and FRI usually had gone down that path.

In 2009, however, FRI decided to consider other options including a new boiler, a new larger boiler, a used boiler and a used larger boiler. Twice, FRI visited an excellent company that specializes in used boilers. Additionally, four meetings were held with university personnel. The decision trees on the conference-room whiteboard were so large that they extended onto walls, floors and ceilings. None, however, bore useful fruit.

I was the decision maker. The cost of every option was at FRI's expense. It was the fourth meeting, and it was decision time — and I wasn't ready. In a semi-exasperated state I stumbled upon a question that I never asked the university personnel before, "What would you do?" They answered almost in unison, "That's easy, we'd hire Lucky Wilson." "Who the heck is Lucky Wilson?" I said. "He's the best boiler man in the state, but we can't use him because he is never the low cost bidder. We don't even ask him to bid anymore."

You have already probably guessed as to how this story turned out. Lucky Wilson and his team inspected the damage, welded the tube sheet, rewelded the tube ends, and the boiler has performed very well ever since. The cost to FRI was roughly an additional 20% over the low cost bidders.

Cost is an important variable in any project, but, performance is the most important variable. A multiplicity of bids makes sense, but, it also makes sense to allow a vendor whose done something efficiently before, to do it again.

Unfortunately for you, Lucky Wilson's real name has been withheld to prevent the Kansans and Texans from finding out about him. FRI doesn't want his price to go too high. ■

Mike Resetarits
resetarits@fri.org

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Pressure measurement considerations

Pressure measurement in the chemical process industries (CPI) is crucial to many unit operations, and selecting the most effective pressure sensors for a given situation can be complicated by a range of factors. An initial key to selection is establishing an accurate understanding of exactly what is meant when the term "pressure" is used, since there are different types. Other critical considerations include the following: media compatibility, environment, process control, electrical isolation and output signal.

Pressure types

Pressure measurements can be affected by what type of pressure sensing equipment is used, and understanding the different types of pressure is a prerequisite for selecting sensors or gages for your application. Accuracy can suffer if pressure types are misunderstood. Differences in pressure types have everything to do with the reference point for a given pressure measurement. Here are definitions for five common pressure types:

Gage pressure — Gage pressure, the type that most people first imagine when thinking of measuring pressure, covers a positive pressure range. Its zero (reference) point is set at ambient pressure, and it is unaffected by changes in barometric pressure because the sensor is open to the atmosphere. This allows the current atmospheric pressure to be the reference against which all subsequent changes in pressure are measured. Gage pressure effectively can measure pressures below 1 psi, as well as pressures up to 200,000 psi.

Vacuum pressure — Like gage pressure, vacuum pressure's zero point is ambient pressure, and sensors measuring it are vented — and therefore unaffected by barometric change. Since vacuum pressure refers to a negative pressure range, the distinction between vacuum and gage pressure is really a function of direction and magnitude. Sensors measuring this type are commonly used in vacuum pump systems and applications where suction is required.

Compound gage pressure — This pressure type is the combination of gage and vacuum pressure in that it involves both positive and negative pressure changes. Its zero is therefore set at atmospheric pressure, and it is vented. The value of a compound gage is seen when used in applications where the pressure fluctuates from positive to negative and vice-versa. Sensors measuring this pressure type typically do not exceed 100 psi in range.

Sealed pressure — Sealed pressure refers to a situation where the pressure sensor is not vented. This is primarily done to protect the sensor, by avoiding the introduction of moisture or dust into the sensor housing. The sensor is sealed with a pressure equal to the atmospheric pressure at the time of sealing. This pressure then becomes the reference pressure against which all pressure changes are measured.

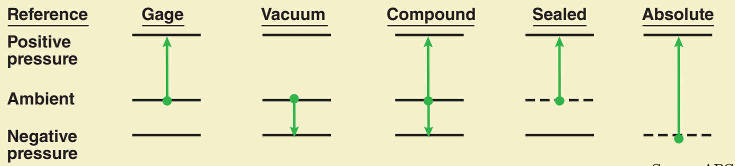
Because it is sealed, unvented pressure sensors are unavoidably affected by barometric pressure changes. It is not typically used in low-pressure applications because the barometric shift of a few psi would affect measurement accuracy significantly. However, at 1,000 psi and above, the relatively small shift would go unnoticed and can be smaller than the error band of the sensor.

In one real-world case, a sealed pressure type sensor was calibrated at a manufacturing facility in Utah and then shipped to Indiana. The atmospheric pressure differences between the locations caused the unit to fail in Indiana, while it worked properly in Utah.

Absolute pressure — Absolute pressure is used when the zero point must be set to absolute zero. To achieve this, the sensor is also sealed, but under a vacuum condition, so that air molecules are removed from the enclosure. This then becomes the reference point and allows measurements to be made with reference to absolute zero. By definition and design, this is sensitive to barometric changes. Unlike sealed pressure, absolute pressure is often used in low-pressure applications measuring atmospheric conditions, such as in weather stations, aircraft and laboratories.

MAIN FACTORS TO CONSIDER FOR CHEMICAL PRESSURE MEASUREMENTS		
Factor	**Reason**	**Solution**
Media compatibility	A pressure-sensing element will come in contact with varying concentrations of chemicals, temperatures and pressure ranges depending on the industry sector in which the application appears, including petrochemicals, food, pharmaceuticals, water, refrigeration, alternative energy or power generation	Pressure sensors constructed from one-piece 316L stainless steel, nickel and cobalt-based superalloys are free from internal welds, O-rings and very thin isolation diaphragms offer excellent media compatibility for most chemicals. The one-piece design ensures outside media do not permeate the sensor body
Process control	New processes for heavy oil, alternative energy and water purification systems demand extreme operating conditions, such as low ambient temperatures (–50°C), high media temperature (150°C), as well as complex and volatile gas-liquid mixtures	Pressure sensors with new technologies and wetted materials are needed. High-temperature, oil-free, bulk silicon piezoresistive sensors are ideal for these emerging markets. Superalloys, such as Inconel, Hastelloy and Waspalloy, with thick sensing diaphragms, offer the best solutions without the need for complex sensor packaging and expensive secondary seals
Environment	Rain, ice, dust and pressure washers can cause water to seep into sensor housings and cause electronics to shortcircuit	Absolute and sealed-gage reference pressure sensors protect electronics from these conditions. If venting is required to maintain accuracy at low pressures, provisions must be made for dry, non-corrosive environments for sensors to "breathe"
Electrical isolation	Improper grounding and lightning strikes can cause electrical failures of pressure sensors, as a result of isolation failure	Pressure sensors with custom electronics and a sensing element able to withstand 500 V d.c. isolation can work in extreme electrical conditions
Output signal	Depending on distance and environment, certain output signals can experience signal loss or generate noisy signals	A 4–20-mA output signal is recommended for transmission lengths greater than 15 ft in environments with electrical noise

Table content submitted by Karmjit Sidhu, vice president of business development at American Sensor Technologies (Mount Olive, N.J.; www.astsensors.com)



Source: APG

Notes

Material on pressure types was contributed by Elden Tolman, product design engineer at Automation Products Group Inc. (APG; Logan, Utah; www.apgsensors.com).


Mroz


Aydin


Dumba


Simm


Sipla

Chester Mroz becomes president and CEO of **Yokogawa Corp. of America** (Houston), the North American division of Yokogawa Electric Corp.

Alaaddin Aydin becomes sales director for Germany for **Maag Group** (Grossostheim, Germany), a maker of gear pumps and pelletizing systems.

Greene's Energy Group (Houston), a provider of services for drilling, production, pipeline, and process operations, names *Maury Dumba* vice president of business development.

Integrated Project Services (Lafayette Hill, Pa.), a full-service engineering, construction, commissioning and qualification company dedicated to the life sciences industry, names *Jeffrey Odum* biotechnology expert and director of its North Carolina operation.

The Penspen Group (Surrey, U.K.), an independent family of companies that provides a range of services to the oil-and-gas industries for pipelines, transportation, storage and production facilities, appoints *Mike Simm* as its new director of oil-and-gas-field engineering.

Greg Sipla is named executive vice president of **Tegrant Corp.** (DeKalb, Ill.), a manufacturer of engineered packaging solutions and energy-efficient components.

UOP LLC (Des Plaines, Ill.), a Honeywell company, names *Mike Millard* vice president and general manager of its catalysts, adsorbents and specialties business. ■

Suzanne Shelley

FOCUS ON

Packaging, Transportation and Storage

New Pig

Milliken

Beumer Group

Pharmacontrol Electronic

Efficiently stack a wide range of packages

The Robotpac (photo) is a fully articulated and fully automatic robot that reliably and efficiently palletizes and depalletizes even complex packing situations. Designed for use with a wide range of packaging containers — such as bags, crates, canisters or trays — the Robotpac also saves floorspace, and features an easily adaptable gripping system. — *Beumer Group GmbH, Beckum, Germany*
www.beumer.com

A plastic clarifier that produces glass-like transparency

Millad NX 8000 is a clarifying agent for polypropylene (PP) that can render the plastic exceptionally clear and bright. The properties of PP treated with the Millad NX 8000 allow for packaging materials that have high overall "shelf appeal" for many consumers, according to the company (photo). Further, with this PP clarifier, transparency is no longer limited to thin or highly oriented parts, allowing thicker-walled parts to approach the look of clear materials, such as glass or amorphous polymers. — *Milliken & Co., Spartanburg, S.C.*
www.millikenchemical.com

This drum lid is ideal for flammable or combustible materials

Ideal for flammable or combustible materials, the latching drum lid from this company has fusible plugs that are approved by the insurance company FM Global. The latching drum lid (photo) can convert a 55-gal steel drum into a safe storage container for oil- or solvent-soaked materials. It can easily attach to new or reconditioned drums, and allows access to drum contents without having to remove the drum ring, lid or bolt. The latching handle opens and closes easily with one hand. In case of a fire, the seals melt to vent pressure and prevent drums from bursting. — *New Pig Corp., Tipton, Pa.*
www.newpig.com

Apply serial numbers to each unit for secure supply chain

The Track & Trace electronic monitoring system (photo) from this company is for pharmaceutical packaging. It

Note: For more information, circle the 3-digit number on p. 78, or use the website designation.

Windmöller and Hölscher

CDF

Colder Products

provides a way to individually label each packaging unit (including single folding boxes, shipping cases and pallets) with a serial number. The codes guarantee verification of individual units and allow complete verification of the unit's source. The Track & Trace System increases patient safety by preventing the use of counterfeit medicines in the pharmaceutical industry. — *Pharmacontrol Electronic GmbH, Zwingenburg, Germany*
www.pharmacontrol.de

Containers that offer environmental benefits

The Cheertainer is a form-fit, bag-in-box container (photo) that offers environmental benefits in logistics, storage and waste disposal, the company says. For example, by shipping flat, the Cheertainer can reduce transport and handling costs by ten times compared to rigid packaging. Also, the bag-in-box format consumes less plastic in product manufacture than rigid packaging. This translates to a reduction in landfill disposal by 92%, says the company. The Cheertainer is available in sizes from 3 to 25 L. — *CDF Corp., Plymouth, Mass.*
www.cdf1.com

This pump is a single-use version of the original

Designed for filling containers with pharmaceutical products, a new version of this company's rolling diaphragm pump is designed for one-time use. The single-use pumps are gamma-irradiated to ensure complete sterilization of the system, and are pre-validated. They can eliminate the cleaning and sterilization step from pharmaceutical and biological product processes. — *Bosch Packaging Technology, Minneapolis, Minn.*
www.boschpackaging.com

This program allows realtime supply-chain product tracking

A radio-frequency identification (RFID) pilot program by this Norwegian organization allows participating manufacturers and food producers to track their products throughout the supply chain in realtime. The organization leases plastic pallets equipped with RFID tags for product transportation. Handheld RFID readers read the tags and encode the serial shipping container code into the tag user's memory component. The readers transmit the ID number, which is linked to the shipping details, to the company's backend system, as well as specialized software that stores the data and makes them available for online use. — *Norsk Lastbærer AS, Oslo, Norway*
www.nlpool.no

This packaging machinery is mobile

The Topas FFS (form-fill-seal) line (photo) is a moveable machine for bagging a wide range of free-flowing bulk goods. With a compact design, it can move among different docking stations underneath multiple silos. The bag-packing apparatus can be assembled to move on wheels, rails or air-cushion systems. The Topas FFS machinery can accommodate bag sizes for products weighing between 5 and 50 kg. The Topas is also available with a weighing system, volumetric dosing ability, an air-evacuation system, edge-sealing and other features. — *Windmöller & Hölscher KG, Lengerich, Germany*
www.wuh-group.com

Use this storage tank for potable water

Designed for storing potable water in industrial, commercial and residential settings, the HighDRO Potable Water Storage Tank is both effective and economical, says the company. The tanks range in size from 300 to 60,000 gal, and are constructed from either factory-welded stainless steel or factory-coated carbon steel. The lightweight steel shell is lined with a polymer composite material for high strength and long life. The water tanks are pressure-tested, and comply with several relevant ANSI standards. — *Highland Tank, Stoystown, Pa.*
www.highlandtank.com

Tune this feeder by turning a wrench

The model HS8 vibratory drive feeder from this company is ideal for packaging solid materials because the tray can be easily tuned by tightening or loosening a bolt with a wrench. The feeder avoids the need to adjust springs on the vibratory drive. — *Eriez Manufacturing Co., Erie, Pa.*
www.eriez.com

These fittings protect workers from chemical exposure

The DrumQuik assembly (photo) is a dip-tube-based system for dispensing liquids from drums and intermediate bulk containers (IBCs). It is designed to dispense fluid in a closed manner, protecting workers from chemical exposure while at the same time protecting the chemicals from outside contamination. The DrumQuik system features a connection that allows rapid hookup and disconnect, as well as a valve that allows automatic shutoff. — *Colder Products Co., St. Paul, Minn.*
www.colder.com ■

Scott Jenkins


ERIC ABBEY / OWNER
LOVING PETS CORPORATION
DECORATIVE FEEDING BOWLS AND PET TREATS
CRANBURY, NJ
SINCE 2005 18 EMPLOYEES
NO SMALL ACHIEVEMENT:
SELLING MORE WITHOUT GOING BROKE
CHALLENGE: Eric was enjoying astronomical growth. Orders for the Bella Bowl™, the company's top seller, were going through the roof. But demand was putting a strain on Eric's relationship with his supplier, not to mention his cash flow.
SOLUTION: Eric had the Cash Flow Conversation with his PNC banker, who used his manufacturing industry knowledge to tailor a solution to fit Eric's specific needs. They agreed that increasing Eric's line of credit[1] would help keep production lines flowing smoothly — and allow Eric and his team to go out and sell even more, without worrying about cash shortfalls.
ACHIEVEMENT: Loving Pets recently sold more than 330,000 Bella Bowls™ in a single month — the most ever. Now that Eric's cash flow is steady, he can focus on taking his business to the next level.
WATCH ERIC'S FULL STORY at pnc.com/cfo and see how The PNC Advantage for Manufacturers can help solve your business challenges, too. Call 1-877-535-6314 or visit a PNC branch to start your own Cash Flow Conversation today.
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LEVERAGE ONLINE TECHNOLOGY
ENSURE ACCESS TO CREDIT
PNC BANK
for the ACHIEVER in us all℠
EQUAL HOUSING LENDER
The person pictured is an actual PNC customer, who agreed to participate in this advertisement. Loving Pets' success was due to a number of factors, and PNC is proud of its role in helping the company achieve its goals. 1 All loans are subject to credit approval and may require automatic payment deduction from a PNC Bank Business Checking account. Origination and/or other fees may apply. Banking and lending products and services and bank deposit products are provided by PNC Bank, National Association, a wholly owned subsidiary of PNC and Member FDIC. Bella Bowls is a registered trademark of Loving Pets Corporation. BBK-5025 ©2011 The PNC Financial Services Group, Inc. All rights reserved. PNC Bank, National Association. Member FDIC

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Harnessing the Power of a CYCLONE

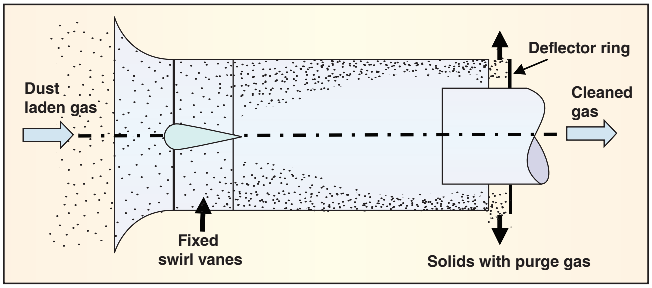


FIGURE 1. In a uniflow cyclone the cleaned air exits the cyclone in the same direction as the inlet air

Simple construction and low costs established this technology long ago as a workhorse for gas-solid separation. These guidelines incorporate nearly a lifetime of experience, to bring even better performance within reach

Shrikant Dhodapkar
The Dow Chemical Co. and
William L. Heumann, Consultant

Due to their simplicity of construction, lack of moving parts, ability to operate at a wide range of temperatures and pressures, low capital and operating cost, cyclones have been the workhorse for gas-solid separation in a wide variety of industries. If properly designed and installed, cyclones can be used to control particulate emissions as low as 5 microns in size, and sometimes to smaller sizes in extreme applications. They can be used as primary separators, pre-cleaners to reduce solids loading or as classifiers to separate incoming dust into various size fractions.

Successful applications of cyclone technology can be found in numerous industries, such as the following (with typical examples):

- Chemical (product recovery after pneumatic conveying, process separation)
- Petroleum (FCC cracking units, petroleum coke process)
- Mineral (smelting operations, ore refining)
- Agricultural (grain processing and handling)
- Fine chemicals (Powder coatings, separation, classification, grinding circuits)
- Coal (pulverization operations, grinding circuits)
- Food processing (product separation and recovery)
- Pharmaceuticals (product separation and recovery)
- Environmental (stack sampling)
- Power (ash removal and emission control)
- Automotive (removal of particles at air intake)

The earliest recorded patents on cyclone design date back to the 19th century. Cyclone designs have traditionally evolved out of empirical studies where researchers had extensively investigated certain cyclone geometries. For the most part, the development of cyclone technology has remained empirical — driven by data from laboratories and large-scale installations [*1–4*]. However, in the past 50 years, significant progress has been made on the theoretical front, and most recently on computational fluid dynamic (CFD) modeling of swirling flows [*5*].

CYCLONE CLASSIFICATION

Cyclones can be broadly classified into two categories based on the direction of exit gas — uniflow cyclone (also known as swirl tubes; Figure 1) and reverse flow cyclone (Figure 2). In a uniflow cyclone the cleaned air exits the cyclone in the same direction as the inlet air, whereas for reverse flow cyclones, the vortex within the cyclone reverses direction and exits from the top of the cyclone. Key features of each type of cyclone are summarized in Table 1.

In this article, we focus on the features, design and performance characteristics of reverse flow cyclones, which are by far the most common designs in the chemical process industries (CPI).

Cyclones, used as gas-solid separators, are designed to remove the smallest particle in the incoming dust-laden gas with the highest possible efficiency. The design objective is to minimize particulate emissions while maintaining a reasonable pressure drop. Cyclones for classification applications are designed to generate a sharp cut where particles above a designated size are theoretically collected at 100% efficiency and below it are allowed to exit with the gas.

Various cyclone designs have evolved during the past two centuries, mostly through empirical investigations and

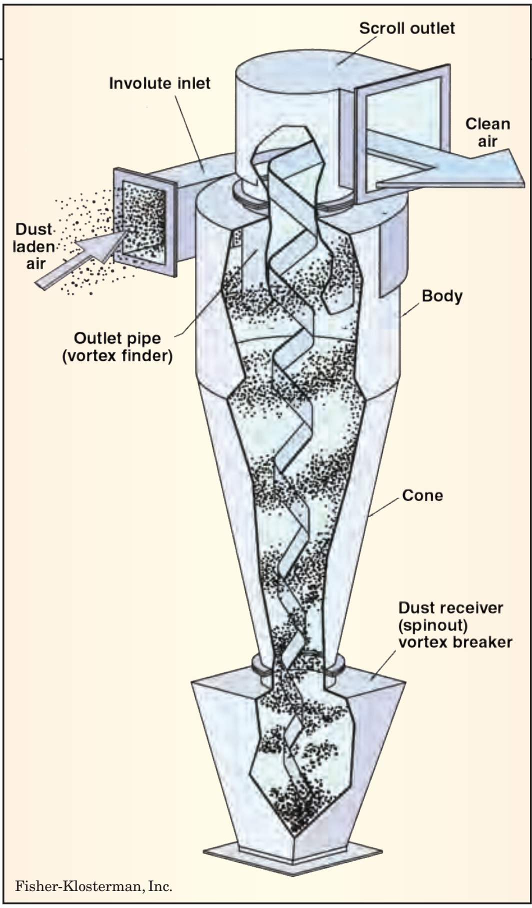
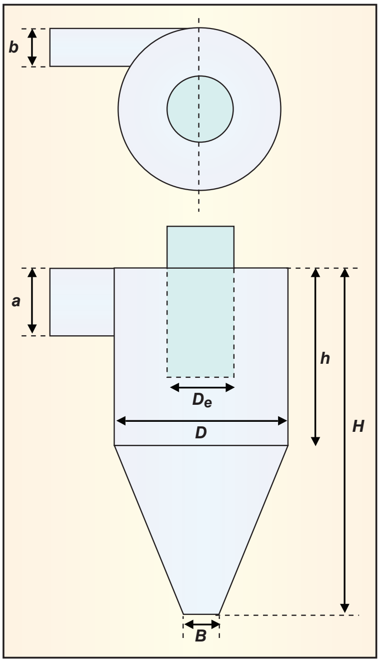


TABLE 1. COMPARISON OF UNIFLOW AND REVERSE FLOW CYCLONES

Uniflow Cyclone	Reverse Flow Cyclone
Consists of a cylindrical tube. Conical section is rare	Consists of a cylindrical section at the inlet and conical section at the dust exit
Vortex does not reverse direction	Outer vortex reverses direction. Inner vortex is in the opposite direction
Dust is removed with a stream of gas (5–10% on incoming stream)	Dust is removed as solids
Easy to install in a bank of multiple cyclones	Standalone applications are more common than multiple cyclones
Does not require seal at the solids exit	May require seal at the solid exit

FIGURE 2 (left). Unlike uniflow cyclones (Figure 1), where the cleaned air exits the cyclone in the same direction as the inlet air, for reverse flow cyclones, the vortex within the cyclone reverses direction and exits from the top of the cyclone



KEY FOR FIGURE 4

- *a* = cyclone inlet height
- *b* = cyclone inlet width
- *B* = dust exit or solids outlet at bottom
- *D* = cyclone barrel (cylindrical section) inner diameter
- D_e = exit duct or vortex finder inner diameter
- *h* = height of the cylindrical section
- *H* = total height of the cyclone (flat top to dust exit)
- *S* = length of vortex finder tube

FIGURE 4 (left). Cyclone geometry for conventional designs is defined by critical dimensions as shown here

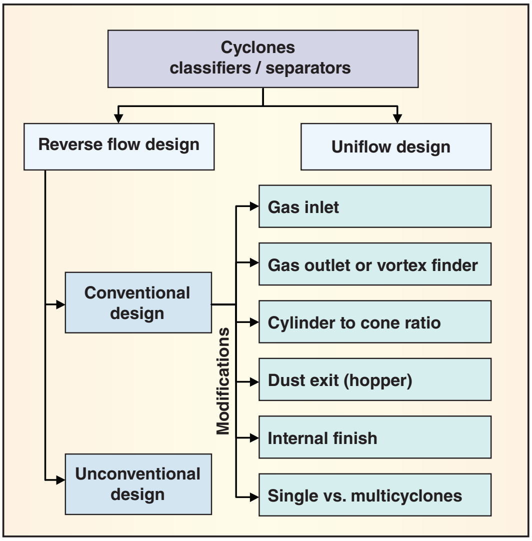


FIGURE 3 (left). A number of different characteristics (modifications to conventional designs) can affect the performance and duty of reverse flow cyclone designs

imaginative explorations. Some recent efforts with computational tools — CFD, or the combination of CFD and discrete element method (DEM) — have validated previous designs and opened up possibilities for further improvements.

Most variations in conventional designs, as outlined in Figure 3, are geared toward modification of certain features of cyclone geometry while retaining the basic concept (Figure 2). Examples of unique (unconventional) designs can be found in the patent literature — typically addressing a niche or a gap in process application.

WORKING PRINCIPLE

A three-dimensional rotational and spiraling (swirling) motion is imparted to the incoming dust-laden gas stream as it enters the cylindrical section of the cyclone (Figure 2). The spiraling or swirling motion can be imparted either using a tangential inlet or with axial swirl vanes. This is commonly known as the outer vortex but is really a single vortex flow that has been "pulled" into itself. The centrifugal forces generated by this swirling motion are orders of magnitude higher on the dust particles as compared to the gas molecules. As a result, the particles preferentially migrate toward the wall of the cyclone. The outer vortex transports the particle-rich layer downward toward the cone section and, subsequently, the particle discharge. The continu-

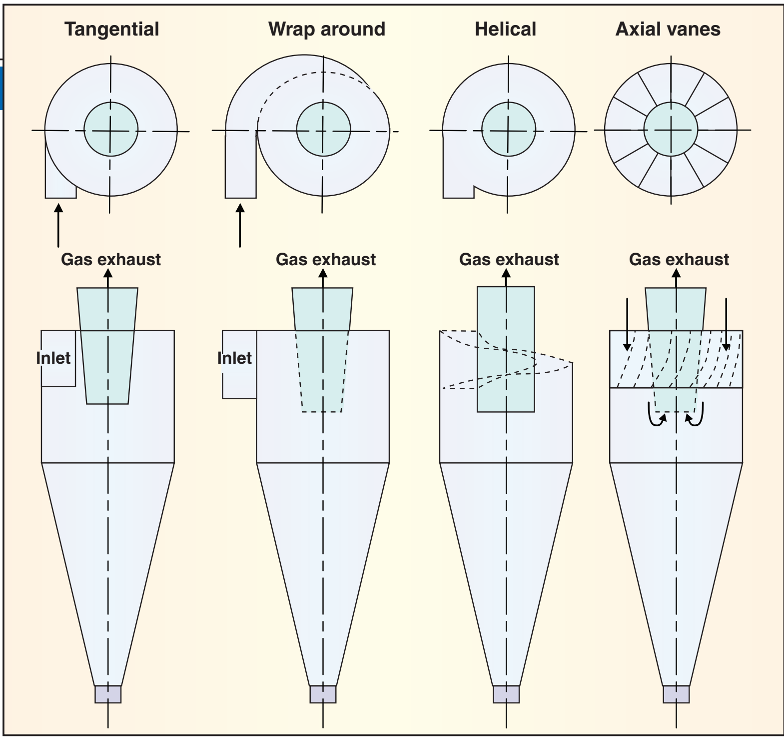


FIGURE 5. Gas vortex can be generated by different gas inlet configurations

ally reducing diameter of the outer vortex transitions eventually into an inner vortex, which travels in the opposite direction — moving toward the gas exit tube at the top of the cyclone. Many particles can be expected to be lost if they enter the inner vortex, therefore, the flow pattern in a cyclone should be such that:

- All particles are separated before the flow reversal occurs
- Particle reentrainment is minimized during transition from outer to inner vortex

The velocity profiles in the outer and inner vortices, their stability and the residence time of particles within the separation zone are key factors affecting the separation characteristics of a cyclone. Major parameters influencing separation efficiency are:

- Inlet gas velocity or flowrate
- Gas properties: density, viscosity, composition, pressure
- Particle properties: density, shape, size, size distribution, friability, cohesiveness, electrostatic properties
- Cyclone geometry: geometric dimensional ratios
- Cyclone diameter
- Dust loading or concentration
- Wall surface roughness
- Configuration: Inlet, outlet designs, air leakage from bottom, disengagement hopper and so on

Cyclone geometry for conventional designs is defined by critical dimensions as shown in Figure 4.

Oftentimes, the dimensions are quoted as a ratio of a geometrical feature with the cyclone diameter (*D*). Geometrically similar cyclones (regardless of the size) are said to belong to the same "family". Common cyclone designs [*1*, *2*, *4–6*] have been tabulated in Table 2 as a reference guide.

Different types of gas inlet configurations are summarized in Figure 5. The tangential inlet design is by far the most common, least expensive, and mostly easily made to accommodate unusual construction requirements. Tangential inlet has been reported to be the most efficient design. However, in the authors' experience, wrap-around inlets can be equally or more efficient when adjusted for equivalent cyclone diameter at a given throughput. Wrap-around inlets are advantageous when the dust loading is high and in high throughput designs. Axial inlets are most often used in multi-cyclone configurations. Similarly, many creative variations to the simple cylindrical gas outlet design (vortex finder) can be found in practice (Figure 6). Conical designs are known to help stabilize the vortex and increase pressure recovery.

PERFORMANCE METRICS

The performance of a cyclone is evaluated on three attributes:

1. Overall collection efficiency (or emission rate of uncollected dust)
2. Pressure drop across the cyclone
3. Total cost of ownership: Capital (purchase, installation) and operating costs (energy, maintenance)

Fractional collection efficiency

If an engineer is to judge the relative merits of competing designs, then there must be a metric for efficiency. In the case of cyclones, the collection efficiency depends on particle size — the smaller the particles, the lower the removal efficiency. The behavior is best explained by the concept of fractional collection efficiency (also known as grade efficiency; Figure 7).

Fractional efficiency is the defined as the weight fraction of incoming dust of a given particle size that is collected.

$$\text{Fractional Efficiency}\ (dp_i) = \frac{\text{Weight of separated dust with particle size } dp_i}{\text{Weight of incoming dust with particle size } dp_i} \quad (1)$$

An ideal fractional efficiency curve would be a step-function with a vertical line at the critical diameter or cut-size. However, an S-shaped curve is observed in practice. Particle reentrainment after collection, agglomeration of fines fraction, turbulent mixing due to wall roughness, random differences in particle trajectory and particle attrition are often cited as the underlying reasons.

In the S-shaped curve, the particle size corresponding to 50% efficiency is called the cut-size (or dp_{50}). It is the particle size that has a 50/50 chance (equally probable) of being collected. Cut-size is often used as a measure of the collection efficiency of the cyclone. However, cut-size alone is an insufficient measure. One must specify the sharpness of cut (slope of the fractional efficiency curve) or additional points on the curve. One way to specify sharpness of cut is to take the ratio of particle sizes corresponding to two arbitrary efficiencies on the fractional efficiency curve, for example:

$$\textit{Sharpness of cut} = dp_{80} / dp_{20}$$

Where subscripts 80 and 20 refer to particle size corresponding to 80% and

TABLE 2. COMMON CYCLONE DESIGN RATIOS								
Design name	Inlet type	a/D	b/D	De/D	S/D	h/D	H/D	B/D
Stairmand, high efficiency	Tangential	0.50	0.20	0.50	0.50	1.50	4.00	0.38
Swift, high efficiency	Tangential	0.44	0.21	0.40	0.50	1.40	3.90	0.40
Lapple, general purpose	Tangential	0.50	0.25	0.50	0.63	2.00	4.00	0.25
Swift, general purpose	Tangential	0.50	0.25	0.50	0.60	1.75	3.75	0.40
Stairmand, high throughput	Wrap around/scroll type	0.75	0.38	0.75	0.88	1.50	4.00	0.38
Swift, high throughput	Wrap around/scroll type	0.80	0.35	0.75	0.88	1.70	3.70	0.40
Storch T1	Tangential	0.28	0.28	0.34	0.39	1.50	5.31	0.18
Storch T2	Tangential	0.84	0.24	0.48	1.06	2.10	4.90	0.38
Storch T3	Tangential	0.87	0.32	0.56	1.05	2.40	4.30	0.48
Storch T4	Tangential	1.00	0.15	0.45	1.13	3.50	6.21	0.35
Tengbergen	Tangential	0.49	0.27	0.40	0.57	0.65	2.33	0.40
Muschelknautz	Tangential	0.52	0.15	0.33	0.89	0.73	2.40	0.67

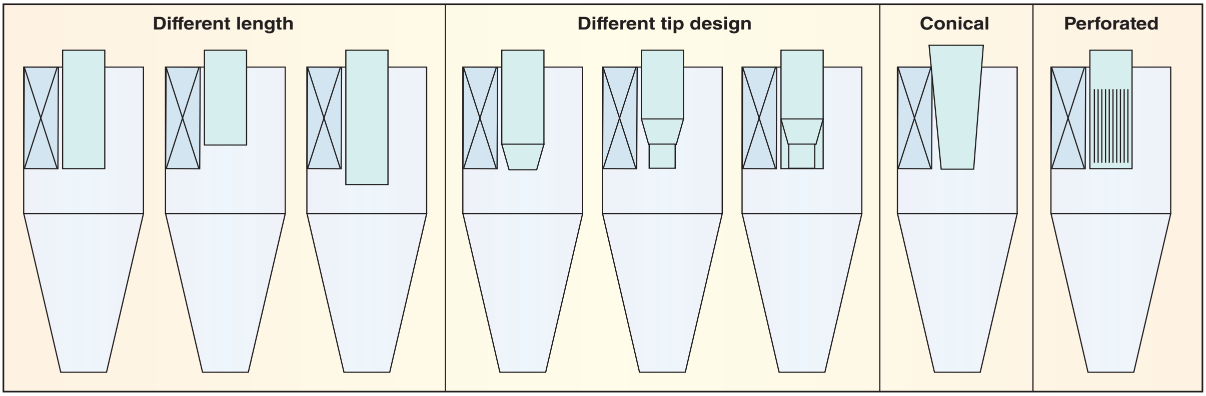


FIGURE 6. Many variations to the simple cylindrical gas outlet design (vortex finder) can be found in practice. Conical designs, for example, are known to help stabilize the vortex and increase pressure recovery

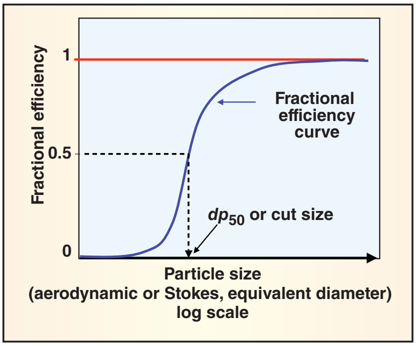


FIGURE 7. Fractional efficiency is the defined as the weight fraction of incoming dust of a given particle size that is collected

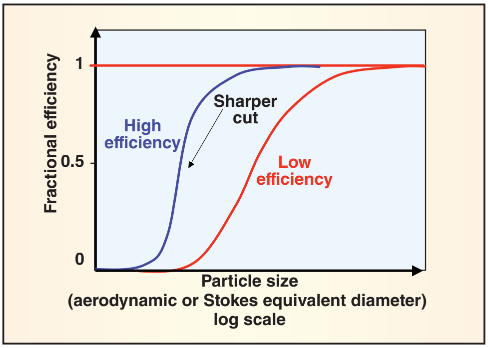


FIGURE 8. For objective comparison of various cyclone designs, one must compare the fractional efficiency curves of the quoted cyclones at the proposed operating conditions

20% fractional efficiencies respectively.

For objective comparison of various cyclone designs, one must compare the fractional efficiency curves of the quoted cyclones at the proposed operating conditions (Figure 8). A qualified vendor should be able to provide such curves upon request. The reader is cautioned to check the source and basis for fractional efficiency curves. Calculated theoretical curves without experimental validation are not considered reliable.

It is important to note that differences in fractional efficiency curves do not imply a difference in overall performance (emission rate) of a cyclone. It also depends on the particle size distribution of the incoming dust as explained later.

Total collection efficiency

Performance guarantee statements, such as "95% efficient at 5 microns" or "collection efficiency of 99.9%", are often made by vendors. Such statements are meaningless unless one understands the basis of the calculation. Overall efficiency of a cyclone depends on the fractional efficiency curve of the cyclone and the particle size distribution of incoming dust (Figure 9). The fractional efficiency is a function of cyclone design and operating parameters (gas flowrate, gas-solid properties, solid loading). It can also be affected by other factors, such as air leakage from the bottom, or presence of bends at the inlet and outlet.

A design labeled as a "high efficiency" cyclone design rated at "99.9% efficiency" for coarse particles may separate only a fraction of incoming particulate if the incoming dust is extremely fine.

It is easier to measure the total collection efficiency of an operating cyclone than to estimate or measure its fractional efficiency. Using the particle size distribution of inlet dust and fractional efficiency curve provided by the vendor, one can estimate the total collection efficiency and compare it with the measured value. Further investigation must be conducted if the differences are unacceptable.

For environmental applications, the total emission rates are used as a measure of cyclone performance. The particle size distribution and specific gravity of incoming dust must be specified if such a metric is used.

Key factors affecting efficiency

Typically, and within a broad range of operating conditions, the collection efficiency of a cyclone will respond as follows:

- Increase with increase in inlet velocity
- Increase with increase particle specific gravity
- Increase with increase in solids loading
- Increase with decrease in gas temperature
- Increase with decrease in cyclone diameter
- Increase with decrease in gas outlet diameter (vortex finder)
- Increase with increase in particle residence time in cyclone

The magnitude of these effects may differ from one cyclone family to another.

The specific gravity of gas decreases with increase in temperature, while the gas viscosity increases with increase in temperature. The effect of gas viscosity is dominant. Therefore, the overall efficiency decreases with increase in temperature.

An increase in dust loading increases the collection efficiency of a cyclone. Particle agglomeration of fines fraction coupled with sweeping action of coarse particles at higher loadings is one of the explanations. The following empirical equation by Smolik [4] can be used for calculation of efficiency improvement due to solids loading.

$$f(c_2) = 1 - (1 - f(c_1))\left(\frac{c_1}{c_2}\right)^{0.18} \tag{2}$$

Where $f(c_1)$ and $f(c_2)$ are fractional efficiencies at c_1 and c_2 concentrations (any units) respectively.

A rule of thumb for an acceptable range of inlet gas velocity is 45 ft/s (14 m/s) to 120 ft/s (37 m/s) with a typical velocity being around 65 ft/s (20 m/s).

Calculating fractional efficiency curve. Fractional collection efficiency can be calculated using any of the following approaches:

- Semi-empirical models
- Theoretical force balance and trajectory calculations
- CFD models
- Scaling from experimental data obtained on geometrically similar units

Theoretical models based on calculation of particle trajectory in a swirl flow have evolved over the past 50 years. Barth, Dietz, Muschelknautz, Leith-Licht and Mothes-Loffler are most notable. A thorough discussion on these models can be found in Hoffman and Stein [5].

Performance characteristics of a new cyclone can be calculated using laboratory test data on a geometrically similar cyclone (same family). The Stokesian scaling approach [5, 6] is commonly used. The *x*-axis (particle size) of the fractional efficiency curve (Figure 7) is shifted using the new estimated particle size. The corresponding *y*-axis (fractional efficiency) remains unaltered.

$$dp_{new} = dp_{test}\sqrt{\frac{\rho_{p-test}}{\rho_{p-new}}\frac{U_{gi-test}}{U_{gi-new}}\frac{\mu_{g-new}}{\mu_{g-test}}\frac{D_{new}}{D_{test}}} \tag{3}$$

Where
dp = particle size
ρ_p = particle density
U_{gi} = gas velocity at cyclone inlet
μ_g = gas viscosity at operating conditions
D = cyclone body diameter

Subscript "test" corresponds to the test data, and "new" corresponds to the new application.

Empirical studies by Heumann [3] on industrial scale cyclones suggest that the effect of cyclone diameter (D) is more significant. The following equation has been proposed instead:

$$dp_{new} = dp_{test}\sqrt{\frac{\rho_{p-test}}{\rho_{p-new}}\frac{U_{gi-test}}{U_{gi-new}}\frac{\mu_{g-new}}{\mu_{g-test}}\left(\frac{D_{new}}{D_{test}}\right)^{1.5}} \tag{4}$$

Measurement of particle size distribution. Except in a few rare cases, we do not deal with mono-disperse particulate. Particles within a process are more commonly spread over some range of physical and aerodynamic particle sizes. The methods utilized for characterizing the particle sizes actually measure the particle size distribution (PSD) of the solids and, usually, are presented as a probability density or cumulative probability density functions. It is vital to have an accurate description of the aerodynamic PSD of the solids entering the cyclone to accurately predict the collection efficiency of the cyclone.

Aerodynamic methods actually measure the terminal velocity distribution of the particles, not the size distribution. Since terminal velocity is a more abstract, and difficult concept than particle diameter, these measurements are usually converted to size distributions utilizing Stokes' law for presentation purposes. Proper specification of an aerodynamic PSD in Stokes' equivalent diameters requires that both diameter and density are specified. In all aerodynamic methods, a particle density or specific gravity is used to convert the terminal velocity distribution to a size distribution. For most of the cascade impactors and other probes used with stack testing, it is assumed that particle specific gravity is 1, and the actual specific gravity of the particle is often never measured. Regardless of the measured particle density, it is important to utilize the particle density as specified with the PSD, or adjust both simultaneously.

Svarovsky [4]

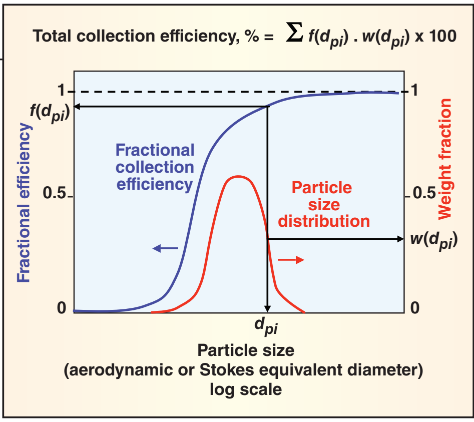


FIGURE 9. Overall efficiency of a cyclone depends on the fractional efficiency curve of the cyclone and the particle size distribution of incoming dust

Pressure drop. The estimation of expected pressure drop due to a cyclone in the expected operating range of gas flowrates and solids loading is particularly important when air mover delivery rate is sensitive to back pressure (for instance, in fans), or the pressure rating of upstream process equipment (for instance, in dryers) is adversely affected.

Pressure drop across any process equipment is the difference between static pressures at the inlet and the outlet. The pressure drop is an indication

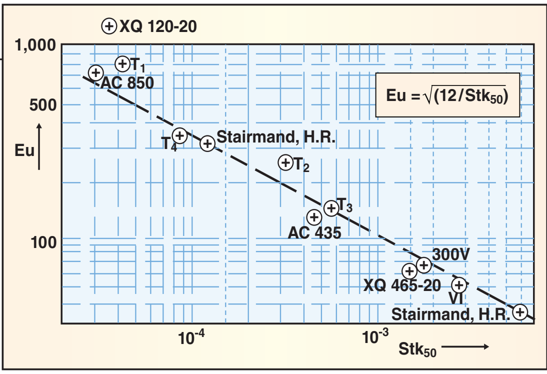


FIGURE 10. This plot by Svarovsky clearly shows that cyclones with higher efficiency will exhibit higher pressure drop [*4*]

EXAMPLE: PRESSURE DROP CALCULATION

Cyclone design: Stairmand High Efficiency (see Table 2)
$a/D = 0.5$; $b/D = 0.2$; $D_e/D = 0.5$
Cyclone diameter (D) = 1 m = 3.28 ft
Inlet gas flowrate (Q) = 1.83 m^3/s = 3870 ft^3/min
Gas velocity at inlet (U_{gi})= 18.3 m/s = 60.0 ft/s
Gas density (ρ_g) = 1.2 kg/m^3 = 0.075 lb/ft^3
Solids concentration at inlet (c) = 5.0 g/m^3

$$\Delta P_{air-only} = \frac{16\left(\frac{a}{D}\right)\left(\frac{b}{D}\right)}{\left(\frac{D_e}{D}\right)^2}\left(\frac{\rho_g U_{gi}^2}{2}\right) = \frac{16(0.5)(0.2)}{(0.5)^2}\left(\frac{1.2(18.3)^2}{2}\right) \; Pa$$

$\Delta P_{air-only}$ = 1,286 Pa = 5.17 in. H_2O

$$\Delta P_{with-solids} = \Delta P_{air-only}(1-0.02c^{0.6}) = 1{,}286(1-0.02[5]^{0.6})$$

$$= 1{,}218 \text{ Pa} = 4.89 \text{ in. } H_2O$$

❑

of dissipative (non-recoverable) energy losses per unit volume of process fluid. Cyclones are unusual in the sense that the exit gas, due to its swirling action, has a significant dynamic component in the radial direction that affects the static pressure measurement at the wall of the outlet. Consequently, the measured difference in static pressure between inlet and outlet is often lower than actual pressure drop. For lab or pilot scale studies, venting the cyclones to the atmosphere and measuring the inlet pressure is the best option. However, for in-process measurement, one may choose a location further downstream of the outlet and then subtract the line losses between cyclone outlet and measurement location. If fixed pressure measurement devices are utilized, it may be necessary to purge the instrument lines to ensure they do not become blocked by particulate matter. A purge velocity of 0.5 m/s has been found to be sufficient to keep the taps clean.

A generalized version of pressure drop equation is as follows:

ΔP= *Euler number* × *Velocity head*

$$\Delta P_{air-only} = \frac{16ab}{D_e^2}\left(\frac{\rho_g U_{gi}^2}{2}\right) \quad (5)$$

Euler number has been found to be weakly sensitive to Reynolds number in the typical operating range of cyclones.

For lightly loaded cyclones, the equation proposed by Shepherd and Lapple [7] has been found to be most reliable.

$$\Delta P_{air-only} = \frac{16\left(\frac{a}{D}\right)\left(\frac{b}{D}\right)}{\left(\frac{D_e}{D}\right)^2}\left(\frac{\rho_g U_{gi}^2}{2}\right) = \frac{16\left(\frac{a}{D}\right)\left(\frac{b}{D}\right)}{\left(\frac{D_e}{D}\right)^2}\left(\frac{\rho_g\left(\frac{Q}{ab}\right)^2}{2}\right) \quad (6)$$

Where
a = Inlet height, m
b = Inlet width, m
D = Cyclone diameter, m
D_e = Gas exit duct (vortex finder) diameter, m
Q = Actual gas flowrate at the inlet, m^3/s
ρ_g = Gas density at operating conditions, kg/m^3
U_{gi} = Gas velocity at the inlet of the cyclone, m/s
$\Delta P_{air\text{-}only}$ = Pressure drop in Pascal (1.013×10^5 Pa = 1 atm = 14.7 psi)

Interestingly, the pressure drop across a cyclone decreases with increase in dust loading initially and then increases again for heavily loaded gas stream.

The following equation by Smolik [4, 5] can be used to calculate the pressure drop reduction due to dust loading.

$$\Delta P_{with-solids} = \Delta P_{air-only}(1-0.02c^{0.6}) \quad (7)$$

Where
c = solids concentration in gas at cyclone inlet, g/m^3

See the box, above, for a calculation example.

Performance evaluation

Svarovsky [*4*] plotted the pressure drop characteristics (represented by Euler number [Equation (8)]) versus collection efficiency (represented by Stokes number [Equations (9) and (10)]) for various industrial cyclones (see Figure 10).

$$Eu = \frac{\Delta P}{\frac{1}{2}\rho_g U^2} \quad (8)$$

$$Stk_{50} = \frac{dp_{50}^2 \rho_p U}{18\mu_g D} \quad (9)$$

$$U = \frac{Q}{\left(\frac{\pi}{4}D^2\right)} \quad (10)$$

Where
D = Cyclone diameter, m
dp_{50}= Cut-size or particle size corresponding to 50% collection efficiency, m
ΔP = Pressure drop across cyclone, Pa
Q = Gas flowrate, m^3/s
U = Characteristic axial (gas) velocity based on cyclone diameter, m/s
ρ_g = Gas density at operating conditions, kg/m^3
μ_g = Gas viscosity at operating conditions, kg/(m-s) or Pa-s

Cyclones with higher efficiency will exhibit higher pressure drop. Figure 10 shows that cyclones with lower Stokes' number (lower cut-size or higher efficiency) have higher pressure drop. Therefore, there is always a trade-off between pressure drop and collection efficiency. The data (Figure 10) can be represented by the following equation:

$$Eu = \sqrt{\frac{12}{Stk_{50}}} \quad (11)$$

This relationship can be further exploited to benchmark the performance of an installed cyclone (Figure 11).

CYCLONE SPECIFICATION

Process and site conditions

Due to the simplicity of cyclones and the lack of moving parts in the process flow stream, cyclones are frequently used in severe applications. Even in common, relatively non-severe applications, there are frequently process conditions that significantly impact the proper design of a cyclone. In some cases, the desire for high performance from the cyclone must be balanced with maintenance, operability, or other economic factors that result from the process conditions.

One common example is cyclones used in conjunction with fluidized bed reactors. In many of these applications, the fluidized bed catalyst is expensive, which argues for the highest possible cyclone efficiency. There are several conflicting process considerations though. For numerous reasons, it is often better to use cyclones that are installed internal to the fluidized bed vessel. The physical dimensions of the vessel are driven by the desired reaction kinetics and over-sizing a fluidized bed can be very costly. Many times, the bed material is comprised of abrasive particles. Maintaining and replacing cyclones within a vessel can very difficult, so these cyclones are often designed for longevity. This might mean that the cyclone construction is of an abrasion-resistant material or lining, which is very heavy and expensive. Often, cyclone geometry is altered to accommodate the economical installation and repair of the lining. Velocities are often minimized since the rate of erosion is greatly affected by the cyclone inlet velocity and to a lesser extent, outlet velocity. As previously described, reduced inlet or outlet velocity, or both, will reduce the cyclone collection efficiency.

One of the most important process variables to define for proper cyclone operation is the range of conditions that the cyclone should operate between. Engineers should use care to specify the normal operating conditions as accurately as possible, and to provide the desired range if the conditions are variable or there is some uncertainty about the proper operating conditions (for example, normal, minimum and maximum). It is very common to find cyclones that are operating improperly because they were "over-designed." Engineers should avoid the desire to add a "safety factor" to process variables used for the primary design of the cyclone. Many times by trying to make a cyclone design "safe", the result is ensuring the cyclone performs less than optimally.

A typical turn-down ratio for a cyclone is around 1.5:1 between the minimum and maximum flow conditions, but can reach 3:1 in some unique installations. The real limits on turn-down are that, at the lowest flow condition, the inlet velocity in the cyclone should exceed the minimum velocity at which the solids that are being transported will stay in suspension. This is known as the saltation velocity. The maximum velocity should not exceed either of the following: the velocity at which the cyclone will exhibit significant acoustical noise generation (Ranque-Hilsch vortex separation) and initiate particle attrition, thereby effectively reducing the collection efficiency. As a practical limit, this starts to become a consideration above 120 ft/s (36.5 m/s) and 160 ft/s (48.8 m/s) inlet and outlet velocities, respectively. Cyclone pressure drop varies exponentially with the velocity, if all other variables remain constant. For most cyclones, the empirical exponent for pressure drop versus velocity is between 2.1 and 2.3. So if the flowrate and subsequent range of flows is to be 2:1 for a given cyclone, we can expect the range of pressure drop to be over 4:1 from the maximum to the minimum flow condition. In most systems, this is not an attractive range of design for the blower or fan.

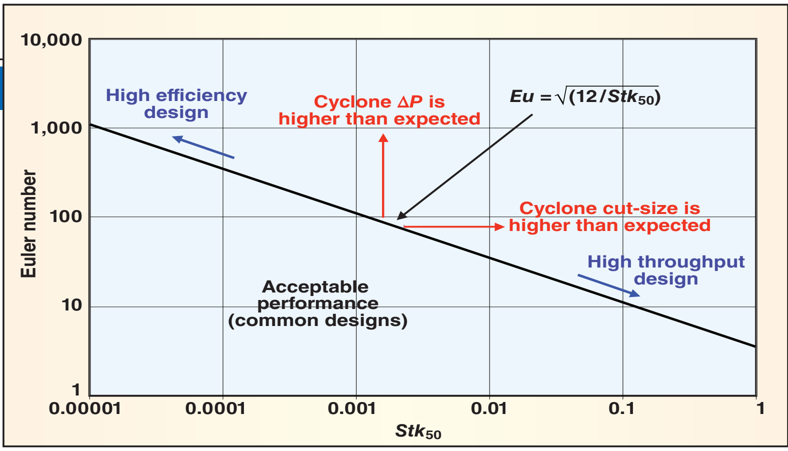


FIGURE 11. The relationship in Figure 10 can be further exploited to benchmark the performance of an installed cyclone

Multi-cyclones. Smaller diameter cyclones (at the same inlet gas velocity and solids concentration) will be more efficient than a larger diameter cyclone. Therefore, a battery of smaller cyclones in parallel must always outperform a single large cyclone. In practice, however, that is not always true. The difficulties associated with equally distributing incoming gas and solids and creation of crosscurrents through the hopper along with compromises in design required to cluster the cyclones may outweigh the benefits. Smaller cyclones may also tend to plug if the collected solids are sticky and cohesive. On the other hand, multi-cyclone configurations are compact and require less headspace. This requirement is critical in installations where cyclones are internal to a process vessel (e.g. reactor). A larger turn-down in gas flow can be achieved if some of the cyclones can be taken off-stream.

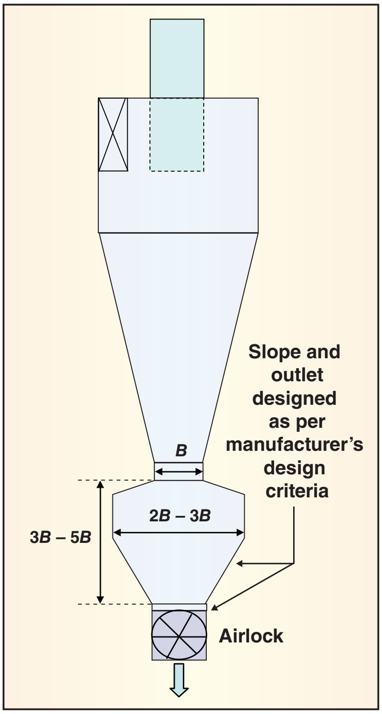


FIGURE 12. A disengagement hopper arrangement at the bottom of the cyclone is an efficient approach to mitigate re-entrainment

For proper design of cyclone, the following process and mechanical specifications should be provided to the vendor:

TABLE 3. TROUBLESHOOTING GUIDE		
Symptom	**Possible Cause**	**Solution**
1. Collection Efficiency is lower than expected	Design basis is wrong	Verify specified design conditions and vendor performance predictions are correct
		If higher ΔP can be provided by the system air mover and the collection efficiency is close to the desired level, modify cyclone inlet and/or outlet to increase the velocity
		Replace the cyclone with a cyclone of better design
	Gas leakage into the cyclone	Check and repair any leaks or holes
		Check to make sure flange connections are properly gasketted and tight
		Check and repair feeder valves for proper operation and gas tightness
	Inlet or outlet ductwork is improperly designed	Check and repair inlet and outlet ductwork if any flow disturbance is induced into the cyclone
	There is an internal obstruction	Ensure that any access doors are flush and smooth
		Ensure that there are no instruments or probes sticking into the cyclone flow stream
		If the cyclone is lined, check for and repair any major erosion that causes sharp edge disturbance to the flow stream
		If plugging is occurring see item below
2. Plugging	Feeder valve is sized improperly for the particulate loading and density	Resize and replace the airlock valve at the outlet
	Cyclone discharge diameter or dipleg is too small for the particulate loading and apparent density	Redesign and replace lower sections
	Dipleg plugs	Add dipleg purges if problem is caused by poor aeration (although the introduction of purge gas itself can reduce collection efficiency this is preferable to 0% collection resulting from a plug).
		Check and repair dipleg discharge valve
	Particulate matter build up on surfaces	If caused by condensation, insulate and/or heat trace
		Consider non stick coatings or polished surfaces
		Periodic cleaning with vibration, air cannon or both
		Replace with a cyclone with greater internal clearances
		Provide easy access for cleaning and maintenance

(Continues on p. 42)

Process specifications:
- Gas flowrate: (normal, minimum, maximum)
- Operating gas temperature: (at normal, minimum, and maximum)
- Operating gas pressure: (at normal, minimum, and maximum)
- Gas compositions: (at normal, minimum, and maximum)
- Condensable components: humidity
- Composition and characteristics of incoming dust (such as hygroscopic, explosive, abrasive and so on)
- Particulate loading: (at normal, minimum, and maximum. It is also important to specify an “upset” load if one can occur)
- Aerodynamic particle size distribution with specified particle density or specific gravity
- Desired collection efficiency or allowable emission rate
- Allowable ΔP

Mechanical specifications:
- Design temperature: (minimum, maximum)
- Design pressure: (minimum, maximum)
- Ambient conditions (minimum, maximum)
- Location (indoor versus outdoor)
- Applicable design code(s)
- Mounting or support requirements
- Installation envelope dimensions
- Preferred materials of construction
- Special features required: (for instance, access doors, poke holes, insulation, heat tracing or jacketing, abrasion resistant lining, internal finish or coating, external paint or finish specifications, and so on)
- Accessories desired: (for instance, airlock or other feeder valves, diplegs, dust receiver vessels, fire/explosion suppression system, blowers, and so on)
- Noise specification

Installation guidelines

Cyclones do not have any moving parts but, when properly designed and operated, can provide impressive performance. Such performance is purely a function of the internal flow patterns that are set up within the cyclone. For this reason, it is vital that the cyclone be installed and operated in a way that these flow patterns are not inadvertently disturbed.

Cyclones are designed to discharge the collected particles into a gas tight area that is sufficiently remote from the actual discharge point of the cyclone. Active vortex flow and the potential for re-entrainment of fine particles that have been collected will extend far below the actual discharge of the cyclone. Vortex severity is a function of the cyclone geometry and flowrates. A minimum of three cyclone discharge diameters (B) of clearance between the cyclone discharge and the closest point at which collected particles may accumulate should be provided. If the cyclone velocities are high, the particles to be collected are very fine, or both, greater clearance is advised. A disengagement hopper arrangement at the bottom of the cyclone is an efficient approach to mitigate such re-entrainment (Figure 12).

Gas leakage from the bottom is the most frequent cause for loss of efficiency in a process cyclone. Many cyclones are operated under negative pressure relative to the final solids

TABLE 3. TROUBLESHOOTING GUIDE (Continued)		
Symptom	**Possible cause**	**Solution**
3. Erosion	Cyclone inlet velocity is too high	Replace the cyclone or modify the inlet so that the inlet velocity is as low as possible (just above the saltation velocity at the minimum flow condition)*
		Reduce the gas flowrate if possible
	Particulate is abrasive	Use the lowest possible inlet velocity
		Make the cyclone out of more abrasion resistant construction. If a combination of corrosion is occurring with erosion then the materials of construction must first be corrosion resistant since virtually all materials will abrade away rapidly when in an oxidized state
		Use cyclones that have larger diameters
		Design the installation and cyclone itself so that worn parts can be replaced and/or repaired as economically as possible
4. ΔP is too high	Design basis is wrong	Verify specified design conditions and vendor performance predictions
		If the high ΔP is not causing any real problem, leave it alone. The cyclone should be providing higher collection efficiency than specified
		Modify air moving portion of the system to accommodate higher ΔP
		Enlarge the cyclone inlet or outlet pipe to reduce velocity (note this will reduce the cyclone collection efficiency)*
		Replace the cyclone
	Excess air leaking into upstream ductwork	Repair ductwork
5. ΔP is too low	Design basis is wrong	Verify specified design conditions and vendor performance predictions
		If the low ΔP is not causing any real problem, leave it alone.
		If the cyclone efficiency is too low by a small margin, modify the inlet and/or outlet to increase velocity*
		Increase the gas flowrate to the cyclone
	Leaks into the cyclone	Repair
	Reduced swirl intensity	Clear internal obstructions, accumulation on the walls, repair damage

* Modification to the inlet may require changes to the vortex finder in order to avoid direct impingement of particles or short circuiting of flow

discharge location. Even in those installations, where the cyclone inlet pressure is positive relative to the final discharge, it is common for the pressure above the discharge point to be negative due to the vortex flow. In these cases, if the valve or container through which the cyclone discharges its solids is not gas tight, a reverse flow will be pulled into the cyclone causing a significant reduction in collection efficiency. It should also be noted that a rotary airlock should not be installed directly at the outlet of a cyclone. It can lead to loss of efficiency due to reentrainment. A vertical tube (collar) or disengagement hopper configuration between the rotary airlock and the cyclone bottom is recommended.

Clogging of dust outlet can be problem with smaller cyclones handling cohesive solids. There are three possible solutions to this problem:

- Choose a design with larger outlet
- Choose a larger cyclone diameter
- Ensure reliable flow out of disengagement hopper

Gas inlet and outlet piping (ductwork) can also have a significant effect on cyclone performance. The most common problems with inlet ducting are elbows that are too close to the cyclone inlet. Horizontal elbows should be arranged in the same flow rotation as the cyclone and, if not, should be at least four duct diameters away from the cyclone inlet. Vertical elbows should be at least two duct diameters away from cyclone inlet where possible to ensure that downstream shedding eddies do not adversely affect the flow into the cyclone.

Another common problem is when solids accumulate on the bottom (floor) of the gas inlet. Often, the disruption to flow caused by the turbulence of gas over the accumulated solids causes a significant loss in collection efficiency. Most often, this problem is caused by a combination of low velocities, poorly designed transitions, and/or vertical elbows that are closely coupled to the cyclone inlet. Most cyclones have rectangular inlets and most piping or ductwork leading up the inlet is round. To connect the two, a transition is required. Transitions should be gradual with an included expansion angle of no more than 22 deg. when possible. This expansion angle will help prevent solids from accumulating at bottom of the inlet transition. If the average cyclone inlet velocity is low (within 20% of the saltation velocity), a "flat bottom" transition may be advised. In this case, the bottom of the horizontal duct is on the same elevation as the bottom of the cyclone inlet and all of the vertical transition is along the top of the rectangular to round transition piece. If a transition is expanding along one axis only, it is best not to exceed 15 deg. in expansion angle.

If the elbow is close coupled to the cyclone inlet, where the gas is turned from vertically upward to horizontal, the solids may settle out on the bottom of the cyclone inlet. This is especially true as the elbow radius becomes smaller, the elbow is closer to the cyclone inlet, and if used with a sharply expanding transition along the bottom surface.

The most important consideration with the outlet piping is to ensure that it does not significantly impede the spinning of the gas within four pipe diameters of the cyclone gas outlet. Any significant reduction of gas rotation prior to this distance can reduce the spinning motion within the cyclone and reduce cyclone collection efficiency. Generally speaking, elbows and transitions do not cause a significant impact on the spin and can be used. The engineer should be aware that the pressure losses through these fittings will be much higher than normally predicted for the flow conditions due to the gas spin.

Seemingly small flow disturbances in the cyclone itself can cause significant decreases in cyclone performance. Access doors must be designed and fabricated so that they are flush and smooth. Likewise, instruments should not extend into the flow stream or have recessed pockets that can cause a flow disturbance.

Troubleshooting guide

For common operational problems in cyclones, see the troubleshooting guide (Table 3).

FINAL REMARKS

Cyclones continue to be an indispensable and ubiquitous process technology for gas-solid separation operations. If designed and installed correctly, they work reliably and efficiently. The elegance of their design simplicity hides the complex underlying fluid-particle flow phenomena, which often leads to lack of understanding of critical variables. More in-depth discussion on cyclone design can be found in the references. ■

Rebekkah Marshall

Acknowledgement

Shrikant Dhodapkar would like to acknowledge Prof. B. Pitchumani at I.I.T.-New Delhi (India) for introducing him to the field of particle technology and cyclone theory.

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Authors

Shrikant V. Dhodapkar is a fellow in the Dow Elastomers Process R&D Group at The Dow Chemical Co. (Freeport, TX 77541; Phone: 979-238-7940; Email: sdhodapkar@dow.com) and adjunct professor in chemical engineering at the University of Pittsburgh. He received his B.Tech. in chemical engineering from I.I.T-Delhi (India) and his M.S.Ch.E. and Ph.D. from the University of Pittsburgh. During the past 20 years, he has published numerous papers on particle technology and contributed chapters to several handbooks. He has extensive industrial experience in powder characterization, fluidization, pneumatic conveying, silo design, gas-solid separation, mixing, coating, computer modeling and the design of solids processing plants. He is a past chair of AIChE's Particle Technology Forum.

William L. Heumann is president and cofounder of Andrew Elliot Group LLC (bheumann@gmail.com), a private equity holding company. He currently serves as vice president of engineering for CO_2 Solutions LLC, a company involved with converting petroleum refinery CO_2 emissions into diesel fuel. He was previously president and CEO of Fisher-Klosterman, Inc., a leading manufacturer of high efficiency cyclones. Heumann graduated cum laude from Florida Institute of Technology (Melbourne) with a B.S. in Oceanography; subsequent graduate study has included business-administration courses at Bellarmine University (Louisville) and engineering courses at Speed Scientific School, University of Louisville. He is the developer and co-developer of several patents and proprietary technologies utilizing cyclones and cyclones in conjunction with fluidized bed systems.

Burner Design for Fuel Flexibility and Efficiency

Design of today's industrial combustion burners must allow operation with multiple fuels while keeping emissions low

David Littlejohn, **Robert Cheng**, **Peter Therkelsen**, **Kenneth Smith** and **Sy Ali**
Lawrence Berkeley National Laboratory

Combustion provides heat for many industrial processes and accounts for over 80% of the power used by turbines to generate electricity. Over the past several decades, regulatory action and concerns over environmental air pollutants, such as oxides of nitrogen (NOx), have pushed industrial process designers to develop burners that lower pollutant emissions and prompted manufacturers to switch to cleaner-burning fuels. Going forward, industrial combustion — both for process heat and power generation — will be characterized by an increasingly diverse fuel supply and a greater need to reduce pollutants and carbon dioxide emissions. As substitutes to natural gas, coal and oil, alternative fuels are being considered by the chemical process industries (CPI) for power generation and process heating. These include low-heat-content fuels such as landfill gas, biogas and synthesis gas (syngas), as well as hydrogen.

To take full advantage of these alternative fuels, CPI engineers are exploring a number of approaches aimed at reducing carbon emissions, improving fuel flexibility and increasing efficiency for combustion systems. A key part of the effort is the development of combustor designs that operate effectively using a range of fuels while maintaining low emissions and stable performance.

In this article, we discuss the low-swirl combustor design, its operation and its performance with natural gas, hydrogen and low-heat-content fuels. We believe that the low-swirl combustor design can make a substantial contribution toward a reduced carbon footprint and higher air quality.

New demands on burners

For many years, burners for industrial process heating and power generation were relatively simple devices. The primary criteria for burners were good heat distribution, good flame stability and turndown capability. Until recent decades, emissions were not a primary concern in burner development.

Industrial burner manufacturers have successfully responded to the challenge of reducing emissions from combustion systems. There are a number of lean, premixed burner designs for use with natural gas that can achieve low (sub-15 ppm or even single-digit) NOx emissions. However, concerns about CO_2 emissions and fossil fuel availability, as well as discussions over the creation of a carbon cap-and-trade program or other carbon tax, have created new challenges.

Burners that have been carefully optimized to operate cleanly with natural gas may not be capable of operating with alternative fuels. The combustion properties of these alternative fuels can differ significantly from natural gas. Combustors that have been optimized for clean operation on natural gas may not burn the alternative fuels cleanly, or even worse, may become unstable and get damaged or destroyed.

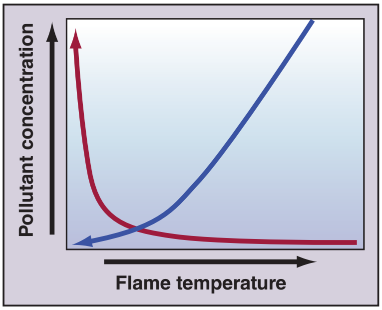


FIGURE 1. CO levels (red) rise as flame temperature decreases. Increasing the fuel-to-oxidizer ratio leads to higher flame temperatures (blue) and higher NOx

The ideal burner design would be able to operate cleanly on both natural gas and alternative fuels, and be able to switch between fuels with little or no change in operating conditions.

Production of pollutants in flames depends on several factors — fuel-air mixing, fuel-air ratio, flame temperature and fuel composition. Gaseous fuels tend to burn more cleanly since they can be mixed with air to produce a uniform air-fuel mixture without undergoing a phase change. It is more difficult to produce uniform mixtures from liquid fuels. Liquid fuels are sprayed into the air for combustion, and fuel droplets are surrounded by a fuel-rich zone until the liquid fuel is completely vaporized. The processes involved with solid fuel combustion are even more complicated. All of these factors must be considered in the development of cleaner-burning combustion systems.

Stoichiometry and temperature

The temperature at which a flame burns depends on the type of fuel used and the flame stoichiometry. In combustion, stoichiometry is a term that is used to describe the ratio of fuel to oxidizer consumed during the combustion process. For example, in the combustion of methane ($CH_4 + 2O_2$ —>

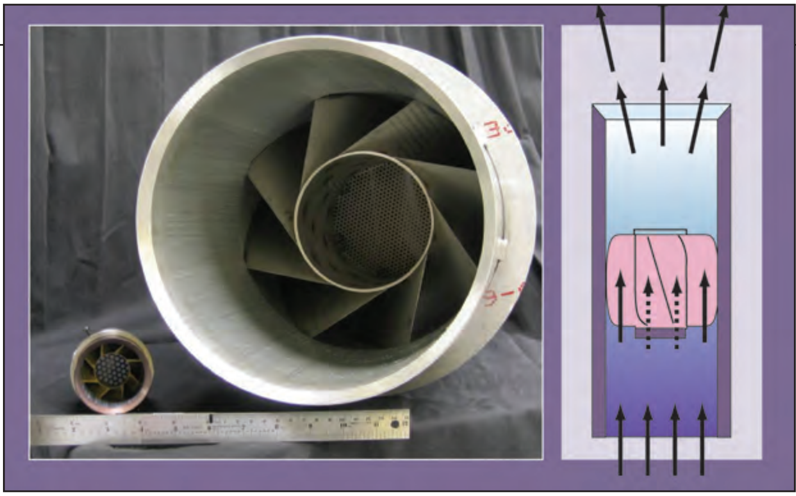


FIGURE 2. With a series of vanes at exit angles of about 35–40 deg, the low-swirl burner splits the flow of incoming air into a non-swirling center surrounded by a swirling annular flow

FIGURE 3. The interaction of the flows at the exit of the swirler assembly creates a flow profile that expands radially outward

CO_2 + $2H_2O$), twice as much oxygen is consumed as methane on a mole or volume basis. The equivalence ratio of a system is defined as the ratio of the experimental fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio. The equivalence ratio may be expressed as either: phi (fuel-to-oxidizer) or lambda (air-to-fuel).

In the methane combustion reaction above, there is no residual oxygen and no residual fuel, so the system has an equivalence ratio of one both as fuel-to-oxidizer ratio or air-to-fuel ratio. The equivalence ratio phi will be used in this article when discussing fuel-air mixtures. When there is less fuel than air available for the flame (phi <1), the flame is lean and burns at a lower temperature than a flame at stoichiometric conditions. A rich flame with more fuel than available air (phi >1) also burns at a lower temperature than a stoichiometric flame, but generates partially oxidized species from the fuel, including carbon monoxide, formaldehyde and other aldehydes. Since these species can contribute significantly to poor air quality, rich flames are generally avoided.

NOx production paths

NOx are regulated pollutants, and consist primarily of nitric oxide (NO) and nitrogen dioxide (NO_2). In a flame, NOx can be formed by three different processes to generate thermal NOx, fuel NOx and prompt NOx.

Thermal NOx is produced at high temperatures by elementary reactions of the Zeldovich mechanism:

$$N_2 + O \longrightarrow NO + N \qquad (1)$$

$$N + O_2 \longrightarrow NO + O \qquad (2)$$

$$N + OH \longrightarrow NO + H \qquad (3)$$

Fuel NOx is produced from combustion of nitrogen-containing fuel components. Fuel-generated NOx can be avoided by using fuels without significant quantities of nitrogen-containing compounds.

Prompt NOx is produced by radical reactions in the flame. However, this is a relatively small channel for NOx production, and generally not as important to overall NOx emissions as thermal NOx. In most combustion systems, thermal NOx is the dominant production channel, and NOx emissions can be controlled by limiting the flame temperature.

The dependence of NOx and carbon monoxide concentrations on flame temperature are shown for lean flames in Figure 1. At very lean conditions, the flame temperature is not sufficiently high to completely burn out CO, and CO levels rise rapidly as the flame temperature decreases. As the fuel-air mixture is made increasingly lean, it approaches the lean blowout limit where the flame does not release sufficient heat to sustain itself. On the other side of the graph, flame temperature, and NOx, increase as the fuel-to-oxidizer ratio increases.

Low-NOx burner design

Low-NOx burner design involves several factors. One factor is to establish mixing of the air and fuel before they flow into the flame zone, so the flame burns at a uniform and well-defined temperature. If air and fuel are poorly mixed, there will be fuel-rich regions and fuel-lean regions within the flame zone. The fuel-rich regions will burn with a high flame temperature, generating excess NOx, and possibly burning incompletely due to excess fuel. The fuel-lean regions will not generate much NOx, but may burn at too low a temperature for complete combustion.

An effective gas-mixing system should be integrated into a low-emissions burner design, but the creation of a volume of mixed fuel and air in the burner upstream of the flame zone can introduce some safety concerns. Proper control of the flame position must be maintained to avoid the flame flashing back to the fuel injection zone. The fuel injection system should be insensitive to pressure fluctuations in the flame zone to avoid combustion oscillations.

Premixed burners can often operate effectively over a range of lean equivalence ratios. For maximum efficiency, the burner should be set to operate at the highest flame temperature that will produce acceptable NOx emissions and will not damage the downstream section of the combustion system.

One advanced premixed burner design that is capable of very low-emission operation is the low-swirl burner (Figure 2). The low-swirl burner is a scalable design that has demonstrated excellent operating stability while achieving low-emissions performance. The concept was developed as a flame research tool by one of the authors (Robert Cheng), and is used for industrial heating applications.*

*__Note:__ The low-swirl burner design has been licensed by Honeywell's Maxon Corp. (Muncie, Ind., www.maxoncorp.com) for process heating over a specific heat-output range and was commercialized for natural gas operation. The low-swirl burner technology is available for licensing for other applications.

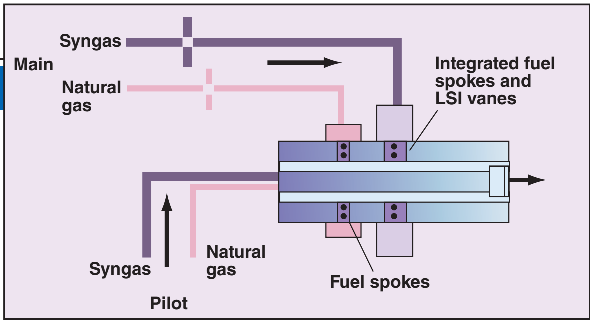


FIGURE 4. Incorporating two fuel circuits in the combustor assembly allows operation of the turbine at full load with any of the fuels, and switch between fuels without shutting down

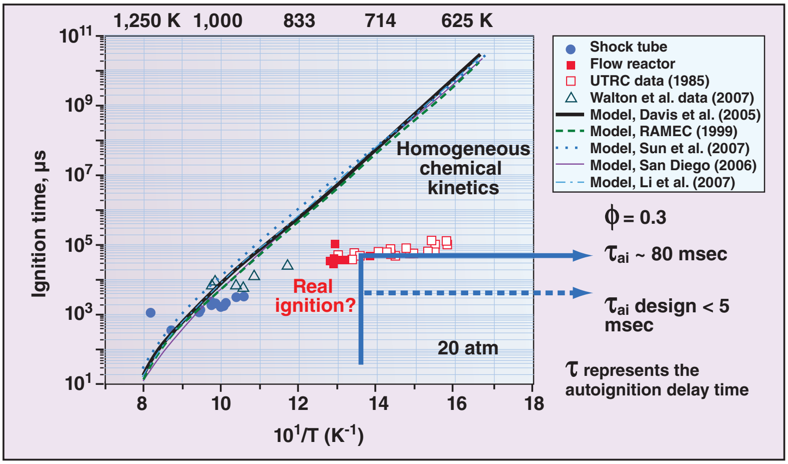


FIGURE 5. If fuel is injected into air at conditions suitable for autoignition, there is a time delay before ignition occurs. Experiments and models of ignition delay disagree

The low-swirl burner splits the flow of incoming air into a non-swirling center flow surrounded by a swirling annular flow. The swirl in the annular region is generally created by a series of vanes with exit angles of about 35–40 deg. The interaction of the flows at the exit of the swirler assembly creates a flow profile that expands radially outward. This interaction causes the axial flow velocity to ramp down as the flow expands outward (Figure 2, diagram). This velocity downramp creates the unique flame stabilization mechanism of the low-swirl burner. Once the burner is lit, the flame settles in the region downstream of the swirler exit, where the flow velocity matches the turbulent flame speed of the fuel-air mixture (Figure 3). The burner design can accommodate fuels with a wide range of flame speeds. The flames of fuels with high flame speeds, such as hydrogen, will burn close to the burner exit, while the flame of low-heat-content fuels, such as landfill gas (with low flame speeds) will settle at a lower velocity region farther from the burner exit.

Low-swirl burner and flex-fuel

Development of fuel-flexible combustors (also referred to as injectors) in turbines for electricity generation is an important potential application for integrated-gasification combined-cycle (IGCC) power plants. As an example of the process required to modify burner designs for operation with alternative fuels, we discuss an investigation adapting the low-swirl burner for operation with both natural gas and syngas in power turbines. With U.S. Dept. of Energy support, research is underway to explore design concepts to adapt the low-swirl-based combustor for turbines that will allow operation with natural gas, medium-hydrogen-content (unshifted) syngas, and high-hydrogen-content fuels.

What are the most important issues associated with designing a turbine combustion system that can operate efficiently and cleanly on multiple types of fuel? The following issues should be considered: First, compare the properties — such as heat content, density, flame speed, range of flammability and autoignition temperature — of the fuels to be used.

One parameter that is used to assess fuel interchangeablity is the Wobbe Index (W.I.), which is defined as the higher heating value divided by the square root of gas specific gravity. The W.I. is helpful in assessing fuel supply and control issues for a combustion system, but it does not address the combustion properties of the fuels. Wobbe Index values for natural gas, hydrogen, and medium hydrogen syngas and high hydrogen syngas are listed in Table 1. Natural gas and hydrogen have similar W.I. values, but the syngas blends are significantly different. This indicates that the fuel circuit in a natural gas combustor could be used for hydrogen, but a different fuel circuit would be needed for the syngas blends.

The combustion properties of the fuels add another layer of complexity to the analysis. The specifications of a 200-MW (F class) power turbine will be used to investigate the operating conditions for a conceptual turbine combustor based on the low-swirl design. The airflow from the turbine compressor is roughly constant at full load. The turbine combustor will have a well-defined heat release, and this value can be used to determine the fuel flowrates. Selected values for operating parameters are listed in Table 2. Flame temperature will be constrained by NOx production and should be about 1,840K to achieve single-digit NOx emissions. The primary zone refers to the flame region. A portion of the incoming air is split off before the combustor and injected downstream of the flame to reduce the temperature to about 1,700K, the upper limit for the turbine inlet temperature. The flowrate of unshifted (medium-hydrogen) syngas is substantially higher than that of other fuels.

The values in Table 2 can be used to develop a conceptual combustor design that can utilize all of the fuels of interest. The flowrates and the fuel combustion properties suggest that it would be difficult to use a common fuel system for all three fuels. By incorporating two fuel circuits in the combustor assembly, it will be possible to operate the turbine at full load with any of the fuels and switch between fuels without shutting down (Figure 4). The flowrate of medium-hydrogen syngas will require a supply system with a larger cross-section than natural gas. High-hydrogen syngas can be supplied at a lower pressure than the medium-

TABLE 1. PROPERTIES OF POTENTIAL FUELS FOR A GAS TURBINE IN AN IGCC PLANT				
	Natural gas	100% H_2	Medium H_2	High H_2
Specific gravity	16.4	2.0	20.6	7.3
Molecular wt., kg/kmol	0.54	0.07	0.71	0.25
Density at std. temp. and pressure, kg/m^3	0.65	0.08	0.86	0.30
Lower heating value, kJ/kg	47,450	120,580	11,193	27,842
Lower heating value, kJ/m^3	32,676	10,059	9,687	8,457
Wobbe Index, MJ/m^3	44.2	38.3	11.4	17.0

TABLE 2. POWER TURBINE OPERATING PARAMETERS FOR NATURAL GAS AND TWO SYNGASES			
	Natural gas	Medium H^2	High H^2
Fuel temperature, K	458	366	366
Primary zone temperature, K	1,839	1,839	1,842
Mass flow (fuel), kg/s	12.4	57.1	22.4
Mass flow (air), ks/s	382	382	382
Primary zone fuel-to-air	0.032	0.149	0.059
Total mass flow, kg/s	466	511	476
Normalized mass flow	1.00	1.13	1.05

hydrogen syngas to provide a suitable flowrate through the same circuit.

Since hydrogen-containing fuels are more susceptible to flame flashback and autoignition, the injection site for these fuels is placed as close as possible to the combustor exit. This arrangement minimizes the volume of mixed air and fuel upstream of the flame zone. The natural gas injection site can be optimized for natural gas injection and located upstream of the syngas injection site. The dual-fuel-channel concept will minimize the modification of the low-swirl injector design developed for turbines, provide acceptable fuel injection pressures for all fuels and will allow seamless transition between fuels.

At present, only a conceptual design for a fuel-flexible, low-swirl combustor for power turbines has been developed. Considerable development and testing will be required to establish a geometry that will satisfy all of the requirements of such a burner. There are a number of potential issues to be explored, including:

- Fuel injection and mixing
- Variations in flame speed and flammability with fuel composition
- Flame behavior during transition between fuels
- Turbine instabilities and oscillations
- Cooling and temperature control of the combustor hardware

Coal gasification

Net carbon emissions can be reduced by using fuels from renewable sources or by removing carbon from the fuel stream (either before or after the combustion system). Lowering carbon in the fuel stream has focused attention on hydrogen as a fuel. Hydrogen can be produced by the gasification of coal.

The U.S. is one of a number of regions throughout the world with abundant coal reserves. To reduce the emissions and carbon footprint from coal-based power generation, pilot-scale studies are underway to gasify coal in IGCC plants. Coal gasification systems heat coal with steam and limited amounts of oxygen or air to yield a syngas that consists primarily of CO, CO_2 and H_2. The syngas can be processed by the so-called water gas-shift reaction to generate a mix of primarily H_2 and CO_2 ($CO + H_2O \longrightarrow CO_2 + H_2$).

The high-hydrogen-content syngas can be burned in a gas turbine to generate electricity. It is highly desirable to be able to burn natural gas in the turbine when syngas is not available.

The high concentration of carbon dioxide in the mix simplifies capture of CO_2 for sequestration or other purposes, such as enhanced oil recovery. Capturing CO_2 takes energy, so the goal is to establish a high concentration of CO_2 in the gas stream before separation. There is also an increasing emphasis on improving system efficiency so that more useful energy is extracted for a given quantity of fuel burned.

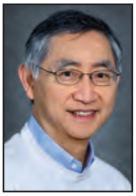
Autoignition in hydrogen-containing fuels is a concern at turbine operating conditions, and continues to be an area of active research. While hydrogen does not have a particularly low autoignition temperature, it has a very low ignition energy. The conditions at which autoignition occurs depend on a number of factors, including the composition of the fuel, the fuel-to-air ratio, pressure and temperature. If fuel is injected into air at conditions suitable for autoignition, there is a time delay before ignition occurs. There is disagreement between experiments and models of ignition delay (Figure 5).

To avoid the possibility of autoignition in a combustor, the residence time for the airflow to pass from the fuel injection point to the flame zone should be kept as short as possible when operating on fuels with high hydrogen content. The design goal for the low-swirl injector, for example, is to keep the residence time below 5 ms, which should supply a suitable safety margin at typical turbine operating conditions. ■

Edited by Scott Jenkins

Author

David Littlejohn is a staff scientist in the Environmental Energy Technologies Division at the Lawrence Berkeley National Laboratory (One Cyclotron Road, Mail Stop 70-108B, Berkeley, CA 94720; Phone: 510-486-7598; Email: dlittlejohn@lbl.gov, Web: www.lbl.gov.) Littlejohn and colleagues conduct research on the development of fuel-flexible combustion systems with ultralow emissions for power turbines and industrial process heating systems. He has a Ph.D. in chemistry from the University of California at Berkeley.



Robert K. Cheng is a senior scientist and leader of the Combustion Research Group in the Environmental Energy Technologies Division at Lawrence Berkeley National Laboratory. He has a Ph.D. in mechanical engineering from the University of California at Berkeley. His research interests are on premixed turbulent flames and their adaption to low-emissions heating and power systems.

Kenneth Smith is presently an independent consultant in the area of advanced combustion technologies for industrial gas turbines. Previously, he was employed at Solar Turbines Inc. for thirty years where his work focused on the development of low emissions combustion systems. Smith earned a Ph.D. in mechanical engineering from Cornell University.

Peter L. Therkelsen is a postdoctoral research associate at Lawrence Berkeley National Laboratory. He has a Ph.D. in mechanical and aerospace engineering from the University of California at Irvine. His research interests are in combustion and energy analysis.

Sy Ali is the principal of Clean Energy Consulting, a contractor for the U.S. Department of Energy. He has held management positions at Rolls Royce, General Motors, Duke Energy, and General Electric. Dr. Ali received his Ph.D. from Michigan State University and is a registered professional engineer.

Non-ideal Gas Calculations Using Analytical Residuals

A refresher on simplified calculations of thermodynamic changes of real gases

Subin Hada and Shafik E. Sadek
Chemical and Biomolecular Engineering
University of South Alabama

Many operations involving ideal gases are readily calculated using a basic knowledge of thermodynamics. Non-ideal gas behavior, however, can deviate significantly from that of ideal gases, and in some cases, large errors can be introduced in process calculations if a gas is improperly assumed to behave ideally. The pressure, volume and temperature (*PVT*) relationship of a gas defines its behavior and is used to account for its non-ideality. This *PVT* behavior of a gas is described by its equation of state (EOS). Knowledge of the EOS allows us to estimate the behavior of the gas more accurately when it is undergoing physical operations, such as compression or expansion.

The introduction of "residual functions" (defined as the difference between a property of the real gas and that property for an ideal gas held at the same temperature and pressure) simplifies the calculation of thermodynamic function changes, such as the enthalpy or the entropy, when the conditions of a gas are changed. For example, the energy required to compress a non-ideal gas may differ significantly from that of an ideal gas and is readily estimated by using the appropriate "residuals." Residuals are determined from the EOS.

Tables or charts of dimensionless expressions of residual enthalpy and residual entropy are available in the literature, but these are awkward to use in computational algorithms. Property algorithms are available in some chemical engineering software but these are not always available to the practicing engineer. Analytical expressions make it easier and more convenient to use residuals in process calculations.

Two equations of state commonly used by chemical engineers are the Redlich-Kwong-Soave (RKS) and the Peng-Robinson (PR). These are pressure-explicit forms (that is, with the pressure expressed as a function of temperature and specific volume.) These equations require only the knowledge of the critical properties of the gases, which are usually readily available, and can be carried out using handheld calculators. An example of an application on gas compression is given.

Definitions

A residual thermodynamic function is defined as the difference between the value of a property and the ideal gas value of that property at an equal temperature and pressure. The residual of a thermodynamic property B of a material at a temperature T and pressure P is:

$$B^R(T,P) = B^{real}(\text{real property at } T,P) - B^{ig}(\text{ideal gas property at } T,P) \quad (1)$$

Because gas behavior approaches ideal gas behavior as the pressure is reduced, the residuals of gases approach zero as their pressure is reduced. Consequently, at a constant temperature, T, the residual function, B^R, can be calculated by integrating the differential dB^R from a lower pressure limit of $P_0 \rightarrow 0$ to the system pressure P.

$$\int_0^P dB^R = B^R = \int_0^P d(B^{real} - B^{ig}) = \int_0^P dB^{real} - \int_0^P dB^{ig} \quad (2)$$

Since thermodynamic properties are functions of state, a change in the thermodynamic property of a material depends only on its initial and final conditions and not on the path taken to make the change. Because of this, residuals simplify the calculation of non-ideal gas property changes in process calculations. The thermodynamic property change between an initial and a final state can be readily determined by using residuals in a three-step calculation. For example, to calculate the change in a property "B" (usually the internal energy, enthalpy or entropy) when a material is taken from an initial temperature T_1 and pressure P_1 to a final temperature T_2 and pressure P_2, the change may be expressed as:

$$\begin{aligned}
&\Delta B(T_1,P_1 \text{ to } T_2,P_2) = \left[B(T_2,P_2) - B(T_1,P_1)\right] \\
&= B(T_2,P_2) - B^{ig}(T_2,P_2) \quad \text{(1st step)} \\
&+ B^{ig}(T_2,P_2) - B^{ig}(T_1,P_1) \quad \text{(2nd step)} \\
&- B(T_1,P_1) - B^{ig}(T_1,P_1) \quad \text{(3rd step)}
\end{aligned} \quad (3)$$

The first and third terms in the last part of the above equation represent the residuals at the final and initial conditions, respectively. The middle term represents the change in property for an ideal gas between (T_1,P_1) and (T_2,P_2), and requires knowing the ideal-gas specific heat. It is important to note that a change with temperature of the Gibbs free

TABLE 1. VALUES OF THE PARAMETERS IN THE EQUATIONS OF STATE	
RKS	PR
$a_c = 0.427480 \frac{R^2 T_c^2}{P_c}$	$a_c = 0.45724 \frac{R^2 T_c^2}{P_c}$
$\kappa = 0.48508 + 1.55171\omega - 0.15613\omega^2$	$\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2$
$\alpha = \left[1 + \kappa\left(1 - \sqrt{T_r}\right)\right]^2$	$\alpha = \left[1 + \kappa\left(1 - \sqrt{T_r}\right)\right]^2$
$a = a_c \alpha$	$a = a_c \alpha$
$b = 0.086640 \frac{RT_c}{P_c}$	$b = 0.07780 \frac{RT_c}{P_c}$
Critical and reduced properties are subscripted c and r ω is the acentric factor Note: The original RK equation of state used the same constants as the RKS equation but without $\alpha = T^{-1/2}$	

TABLE 2. SUMMARY OF THE RESIDUAL FUNCTIONS FOR DIFFERENT CUBIC EOS		
Residual internal energy, U^R		
RKS EOS	$\frac{a}{b}\left(\frac{\kappa T}{\sqrt{TT_c\alpha}} + 1\right)\ln\left[\frac{V}{V+b}\right]$	(10)
PR EOS	$\frac{a}{2b\sqrt{2}}\left(\frac{\kappa T}{\sqrt{TT_c\alpha}} + 1\right)\ln\left[\frac{V+b\left(1-\sqrt{2}\right)}{V+b\left(1+\sqrt{2}\right)}\right]$	(11)
Residual enthalpy, H^R		
RKS EOS	$\frac{a}{b}\left(\frac{\kappa T}{\sqrt{TT_c\alpha}} + 1\right)\ln\left[\frac{V}{V+b}\right] + RT\left(\frac{V}{V^{ig}} - 1\right)$	(12)
PR EOS	$\frac{a}{2b\sqrt{2}}\left(\frac{\kappa T}{\sqrt{TT_c\alpha}} + 1\right)\ln\left[\frac{V+b\left(1-\sqrt{2}\right)}{V+b\left(1+\sqrt{2}\right)}\right] + RT\left(\frac{V}{V^{ig}} - 1\right)$	(13)
Residual entropy, S^R		
RKS EOS	$\frac{a\kappa}{b\sqrt{TT_c\alpha}}\ln\left[\frac{V}{V+b}\right] - R\ln\left(\frac{V^{ig}}{V-b}\right)$	(14)
PR EOS	$\frac{a\kappa}{2b\sqrt{2TT_c\alpha}}\ln\left[\frac{V+b\left(1-\sqrt{2}\right)}{V+b\left(1+\sqrt{2}\right)}\right] - R\ln\left(\frac{V^{ig}}{V-b}\right)$	(15)
Residual Gibbs energy, G^R		
RKS EOS	$\frac{a}{b}\ln\left[\frac{V}{V+b}\right] + RT\ln\left(\frac{V^{ig}}{V-b}\right) + RT\left(\frac{V}{V^{ig}} - 1\right)$	(16)
PR EOS	$\frac{a}{2b\sqrt{2}}\ln\left[\frac{V+b\left(1-\sqrt{2}\right)}{V+b\left(1+\sqrt{2}\right)}\right] + RT\ln\left(\frac{V^{ig}}{V-b}\right) + RT\left(\frac{V}{V^{ig}} - 1\right)$	(17)
Residual Helmholtz energy, A^R		
RKS EOS	$\frac{a}{b}\ln\left[\frac{V}{V+b}\right] + RT\ln\left(\frac{V^{ig}}{V-b}\right)$	(18)
PR EOS	$\frac{a}{2b\sqrt{2}}\ln\left[\frac{V+b\left(1-\sqrt{2}\right)}{V+b\left(1+\sqrt{2}\right)}\right] + RT\ln\left(\frac{V^{ig}}{V-b}\right)$	(19)

energy, ΔG, or the Helmholtz free energy, ΔA, requires knowing the absolute value of the entropy, S (see the relationships listed in the Boxes on p. 51), and cannot be determined without resorting to the third law of thermodynamics. The effect of temperature on the free energies is outside the scope of this paper and will not be discussed here.

Derivation of residuals

The derivation of residuals is shown in most thermodynamics textbooks [*1–3*]. Residuals for single components are calculated from the isothermal relationship expressed by Equation (2):

$$\int dB^R = \int dB^{real} - \int dB \qquad (4)$$

The isothermal differentials for the actual material and ideal gas properties can be expressed in terms of pressure or volume as either one of the following differentials:

$$dB = \left(\frac{\partial B}{\partial P}\right)_T dP \quad \text{, or} \qquad (5)$$

$$dB = \left(\frac{\partial B}{\partial V}\right)_T dV \qquad (6)$$

The differentials $(\partial B/\partial P)_T$ and $(\partial B/\partial V)_T$ are determined from the basic thermodynamic functions (the combined first and second laws) and the EOS used to describe the material's *PVT* relationship. The preferred differential depends on the EOS used, whether it is volume- or pressure-explicit. Pressure-explicit forms are more commonly used, and in this case the differential with respect to volume [Equation (6)] gives a more convenient form to use.

Equations of state

Cubic equations of state are closed-form equations that are modifications of the Van der Waals equation, with constants that are related to the critical properties of the material. The generalized pressure-explicit cubic equation of state [*3*] is given by:

$$P = \frac{RT}{(V-b)} - \frac{\alpha(T)}{(V+\beta-t)(V+\gamma-t)} \qquad (7)$$

where α, β, t and γ are constants specific to the material and related to its critical properties.

An early cubic equation is the Redlich-Kwong (RK) equation which was later modified by Soave and is still commonly used in chemical engineering; it is often called the Redlich-Kwong-Soave (RKS). Another equation still used after many years of application is the Peng-Robinson (PR) equation of state.

The RKS equation of state is:

$$P = \frac{RT}{(V-b)} - \frac{a}{V(V+b)} \qquad (8)$$

The PR equation of state is:

$$P = \frac{RT}{(V-b)} - \frac{a}{V(V+b) + b(V-b)} \qquad (9)$$

The constants in Equations (8) and (9) are expressed in terms of the critical properties as shown in Table 1.

Residuals of thermodynamic functions

Residuals of the thermodynamic functions are determined by combining the basic first and second laws of thermodynamic functions (Box 1 on p. 51) and the Maxwell relations (Box 2 on p. 51). The residual for each thermodynamic function can be determined for the property of interest by applying Equation (2), Equation (6), and the appropriate Maxwell relation to eliminate the entropy term.

Residuals were calculated based on the pressure-explicit Redlich-Kwong-Soave and the Peng-Robinson equations and the results for the five thermodynamic functions are summarized in Table 2.

Example calculations

Two examples are now presented to demonstrate the use of residuals. Both involve the compression of methane at an initial temperature of 200K. For simplicity, the compressions — isothermal and adiabatic — are assumed to be carried out reversibly.

For methane, the following parameters are used [2]:

T_c = 190.56K

P_c = 4.6 MPa

ω = 0.011

$C_P^{ig}/R = 4.568 - (8.975\times10^{-3})T + (3.631\times10^{-5})T^2 - (3.407\times10^{-8})T^3 + (1.091\times10^{-11})T^4$

Example 1: Isothermal flow compression. Determine the work required to compress methane isothermally (at 200K) from a pressure of 1 MPa to 10 MPa. The compression is to be carried out in a continuous flow operation.

Assuming a reversible compression, the work to compress one mole of gas isothermally is the flow work

$$W = \int VdP = \Delta G$$

Where

$$\Delta G = G_2 - G_1$$
$$= \left(G_2 - G_2^{ig}\right) + \left(G_2^{ig} - G_1^{ig}\right) - \left(G_1 - G_1^{ig}\right)$$
$$= G_2^R + \left(G_2^{ig} - G_1^{ig}\right) - G_1^R$$
$$= G_2^R + RT\ln\left(\frac{P_2}{P_1}\right) - G_1^R$$

For the given problem, the Gibbs free energy residuals require knowledge of the gas specific volumes at the two temperature limits. These actual volumes are determined from the EOS. The ideal gas values are computed from the ideal gas law.

Table 3 summarizes the parameters and the properties using the RKS and PR equations of state for pure methane at 200K, and the estimates of the compression energy required. The ideal gas value is also calculated.

The work required to compress the gas isothermally based on the RKS equation of state is about 31% lower than the work required to compress an ideal gas. The work required to compress the gas based on the PR equation of state, is about 34% lower than that required for an ideal gas. The results from the two EOSs agree within about 3%, and both show a significant difference of gas behavior from ideality.

TABLE 3. SUMMARY OF ISOTHERMAL COMPRESSION CALCULATIONS.

	RKS EOS	PR EOS	Units
Parameters			
a_c	0.233	0.249	J m^3/mol^2
κ	0.502	0.392	dimensionless
α	0.975	0.981	dimensionless
a	0.228	0.245	J m^3/mol^2
b	2.984 x 10^{-5}	2.680 x 10^{-5}	m^3/mol
Properties			
V_2	6.603 x 10^{-5}	5.984 x 10^{-5}	m^3/mol
V_1	1.552 x 10^{-3}	1.539 x 10^{-3}	m^3/mol
V_2^{ig}	1.663 x 10^{-4}	1.663 x 10^{-4}	m^3/mol
V_1^{ig}	1.663 x 10^{-3}	1.663 x 10^{-3}	m^3/mol
G_2^R	-1,311	-1,407	J/mol
ΔG^{ig} (=W^{ig})	3,829	3,829	J/mol
G_1^R	-109	-122	J/mol
ΔG (=W)	2,627	2,544	J/mol

TABLE 4. SUMMARY OF ISENTROPIC COMPRESSION CALCULATIONS

	RKS EOS	PR EOS	Units
T_2	359.55	360.02	K
V_2	2.850 x 10^{-4}	2.759 x 10^{-4}	m^3/mol
V_2^{ig}	2.989 x 10^{-4}	2.989 x 10^{-4}	m^3/mol
S_2^R	-2.530	-2.574	J/mol K
ΔS^{ig}	1.414	1.465	J/mol K
S_1^R	-1.116	-1.109	J/mol K
H_2^R	-1,089	-1,215	J/mol
ΔH^{ig}	5,633	5,651	J/mol
H_1^R	-332	-344	J/mol
ΔH (=W)	4,876	4,780	J/mol

Example 2: Reversible adiabatic compression. Determine the work required to compress the gas adiabatically between the two given pressures, starting with a gas at 200K.

If the compression is carried out adiabatically, the work done, W, to compress the gas is equal to its change in enthalpy during an isentropic compression:

$$W = H_2 - H_1$$

And since the compression is carried out adiabatically and reversibly, then

$$\Delta S = S_2 - S_1 = 0$$
$$= \left(S_2 - S_2^{ig}\right) + \left(S_2^{ig} - S_1^{ig}\right) - \left(S_1 - S_1^{ig}\right)$$

Here, the ideal gas entropy change is:

$$\Delta S^{ig} = (S_2^{ig} - S_1^{ig}) = \int_{T_1}^{T_2} \frac{C_P^{ig}}{T} dT - R\ln\left(\frac{P_2}{P_1}\right)$$

BASIC THERMODYNAMIC RELATIONSHIPS

The basic thermodynamic relations for one mole of a single component combine the first and second laws of thermodynamics and are expressed as follows:

Internal energy, *U*

$$dU = TdS - PdV \quad (20)$$

Enthalpy, *S*

$$dH = TdS + VdP \quad (21)$$

Gibbs free energy, *G*

$$dG = VdP - SdT \quad (22)$$

Helmholtz free energy, *A*

$$dA = -PdV - SdT \quad (23)$$

Here, *S* and *V* represent the specific entropy and specific volume of the material; *P* and *T* are its pressure and temperature.

Therefore,

$$\Delta S = S_2^R + \int_{T_1}^{T_2} \frac{C_P^{ig}}{T} dT - R\ln\left(\frac{P_2}{P_1}\right) - S_1^R = 0$$

To calculate the work required, the compressed gas temperature T_2 that satisfies the above equation must first be determined. This is readily done since all the variables in this equation are known (T_1 , P_1 and P_2) with the only unknown being T_2. A trial-and-error procedure using MS-Excel or Mathcad can be set up. Using Excel, for example, a spreadsheet is prepared. The first step is to select some final temperature, T_2. From the EOS, the value of V_2 is determined that satisfies this temperature and the system pressure, P_2, using, for example, Goalseek or Solver. Using these temperatures (T_1 and the assumed value of T_2) and pressures (P_1 and P_2) the overall entropy change, ΔS, is calculated. This calculation is repeated with different temperatures until a value of $\Delta S = 0$ is finally obtained. This will then be the value of T_2 that satisfies both the isentropic change and the EOS.

The compressor work, *W*, can now be calculated. It is equal to the enthalpy change, ΔH, of the gas. Once again, using residuals:

$$W = \Delta H = H_2 - H_1 = \left(H_2 - H_2^{ig}\right) + \left(H_2^{ig} - H_1^{ig}\right) - \left(H_1 - H_1^{ig}\right)$$

$$= H_2^R + \int_{T_1}^{T_2} C_P^{ig} dT - H_1^R$$

Table 4 summarizes the results obtained from the isentropic compression calculation described above.

For comparison with an ideal gas, the final temperature $(T_2^{ig})^*$ after the ideal-gas isentropic compression is calculated this time from $\Delta S^{ig} = 0$. Again, using an iterative calculation, this temperature is determined to be:

MAXWELL RELATIONS

Because the thermodynamic properties are functions of state and are exact differentials, the Maxwell's relations define the effects of pressure and volume on the entropy. These are:

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P \quad (24)$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V \quad (25)$$

$(T_2^{ig})^* = 346\text{K}$

and the work required to compress the ideal gas to the desired pressure of 10 MPa is

Work = $(\Delta H^{ig})^* = 5{,}134$ J/mol

The real gas calculations are about 5% and 7% below the ideal gas compressions based on the RKS and PR equations of state, respectively. The difference in the estimates between the two equations of state is about 2%. ■

Edited by Gerald Ondrey

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Authors

Subin Hada is currently pursuing his Ph.D. in chemical engineering at the Auburn University (212 Ross Hall, Auburn University, AL 36849; Phone: 334-844-2463; Email: szh0020@auburn.edu). He holds B.S.Ch.E. and M.S.Ch.E. degrees from University of South Alabama. As an undergraduate, he co-authored two publications in the field of reactive-chemical, hazard-analysis methods. At the graduate level, he developed a spreadsheet application for unsteady, multi-component two-phase-flow calculations utilizing an interface to a thermodynamic property package during 16-month internship with Evonik Degussa Corp. (Mobile, Ala.). He is a member of AIChE and Tau Beta Pi. He was recognized in the Who's Who Among Students in American Universities and Colleges in 2008, and was awarded the College of Engineering Student of the Year in the U.S. for 2007–2008, and a Mobile Oilmen's Assn. Scholarship in 2006. His research interests are in process and product design, process simulation, reactive hazard prediction and process safety.

Shafik E. Sadek (307 University Blvd N. EGLB 244, Mobile, AL 36688. Phone: 251-460-6160; Email: smaru@comcast.net) received his B.Ch.E. from Cairo University (Egypt). On graduating, he spent two years as an instructor in the organic and organic chemistry laboratories, and in the petroleum testing laboratory in the Chemical Engineering Department at the Faculty of Engineering in Cairo. He received his Sc.D.Ch.E. from M.I.T., after which he was employed by Dynatech R&D Corp., a contract R&D and consulting firm where he worked on numerous industrial and government projects, most of them related to heat and mass transfer. He then joined Ciba-Geigy Corp. at its facility in McIntosh, Alabama. He held different positions at Ciba in Alabama, North Carolina and New York: as a development engineer, as a divisional process manager in the Agricultural Div., as the corporate director of Chemical Development, and as team leader in the Optical Brighteners production unit. On retiring from Ciba, Sadek spent time as an instructor in the Chemical Engineering Dept. of the University of South Alabama, where he taught various courses in thermodynamics and mass transfer operations. He now lives in Mobile, Alabama. Sadek is a member of AIChE and ACS and is a registered PE.

Specifying Gas Turbines

Amin Almasi
WorleyParsons Services Pty Ltd

This guidance can help to improve the specification and operation of these workhorse units, which are used throughout the CPI as both mechanical drivers and power generators

Gas turbines are widely used throughout the chemical process industries (CPI) — especially in petroleum refineries and petrochemical facilities — to provide both mechanical-drive and power-generation capabilities. Presented below are a variety of recommendations related to the selection and arrangement of gas turbines and auxiliaries, performance testing, and proper operation and maintenance of these systems.

In general, gas turbines have always been tolerant of a wide range of fuels including conventional liquid and gaseous fossil fuels, and high- and low-heating-value fuels (such as gasified coal, wood and biofuels and so on). For gas turbines, the primary performance objectives include the ability to demonstrate optimum fuel consumption, maintain low emissions and ensure reasonable reliability.

Ongoing improvements for gas turbines have been achieved by three main factors:

- Metallurgical advances that have enabled the production of gas turbine components with increased temperature ratings
- The application of the cumulative body of advanced knowledge developed by the aircraft-engine industries has benefited many applications in the chemical process industries (CPI), with favorable results
- Advanced computer technology has been used to optimize the design, simulation and operation of gas turbines

All of these factors have contributed to a vast range of ongoing design improvements for the air-compressor itself (for instance, enabling improved pressure-ratio increases), for the combustion system (producing lower emissions and greater fuel efficiency), and for the turbine (for instance, through the development of single-crystal blades, improved cooling strategies and more).

The design and arrangement of individual gas turbine packages is a complex undertaking. When evaluating competing gas turbine options, the user must weigh the needs and requirements of the application against the specific performance attributes and other defining characteristics of the gas turbines offered. Compromises or tradeoffs are often required to balance the application-specific requirements and constraints against competing turbine options. Condition monitoring and predictive maintenance can help to improve overall operation and reliability.

The ability to maintain control of speed in the face of sudden load changes is also important. Today, thanks to advances in modern control technologies, it is possible to simply and effectively control these highly responsive machines.

Gas turbine types and design

There are two main types of gas turbines — aero-derivative gas turbines and heavy-industrial gas turbines — and each varies in terms of its weight, combustor design, turbine design, bearing design and lube oil system. In general, heavy-frame units are slower in speed than aero-derivative gas turbines, and they have higher air flow and tend to require more time- and labor-intensive maintenance and management of spare parts. Meanwhile, heavy-industrial gas turbines typically use hydrodynamic bearings while aero-derivative units typically use anti-friction bearings.

Ongoing advances in the aircraft engine and space technologies sector have been used to provide more easily maintainable, flexible, lightweight and smaller aero-derivative gas turbines for use in other industrial sectors. The key to easing maintenance is to use a modular concept, which enables the removal and replacement of key components without requiring the entire gas turbine to be removed from its support mounts. In general, heavy-industrial units tend to require greater time and effort than aero-derivative units to remove and replace the combustor parts and more effort to inspect or repair the various sections of the gas turbine.

For both power-generation and mechanical-drive services, the general preference among operators has been to use aero-derivative units in remotely located applications (including offshore applications), and to use heavy-frame industrial units in more easily accessible baseload applications. However, there will always be exceptions.

Heavy-industrial gas turbines tend to consume more fuel and approximately 50% more air than aero-derivative units. Because of this, heavy-industrial gas turbines are exposed to greater amounts of potential contaminants in the air and thus face an increased risk of corrosion (especially sulfur-related corrosion). In particular, the large cross-sectional area of the blades and vanes used in heavy-industrial turbines makes them more susceptible to corrosive attack, but their increased size also enables them to tolerate more corrosion compared to the blades of the aero-derivative gas turbines, which tend to be thinner and have a higher aspect ratio.

Hot-end drives. Gas turbines can be arranged in one of two ways: as a hot-end drive configuration or a cold-end drive configuration. The hot-end drive

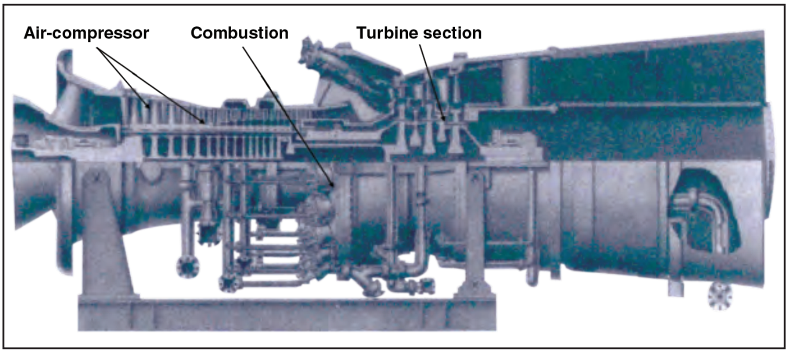

FIGURE 1. **Shown here is an example of a heavy-frame industrial gas turbine. In recent years, metallurgical advances have helped to increase the temperature ratings of all types of turbines. Reprinted with permission from [*1*]**

configuration is more common. In a hot-end drive configuration, the location of the gas turbine output shaft is at the turbine end where exhaust gases can reach high temperatures. This not only affects bearing operation and life, but also makes the turbine more difficult to service, as the train assembly (driven equipment, coupling and so on) must be fitted through the exhaust duct.

In hot-end arrangements, insufficient attention to key design and operational aspects — such as the output shaft length, high temperatures, exhaust duct turbulence, pressure drop and maintenance accessibility — often results in power loss, excessive vibration, shaft or coupling failure, and increased downtime for maintenance.

Cold-end drives. By comparison, in the cold-end drive configuration, the gas turbine output shaft connects to the front of the air-compressor. In such a configuration, the driven equipment can be more easily accessed by operators and maintenance technicians. Unlike a gas turbine with a hot-end drive configuration, driven equipment in the cold-end configuration will be exposed to ambient temperatures only.

However, the cold-end configuration has several drawbacks that must be considered. For instance, the air-compressor inlet must be configured to accommodate the gas turbine output shaft to the driven equipment. This will affect the inlet air duct. This inlet duct must be turbulent-free and provide uniform, vortex-free flow throughout the operating speed range. Problems resulting from a poor design can be catastrophic. For example, inlet turbulence can induce surge in the air-compressor, resulting in complete destruction of the unit.

Inlet air-duct turbulence is also a major reliability concern, since air compressors — particularly axial ones — are very sensitive to surge (that is, unstable operation due to low air flow as result of air duct turbulence). Surge can result in machine destruction in several seconds. This is a major reason why hot-end drive configurations are preferred and more widely used.

In cold-end drive configurations, the potential for air duct turbulence can be greatly reduced with the use of turbulence-free ducting designs, but these impose higher pressure drop, which is not acceptable for some applications.

Figure 1 and Figure 2 show examples of heavy-frame industrial and aero-derivative gas turbines, respectively. Figure 3 shows a large power-generation gas turbine.

Competing designs

Gas turbines can be categorized into two main groups. Single-spool machines and multi-spool machines. In single-spool, integral-output shaft gas turbines, the air-compressor and power turbine are assembled on the same shaft (the gas turbine output is located at the end of this shaft).

Single-spool, integral-output shaft gas turbines — both hot-end drive designs, and cold-end drive designs — are used primarily to drive electric generators (an integral-shaft gas turbine is uncommon for mechanical drive applications). The high torque required to start pumps and compressors under full pressure results in high turbine temperature during the startup cycle (when the flow of cooling air is low or non-existent).

One exception is very large compressors that are driven by gas turbines, as in liquefied natural gas (LNG) refrigeration compressor trains, which typically use a single-spool, integral-output shaft gas turbine (for example, a 40-MW or larger train).

By comparison, a single-spool, split-output-shaft gas turbine is a single-spool gas turbine that drives a free power turbine. Such an arrangement contains an air-compressor and coupled turbine spool, which delivers hot gas to to the turbine, which is coupled to the driven equipment. In this configuration, the air-compressor and its turbine component shaft (the turbine that drives the air-compressor) are not physically connected to the free power-turbine shaft. Rather, these two shafts are coupled aerodynamically. Split-output-shaft gas turbines offer easier startup when used for mechanical-drive applications.

Usually, mechanical drive gas turbines (such as those used to drive a process compressor or large pump) that are referred to as a split-shaft, mechanical-drive gas turbines, are able to attain self-sustaining operation before picking up the load of the driven equipment. Power-generation turbines can be designed to operate at the same speed as the driven equipment, thereby eliminating the need for a gearbox. This can provide an efficiency advantage, because typical gearboxes create losses equivalent to 2–4% of net power generated. However, such a design is limited to hot-end drive configurations, because free-power-turbines should be located next to the air-compressor-turbine hot-gas stream.

Dual-spool gas turbines contain two shafts (each has its own air compressor and turbine section). One shaft passes through the other. In a dual-spool, split-output shaft gas turbine, independent low- and high-pressure compressors and turbines generate the hot gases that drive the free turbine (for higher-power applications, there may be three shafts, each operating at different speeds).

Optimum overrating

Degradation and environmental conditions, such as temperature and humidity, can have considerable impact on gas turbine output power. Discussed below are some guidelines for the sizing of gas turbines based on applicable codes, experiences and lesson learned in various projects.

In general, gas turbines should be designed to provide an average of 12–14%more power than the driven equipment requires (5% as tolerance to meet the driven equipment shaft-brake power), an additional 2% for the gear box (if applicable), an additional 2% for fouling and erosion, and finally an additional 5% for longterm gas turbine deterioration). Care should be taken when selecting the starting device and evaluating its rating.

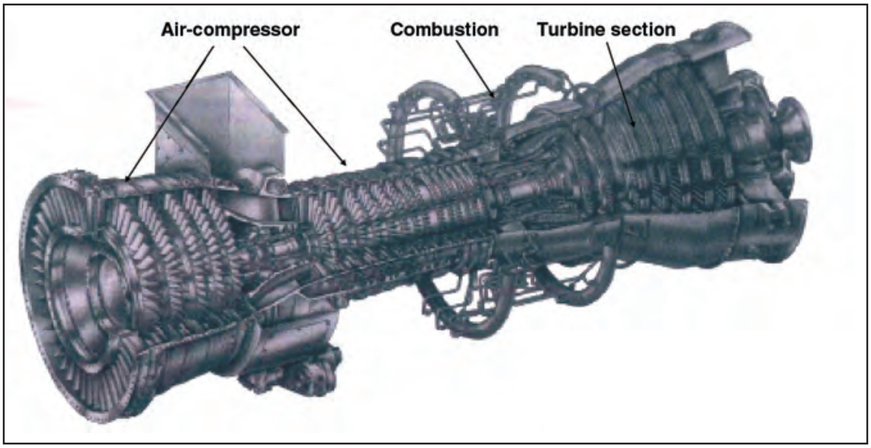

FIGURE 2. With an aero-derivative gas turbine, such as the one shown here, the purge period should be designed to displace a minimum of six times the exhaust-system gas volume (including turbine, exhaust duct, waste-recovery device and exhaust stack) before firing the unit. Reprinted with permission from [*1*]

In general, the preferred starting device is an electro-hydraulic configuration — whereby an electric motor drives a hydraulic pump, which transmits hydraulic power to start the gas turbine. The starting device should be rated to supply minimum 110% of the gas turbine's required starting torque (under worst-case scenarios).

Helper drivers are not recommended except for special cases. A helper driver is a separate rotating machine (based on a motor, engine or similar) that is coupled to the gas turbine train to help the startup train. They may be disconnected after startup or stay in connection during operation. In general, they are not recommended since they decrease reliability and flexibility.

The main exception — very large, compressor trains driven by heavy-frame gas turbines (such as large LNG trains) — often use variable-speed electric motors as helper drivers and power equalizers (for instance, to generate mechanical torque during hot days when gas turbine power is low, and to generate electricity in the winter when gas turbine power is higher than required by the train).

Hot start (that is, startup shortly after gas turbine shutdown, when the machine is still hot) is critical since all complex systems, such as machine cooling systems (particularly the air cooling systems used for the blades) should be ready for this kind of startup (for example to handle hot gas from a still-hot combustion system). The gas turbine should be capable of an immediate hot start at any time after a trip for three consecutive start attempts.

Specification tips

The issues discussed next should be addressed during the specification and purchase of any gas turbine system.

Startup. Cold-start and hot-start restriction details are very important, and such details should be finalized during the bidding stage. Igniters should not remain in the primary combustion zone during operation since extremely high temperature over the long term can degrade them and create reliability and operating problems. The rotating blades and the labyrinths of shrouded rotating blades should be designed to start up without rubbing. Sealing components (such as labyrinths, honeycombs, or abradable surfaces) are required at all internal close-clearance points between the rotating and stationary parts and all external points where shafts pass through the casings.

Maintaining suitable clearances. This is an ongoing challenge in gas turbines, due to the impact of changing temperatures between cold and accelerating conditions. The most severe conditions, which usually occur after a restart, will determine the minimum clearance that should be required.

For variable-speed, mechanical-drive applications, the speed range for single-shaft gas turbines is recommended to be 25% (80 to 105% of rated speed), and for gas turbines with two or more shafts the speed range is recommended to be 45% (60% to 105%).

For power-generation application, the required speed is usually constant, since generator speed and network frequency are fixed.

Compressors. Two types of air-compressors are available — axial compressors (with up to 19 stages) and centrifugal compressors (with one or two impellers). The air-compressor supplies compressed air to the gas turbine combustor to generate hot gases and drive the turbine section. An increase air-supply pressure to the combustor (to increase the air-compressor ratio) is very important to improve turbine power generation.

An increase in air-compressor ratio is the prime contributor in the overall increase in simple-cycle thermal efficiency (efficiency without either heat recovery or steam generation from the hot exhaust gases) to above 35% (particularly for aero-derivative units). Today, aero-derivative gas turbines are available with simple-cycle thermal efficiency above 44%.

Combustors. Combustor design is a complex task. There are two main designs for combustors: the can-annular combustor design and the annular-section design (including the single combustor). Two types of can-annular combustors are available: more-efficient, straight flow-through designs, and reverse-flow combustors. The advantage of the reverse-flow combustor, as used in many heavy-industrial gas turbines, is the use of a regenerator.

Regenerator. A regenerator has many potential configurations, but in general, it uses hot turbine exhaust gases to increase the heat value of the high–pressure, inlet compressor air feed to the combustor. In general the use of a regenerator helps to improve the overall thermal efficiency of the gas turbine system.

Blades. Aero-derivative units use blades that are relatively long and thin (giving them a relatively high aspect ratio) and incorporate tip shrouds to dampen vibration and improve blade-tip sealing characteristics.

By comparison, heavy-frame industrial gas turbines incorporate blades that are relatively short and thick (that is, they have a low aspect ratio) and have no shroud. Ongoing improvements in metallurgy and casting techniques have allowed turbine manufacturers to eliminate mid-span shrouds and lacing wires in many designs.

In all types of gas turbines, the turbine blades are subject to stresses resulting from high temperature, high centrifugal forces and thermal cycling. Most designs rely on various cooling systems, and these cooling mechanisms decrease the effects of the extremely high temperature of the gases delivered from the combustor. But high temperatues are still experienced by the blades.

Shaft. As a rule-of-thumb for power-generation gas turbine packages, the generator shaft diameter should be equal to or greater than the gas turbine shaft diameter because the gas turbine shaft is usually fabricated from higher-grade alloy materials. For mechanical-drive applications, both shafts should have approximately the same diameters (in case of the same operating speed).

For all gas turbines, the shaft materials should be high-strength, suitable grade steel. Proper weld procedures and material compatibility must be considered. Fabrication details should consider anticipated loads that could result from vibration.

Performance curves. The gas turbine manufacturer should supply the following performance curves: net output, net heat rate, exhaust temperature, and exhaust flow versus ambient temperature for the specified fuels at site conditions.

Couplings. Due to their extreme operating conditions, all gas turbines have the potential for blade failures resulting from torsional, lateral or resonance forces or fatigue. The proper selection of couplings (that connect the gas turbine to the driven equipment) is the best way to tune the torsional character of the train and avoid the coincidence of system dynamic natural frequencies and train excitation frequencies that can lead to blade failures.

A variety of coupling options are available:

1. *High-torsional-stiffness couplings (preferably a dry, flexible- diaphragm type) or direct-forged, flanged, rigid connections.* These are optimum selections for all types of gas turbines if proper coupling or connections with suitable load-carrying capacity and misalignment capability are required, if there are no interferences between the system's natural frequencies and the train's excitation frequencies and if transient situations do not impose any specific problems.
2. *Flexible couplings using soft elements like rubber.* These provide greater elasticity and damping, but also tend to require more maintenance since rubber elements may become degraded and require replacement.

Managing excessive excitation

The blades' natural frequencies must not coincide with any source of excitation within a range that spans from 10% below the minimum governed speed to 10% above the maximum continuous speed. Stress analysis should be performed if the torsional, lateral or blade excitation falls close to the train natural frequencies, to ensure that the resonance will not be harmful for the system.

The main potential sources of excitation in a gas turbine train include:

- Unbalance in the rotor system
- First-harmonic passing frequencies of various rotating and stationary components in the train
- The first ten rotor-speed harmonics
- Frequencies generated by gas-passage splitters
- Irregularities in vane and nozzle pitch
- Periodic impulses caused by the combustor arrangement
- Oil-film instabilities (whirl)
- Internal rubbing points
- Diffuser passing frequencies
- Gear-tooth meshing and side bands
- Gear problems
- Coupling misalignment
- Loose rotor-system components
- Whirl resulting from hysteresis and friction
- Boundary-layer flow separation
- Acoustic and aerodynamic cross-coupling forces
- Asynchronous whirl
- Startup or shutdown conditions
- Governor control-loop resonances
- Fuel pressure pulsation
- Rolling element/race frequencies of anti-friction bearings for aero-derivative gas turbines (Note: Anti-friction bearings rely on rolling elements to carry loads, so various frequencies known as rolling element/race frequencies are generated by them)

Auxiliaries. Auxiliaries and accessories (such as a filter inlet system, exhaust system and so on) must be installed with proper supports since they are in the vicinity of a gas turbine, and are thus subjected to vibrations.

Similarly, corrosion protection must be provided for the filter, ducting, and silencer. For instance, the filter house (mounted on top of the gas turbine enclosure) and silencers (including the inlet-silencer perforated-plate element) exhaust plenum and exhaust silencer must be fabricated from suitable grades of stainless steel. Silencers should have a rigid structure and be suitably designed to prevent damage from anticipated acoustical or mechanical resonances or differential thermal expansion.

Inlet and exhaust filters. The inlet and exhaust systems should be designed for a minimum practical pressure drop. A filter with 100% removal efficiency for particle sizes of 3 microns or larger (and minimum 99% removal of particles of 0.5 to 3 microns) is typically used. The filter system requires an entrance screen to prevent debris from entering the system, and the design should include a downward-oriented air inlet or a louver or cowling to keep rain and snow out.

The design should include proper access to facilitate maintenance, a differential-pressure alarm for each stage of filtration, and should use modular construction (via fully factory assembled modules).

Some of the worst effects of turbine hot-section corrosion are experienced in offshore applications or facilities that operate near the sea coast. Sulfidation corrosion instigated by sea salt exposure can be minimized through the design of the inlet-air filtration system and selection of suitable turbine materials and material coatings.

The duct system. The optimum duct system has a minimum number of direction changes, and includes proper turning vanes (to assure uniform flow distribution and to avoid resonance). The system should be designed to ensure a velocity limit of 20 m/s and 30 m/s for the inlet and exhaust, respectively.

The ducts should be sufficiently rigid to minimize vibration (a plate that is 5 to 10 mm thick is generally used), and the access points required for cleaning and inspection should be considered. The ducting and casing design must permit field balancing in the end planes of the rotors without requiring the removal of major casing components (in other words, the machine and ducting arrangement should allow proper access for various rotor rebalancing in situ).

Inlet air and exhaust system. The layout of the inlet and exhaust system must be designed with great care. For instance, the air inlet must be upstream of the exhaust stack during prevailing wind conditions, and its relative position must avoid any recirculation of exhaust gases that could result from any conceivable potential wind conditions. (As a general rule of thumb, the minimum horizontal separation is typically on the order of 7.5 meters). The air inlet should also be elevated a minimum of 5 m from the ground, and the gas turbine exhaust must also be outside of the specified, three-dimensional fire-hazard zone (this is the zone with the greatest potential for flammable gas release, as determined by the site's safety team) and outside any classified electrical areas.

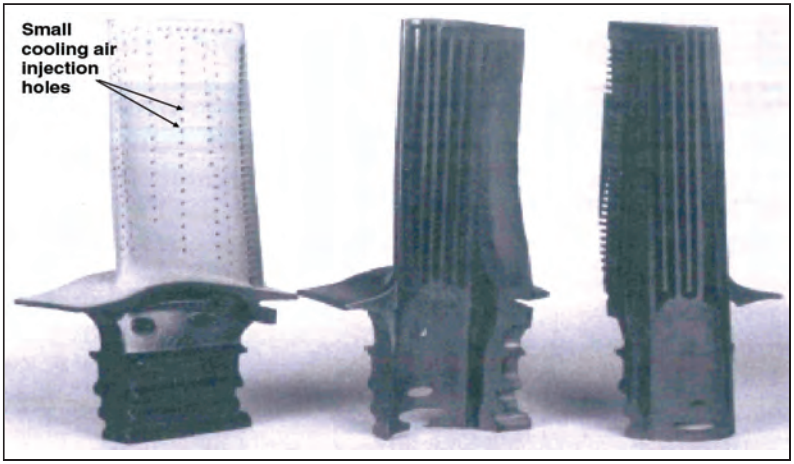

FIGURE 3. **This figure shows the internal structure of high-pressure turbine blades that are equipped with cooling distribution throughout the core of the blade airfoil and root. Reprinted with permission from [*1*]**

Thermal analysis is also necessary, and great care must be executed, especially for extremely cold ambient temperature, or packages are likely to operate over a wide range of conditions.

The lubrication system. In any gas turbine system, the lubrication system is often a source of trouble. Necessary lubrication points and lubrication spare points should be provided. The lubrication oil system for any gas turbine should include two pumps, each of which is sized for at least 20% greater flow than the train oil demand. The oil supply line to critical components should be monitored (mainly with regard to oil pressure).

As a rough indication, the inlet oil temperature and oil temperature rise through the bearing should be maintained at les than 50°C and 30°C, respectively.

Dual removable bundle shell-and-tube oil coolers, in a parallel arrangement, and double filters with removable element and stainless steel piping and valves are typically used. For oil reservoir volume, a retention time of more than eight minutes is recommended. For aero-derivative gas turbines, which typically have anti-friction bearings and use synthetic lubrication oil, the turbine lubricating-oil system is usually separate from the driven equipment lubricating-oil system. And when the gas turbine is equipped with antifriction-type bearings, the use of an instrumented, metal chip-detection system — an on-line system to monitor for metallic debris — is strongly recommended.

With heavy industrial-type gas turbines, hydrodynamic bearings are typically preferred, and these tend to require mineral-based lubricating oils. Such systems tend to require one integral lubricating-oil system per train. In a common oil system, the lubricant is a typically a hydrocarbon oil corresponding to ISO Grade 32 or similar.

The fuel system. The fuel system is also a critical component of any gas turbine system and needs special attention. A fuel strainer (typically a Y-type strainer with stainless steel internals) and a blowdown system with a manual valve is typically included for purging and warming up the fuel system for approximately 20 minutes prior to startup. To prevent condensate mist carryover or hydrate formation (if required), a fuel gas super-heater designed to deliver 40°C fuel gas should be included. If fuel gas compression is required, a screw compressor is recommended.

Evaporative coolers are not recommended due to the possibility of damage on gas turbine internals and decreasing reliability from water carryover or poor water quality. Liquid-to-air heat exchangers to cool the inlet air (for performance enhancement) and steam- or water-injected exchangers for emissions-control purposes are not recommended, because they tend to engender significant maintenance requirements.

Mechanical design issues

The most critical areas for mechanical design are the sealing system, bearing system, number of stages and staging arrangement, casing size and design, casing joint design, rotor dynamics, rotor and blade structural design and performance, gas turbine component material selection, and design and arrangement of power-transmission components.

Turbine section shafts experience high temperature changes during transient operations such as startup, and shutdown. Turning equipment (typically a turning gear or ratchet device) should be furnished where the turbine shaft requires rotation to avoid thermal distortion of the shaft during startup or immediately following a shutdown. The turning equipment should be automatically engaged and preferably driven by an electric motor.

Degradation of each stage or section of gas turbine has a cumulative effect. For instance, a degraded stage or section will create different exit conditions compared to a new stage, and each subsequent stage will end up operating further away from its design point. The main causes of degradation are increased tip clearances, changes in airfoil geometry, and changes in the surface quality of the components. Such degradation is caused by a variety of mechanisms:

- Fouling caused by the adherence of particles to foils and annulus surfaces
- Hot corrosion that results in the loss or deterioration of material from components as they are exposed to hot gases (typically by chemical reactions)
- Abrasion-related erosion resulting from hard or incompressible particles in the gas streams impinging on flow surfaces
- Abrasion resulting from rotating surfaces rubbing on a stationary surface or damage caused by foreign objects striking the flow-path components (the use of an inlet filtration system can help to reduce some of these issues)

Case studies for degradation

In a study on a mechanical-drive gas turbine, the clearance was increased from around 3% (design value) to around 4.5%, and this led to the following changes:

- A 20% increase in the surge flow coefficient (the surge flow coefficient identifies the minimum flow that results in surge — a very dangerous instability that can result in machine destruction even in several seconds)
- A 12% reduction in pressure coefficient (that is, a 12% reduction in the discharge pressure of the air-compressor under constant suction conditions)
- A 2.5% efficiency loss for the entire gas turbine system

Extensive studies showed the performance reduction of the air-compressor section of the gas turbine deteriorated as a result of spraying salt water in the inlet. The resulting deposits caused increased surface roughness on the compressor foils (the majority of the deposits occurred at the first stage and had become insignificant after the fourth stage). This buildup shifted the compressor operating line to both a lower flowrate and a lower pressure ratio.

Several gas turbines being overhauled after three to four years in service showed major degradation issues, mainly related to reduced flow in the air-compressor section and reduced efficiency in the turbine section.

The effect of individual component degradation is also influenced by the control system and the control modes of the gas turbine. Additionally, the method and location of measuring the control parameter (such as temperature and pressure-measuring sensors, which are used to control gas turbines) will determine the behavior of the machine in a degraded state.

It is commonly accepted that gas turbine degradation cannot be entirely avoided, but certain precautions (such as careful selection and maintenance of the inlet filtration system) can clearly reduce the rate of its occurrence and impact. The site-specific conditions that dictate contaminants, their size, concentration and composition, need to be carefully considered during the selection of the inlet filtration system.

Similarly, the rate of deterioration can be slowed by regular cleaning. However, online cleaning (some washing methods without disassembling gas turbine) will usually only clean the first few stages of the air-compressor (because the increase in temperature at later stages will evaporate the washing or cleaning fluid). If the gas turbine internals (especially the blades) can be accessed with moderate effort (for example, when the machine casing is horizontally split) additional cleaning by hand can be effective.

Any degradation of the components will always lead to observable changes in parameters. Because different types of degradation on different components will alter the gas turbine in different ways, this finding can also be used for diagnostic purposes. For example, monitoring of pressure (using discharge pressure against a reference) is the optimum way to monitor degradation (also for the practical reason, flow is usually not as easily monitored compared to pressure).

Condition monitoring

Because degradation or deterioriation in a gas turbine system often creates an unbalanced situation, vibration monitoring is an excellent way to monitor gas turbine systems for signs of ongoing degradation. Vibration monitoring of the casings (using a minimum of two sets for the compressor and turbine casings) is always recommended (using both velocity measurements for low-speed vibrations up to 2k Hz, and accelerometers for higher-speed vibrations and for hot sections). Non-contacting probes are typically used for axial and radial vibration monitoring. For journal bearings, non-contacting X–Y probes mounted at a 45-deg angle from the vertical centerline are typically used, in addition to velocity seismic transducers for bearing housings and two sensor probes for axial- position thrust bearings.

Temperature monitoring at strategic locations — for instance, to track temperatures related to the gas turbine rotating system, oil temperature and hot-air flow path — is also important. Thermocouples mounted at the lubricating oil outlets of the bearings can provide for alarms (and sometimes emergency shutdown). Hydrodynamic thrust and radial bearings are often equipped with replaceable resistance temperature detectors (RTDs).

In a typical installation, six thermocouples may be placed around the turbine exhaust-gas frame to measure the exhaust gas temperatures for alarm and trip capabilities. Heavy-duty industrial turbines usually have two sets of thermocouples, which can monitor and generate an alarm for the maximum-allowable turbine-space temperature.

For aero-derivative gas turbines, two wheel-space thermocouples should be located downstream of the last turbine wheel (using thermocouples and conduits that are as small as possible). Electronic governors should be provided with triple-input sensors and triple processor redundancy (using two-out-of-three voting logic). It should prevent the turbine speed from increasing beyond the specified overspeed limit in any case of loss of rated load (resulting from, for instance, coupling failure or process upset).

In the case of multiple shafts, each shaft should have its own overspeed trip-protection system, which allows for online testing without overspeeding the turbine (that is, the overspeed trip system should be independent of the governor).

Meanwhile, the following automatic-shutdown systems should be considered: Overspeed, low fuel supply, combustor flame out, low lube oil pressure, radial and axial shaft vibration in addition to driven equipment necessary shutdown(s).

When it comes to ongoing operations, it is difficult to identify the rate of degradation. However, as a rule of thumb, the performance degradation during the first 24,000 hours (around three years) of operation can be expected to be around 2 to 6%. This assumes degraded parts are not replaced (if parts are replaced and the machine is properly revamped, the expected performance degradation can be assumed to be around 1 to 1.5%).

Before the gas turbine leaves the manufacturer, it must be tested for performance. Due to difficulties in commissioning new gas turbines, a comprehensive shop performance test should be conducted; this is especially important for units destined for remote areas and offshore applications.

Specific settings for various control, alarm and shutdown thresholds are often the subject of considerable debate. Although certain guidelines can be set up to predict what level is acceptable, analysis of shop performance test results can provide an excellent source of data for this purpose.

Any shop performance test (carried out in accordance with ASME PTC 22) should include measurement and verification of the following important system attributes:

- Inlet system pressure drop
- Exhaust back pressure
- Barometric pressure
- Emissions (specified levels of NOx, CO, CO_2 and unburned hydrocarbons)
- Oil system performance
- Bearing and seal performance
- Starting device
- Fuel system
- Vibration condition and control corrections

It should also include six satisfactory starts and stops in the automatic mode, and should demonstrate satisfactory performance up to a minimum load (typically 50 to 100% load, with a maximum load variation of 5%) and fuel crossover (if applicable). Performance data conducted at the existing shop conditions should be corrected to compare with the guaranteed performance data, using reviewed and accepted performance correction curves (since the manufacturer's shop conditions, such as ambient temperatures and altitude, are usually different with jobsite conditions, these correction curves are necessary to identify optimal site conditions based on available shop performance data).

The purge period (to purge the whole gas turbine system and make it ready for startup) should displace a minimum of six times of the exhaust system volume (including turbine, exhaust duct, waste recovery device and exhaust stack) before firing the unit.

Meanwhile, the ignition temperature of the gas should be higher than the surface temperatures of gas turbine. Generally high temperatures and pressures can lead to damages and safety issues. To avoid this, an independent pressure relief valve (PRV) should be provided for protection.

On the other hand, temperatures and pressures that are too low may also lead to low efficiency. When a noise enclosure is required, a ventilation system that is used to generate a negative pressure within the enclosure (when located within a safe area) or a positive pressure (when located within a hazardous area) that has two 100% ventilation fans — one operating and one standby fan, each sized for 100% capacity required for the enclosure — with controls including automatic start, should be considered.

Closing thoughts

This article provides recommendations for the optimization of gas turbine arrangements for a large variety of power and compression applications. It is intended to support users during the specification and purchase of gas turbine packages. The impact of degradation on gas turbine performance underscores the importance of condition-monitoring systems. Proper design and selection of inlet filtration and treatment systems, together with proper maintenance and operating practices, can significantly affect the level of performance degradation, environmental impacts and thus time between repairs or overhauls. ■

Edited by Suzanne Shelley

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Author

Amin Almasi is a lead rotating equipment engineer at WorleyParsons Services Pty Ltd. in Brisbane, Australia. (amin.almasi@worleyparsons.com). He previously worked in Technicas Reunidas (Madrid) and Fluor (various offices). He holds a chartered professional engineer license from Engineers Australia (MIEAust CPEng-Mechanical), and a chartered engineer certificate from IMechE (CEng MIMechE), RPEQ (Registered Professional Engineer in Queensland). He also holds M.S. and B.S. degrees in mechanical engineering. He specializes in rotating machines including centrifugal, screw and reciprocating compressors, gas and steam turbines, pumps, condition monitoring and reliability. He has authored more than 45 papers and articles dealing with rotating machines.

Optimizing Biological Water Treatment in Petroleum Refining

Biokinetic modeling tools can significantly improve process control performance, a common culprit for permit excursions

FIGURE 1. In this step of the biological wastewater treatment, the activated sludge is aerated

David Kujawski and **Arthur Wong**
Refinery Water Engineering & Associates

Wastewater streams from petroleum refineries present some of the largest ranges of variation in contaminant loadings and contain some of the toughest contaminant profiles to treat. These factors render the wastewater treatment processes difficult to control. The most challenging area of wastewater process control in petroleum refining lies in biological treatment, due to the vast number of control variables present as compared to other chemical-treatment processes. This article discusses the differences in controlling wastewater treatment processes by mean cell-retention time versus food-to-mass ratios, and further elaborates on how biokinetic modeling can be used to build a comprehensive model across normal and transient operating conditions.

The challenges

Operating conditions specific to petroleum refining further aggravate these plants' process control efforts. These conditions can include the following:

- The presence of recalcitrant aromatics, polynuclear aromatics (PNAs) and polycyclic aromatic hydrocarbons (PAHs)
- The presence of a wide variety of nitrification inhibitors
- Eight or even more independent sources of influent, all with varying characteristics, coming from oil processing units whose personnel rarely interact with each other, nor with the wastewater treatment plant's operational staff
- Lack of sufficient early-warning resources to detect loading changes or inhibitory toxics
- Lack of sufficient equalization (through a large mixing tank to buffer the quality of changing influent)
- Insufficient diversion resources (a strategy to divert particularly difficult-to-treat influent, and then introduce it back with high dilution)
- Operation in upset mode more of the time than in design mode
- Operation in dynamic state more often than in steady state

To further complicate matters, most petroleum-refinery wastewater plants are not designed empirically, but rather are based on theoretical design data from someone else's wastewater plant under steady-state conditions, which of course holds for only part of the time in a petroleum refinery. Under the conditions that a refinery's biological wastewater plant has to operate, these assumptions fail more often than not in the real world of process control. For example, to really control the activated sludge process with the most current mean cell-retention time (MCRT) methodology, you have to establish the optimum MCRT range within which to operate for the realization of the specific effluent treatment goals. How do you do this without the biokinetic constants and coefficients for the specific plant design and the specific range of influent profiles, unless you're willing to take an educated guess? Historically, these guesses work well in some industries, but in petroleum refining, these guesses have more often been the number one cause of the inability to control the biological-treatment process, which of course culminates in effluent permit excursions. With the biokinetic constants, however, you can precisely and mathematically determine the MCRT control parameters, and all related realtime process control adjustments.

Moreover, with the tremendous number of variables in a biological wastewater-treatment system, it is extremely difficult to quantitatively interpret the results observed from experimental or unintentional operational excursions from the normal control ranges. The use of biokinetic models as a measurement tool provides the last word in an absolute metric format upon which the success or failure of an operational change can finally be based, without questions raised as to potential interferences in interpretation.

And last but not least, without the actual field determination of the specific biokinetic constants for a given plant, many attempts to operate a true MCRT control program fall short, such that the end result resembles more of a food-to-mass (F:M) control program, based on a trial-and-error operational strategy with its considerable built-

FIGURE 2. This photo depicts the clarification step of the activated sludge process

in error based on analytical methods available for the measurement of the food. This error is more than significant in petroleum-refinery wastewater due to the dependence of the F:M calculations upon biochemical oxygen demand (BOD) and its nonlinear relationship to chemical oxygen demand (COD) or other quick-test substitute parameters.

MCRT vs. F:M control strategy

In some wastewater applications, the use of the F:M strategy for control of an activated sludge process works well. However, in many types of industrial settings, perhaps none more notable than petroleum refining, this strategy falls short of adequate due to the following:

- Wide ranges of relative biodegradability of the substrate (food) in the influent
- Wide ranges of variability in the influent
- The intermittent presence of biologically toxic and inhibitory compounds in the influent

Inherently, the actual calculation of F:M has several pitfalls, including the following:

- In petroleum-refinery wastewater, there is no representative quick test for the substrate. The amount of oxygen consumed in five days (BOD_5) would be representative, but does not meet quick adjustment turnaround times. Total organic carbon (TOC), total petroleum hydrocarbons (TPH) and COD, do not have a consistent linear relationship to BOD_5 in refinery wastewater. As such, considerable error in process control enters into the calculation itself. Conversely, the use of the MCRT strategy does not depend on measuring the substrate
- Unlike the use of MCRT strategy, F:M cannot be directly related mathematically to the microbial growth rates. As such, most of the operational and process control benefits of biokinetic modeling cannot be effectively achieved with F:M. Only MCRT can capture the entire spectrum of benefits that translate in operational cost savings
- Unlike the MCRT strategy, the process for determination of the optimum-target-control ranges for F:M is also not practical under frequently changing load conditions inherent in petroleum-refinery wastewater because of the lag time between the measurement of the food and the mass. As such, the optimum target F:M ranges are usually based on some other plant's design and characteristics, which usually do not match the process considerations for the plant being designed
- Adjustment of sludge wasting rates to control the F:M ratio is a trial-and-error process. With the use of the MCRT strategy, sludge wasting is calculated precisely and administered mathematically to hit the target control range

More 'miles' per bug

The use of biological treatment has a narrow fit in the overall scheme of available technologies applicable for processing wastewater and related sludges. However, when biotechnology does fit (for more, see Biological Wastewater Treatment, *Chem. Eng.* October, 2005, pp. 44–51), there is no alternative that is more cost effective. Within the range of various biological-treatment designs, there is no process more efficient and more controllable than the activated sludge process (Figures 1 and 2).

Based on this premise, a worthwhile goal of petroleum-refining wastewater plants is to initiate a path directed toward maximizing the return on investment of the activated sludge system. In other words, making a longterm concerted effort toward trying to have the activated sludge system consume as much of the refinery's wastes as possible. But, how much can an activated sludge system take? What is its true operational capacity based on what really comes down the sewer? How do you determine what the limit really is?

Although biological treatment has proven its effectiveness, trying to determine the parameters for optimizing its performance is not easy. Because of the tremendous number of process variables involved in biological wastewater-treatment, performance and control are not always straightforward. In many cases, metrics deployed to monitor performance and control appear to do so on a macro-view level. But, because there are many other nonbiological, chemical mechanisms occurring simultaneously in a bioreactor, on a micro-view level what may appear to be the result of biological treatment may in fact be facilitated by enzymatic reactions, chemical oxidation, precipitation, adsorption, ligand-complex formation reactions, sludge entrapment, air stripping and more. Now add to that problem the fact that especially with petroleum-refinery wastewater, steady-state conditions are not always prevalent, and in addition, the textbook stoichiometric biomass relationships are frequently skewed by the presence of inhibitory toxic compounds.

In short, when attempting to quantitatively define all of the important metrics related to gauging the true performance of the specific microbiological population functioning in a given plant, there is only one way to accomplish that with 100% reliability, and that is through the use of biokinetic modeling tools. Only if you know the true kinetic and metabolic reactions of microbial growth in a system, are you able to truly control that process. And this knowledge culminates in maximizing the true operational plant capacity, starting with maximization at the individual, microbial cell level.

TABLE 1. RESULTS FROM AN ACTUAL BIOKINETIC MODELING PROJECT		
Biokinetic constant	Before	After
k (Maximum substrate utilization rate)	0.469 mg COD/mg SS-day	0.935 mg COD/mg SS-day
K_s (Half saturation constant)	140.61 mg/L COD	555.56 mg/L COD
K (Specific substrate utilization coefficient)	0.0033 L/mg COD day	0.0017 L/mg COD day
Y (Cell yield)	0.25 mg SS/mg COD	0.33 mg SS mg COD
K_d (Decay coefficient)	0.035 days^{-1}	0.030 days^{-1}
SS = suspended solids		

Fine tuning biokinetic modeling

With the advances of biotechnology over the last decade, direct biokinetic modeling of full-scale operating activated-sludge plants is now a reality. Furthermore, the supplementation of the full-scale modeling efforts with sidestream, bench-scale continuous-feed process simulation in multiple application areas throughout a petroleum refinery is a wave of the future. The key indicator for reaping an operational benefit with this tool falls in target areas where the refinery has little room to play with process control variables due to the sensitive nature of the effluent quality, compliance risks or effects on the production process itself. In other words, process optimization cannot be fully exploited too far from the middle of the established control ranges due to critical restraints. Furthermore, rarely will the sole train of a full-scale plant be allowed to play with changes in more than one variable at one time.

Unfortunately, the relationships of many biological-treatment variables are in fact influenced by multiple correlation phenomena. Sometimes the productive operational adjustments lie at the outer ranges of standard deviations from the normal ranges. And more importantly, in utilizing modern mathematical tools to the fullest extent, the evaluation of a plant's performance variables at the higher ranges of standard deviation are vastly valuable in fine tuning the accuracy of the model itself.

Most petroleum refineries do not have the budget to construct processes with standby units that can be alternately used for experimentation. The use of a simple-to-build and easy-to-operate online bench-scale simulator of a full-scale activated-sludge system would solve the aforementioned problems and add greatly to the accuracy, effective predictability and overall value of the concurrent full-scale plant modeling efforts.

Conducting a modeling study

Using chemical engineering principles, bioengineers have quantitatively created reaction-rate mathematical models that have primarily been used for design and sizing calculations. Similar design models can be constructed based upon real-world observations and collection of material balances and substrate balances across an operating activated-sludge plant. This is predicated upon the proper analytical program to collect mass- and volumetric-flow data along with the corresponding chemical analyses. This is not a trivial task in the confines of an operating wastewater system compared to a controlled laboratory environment, but it can be achieved.

First step: Determine the biokinetic constants and variables, including the following:

θ = Mean cell retention time
$1/\theta$ = Growth rate of microbial population
Y = Cell yield
U = Specific substrate utilization rate
K_d = Decay rate coefficient
K = Specific substrate utilization coefficient
k = Maximum substrate utilization rate
K_s = Half saturation constant (effluent ---> ½ k)
S_e = Effluent substrate (the level of a given contaminant parameter after treatment)

The underlying, biological kinetic expressions can be obtained from fitting operating data as a function of microbial growth rate. The data can be fitted using computerized linear regression analyses, which ensures the predictability of the model.

Second step: Build and calibrate the plant-specific biokinetic model and related equations, including the following:

- Target MCRT model versus effluent quality
- Construct a predictive "what if" model that will allow you to manipulate changes in influent flow and quality
- Assess the extent of inhibitory biokinetic response and adjust the model accordingly
- Determine optimum steady-state operating conditions and determine operating strategy during non-steady-state conditions
- Create a calculative model for process variable adjustments

Once the biokinetic constants are determined, a comprehensive model across all normal and transient operating conditions can be predicted. Predictive control of complex biological systems is the next stage toward achieving maximum utilization of petroleum-refinery-treatment assets as well as maintaining effluent quality. Just as chemical reaction kinetics are used in every upstream unit operation to optimize the process, biological kinetic modeling can be utilized to achieve a greater control over environmental stewardship as well as return on investment.

The biokinetic constants

The key operational biokinetic constants for realtime process control considerations include the following:

Maximum substrate utilization rate, k: This number defines the total contaminant loading capacity of the entire biological plant, and can be calculated in terms of organic (carbonaceous) mass or nitrogenous (autotrophic) mass.

Cell yield, Y: This number defines the biomass production and carbon dioxide generation resulting from biological oxidation, and can be expanded to define the equilibrium shift between the CO_2 and the produced biomass. The ability to measure this enables a plant to control and shift the equilibrium, thus placing a handle on such important factors as sludge disposal and oxygen utilization.

The key operational biokinetic equations for plant performance evaluations and "what if" simulations are the following:

Growth rate versus substrate utiliza-

tion: $1/\theta = (Y)(U) - K_d$

Effluent substrate versus MCRT: $S_e = (1/\theta + K_d)/(Y)(K)$

Biomass generation versus CO_2: $Y = (1/\theta + K_d) / (K)(S_e)$

Case history example

Actual results obtained from the biokinetic modeling of a large U.S. petroleum refinery's wastewater plant are given in Table 1. In this case, the refinery experimented with a process change that represented a controlled change in the metabolic activity of carbonaceous microorganisms deployed in the activated-sludge aeration basin, at the cellular level. The "Before" column represents operation under normal historical conditions. The "After" column represents operation during the experiment.

Two significant knowledge points were gained with the study results shown in the table:

1. The increase in maximum substrate-utilization rate demonstrated that the plant nearly doubled its total-organic-loading capacity by employing the operational changes during the experiment.
2. The increase in cell yield demonstrated that the biomass production increased nearly 30% by employing the operational changes during the experiment.

So what did the plant personnel conclude about its future prospective alternatives? They learned that by deploying the experimental conditions permanently, they could gain a 50% increase in plant capacity, but at a cost of a 30% increase in biomass disposal costs.

If we could leave you with one concluding concept, it would be this: Biokinetic modeling + Source control + Bench-scale continuous plant simulator = State-of-the-art petroleum-refinery wastewater process control ■

Edited by Dorothy Lozowski

Authors

David Kujawski is the vice-president of Refinery Water Engineering & Associates, Inc. (3312 Hwy. 365, Suite 213, Nederland, Texas 77627; Phone: 949-433-0301; Email: dk@refinerywater.info). He has 32 years of experience in water and wastewater treatment in over 200 industrial plants and over 40 oil refineries. Kujawski has degrees in environmental engineering, chemistry and marketing. He has worked for Nalco, Betz-Dearborn, Baker-Petrolite, US Filter, Chevron El Segundo Refinery, Sybron Biochemical and Ashland Oil.

Athur Wong is a senior chemical engineer with Refinery Water Engineering & Associates, Inc. (Phone: 724-309-2463; Email: awong@refinerywater.info). He was formerly the vice president of US Filter Corp., and the technical service manager for Sybron Biochemical. Wong was one of the first to use biokinetic modeling in the field of petroleum refinery wastewater. He holds a B.S.ChE. from the University of Pittsburgh and has spent more than 26 years in the environmental engineering field.

CHEMICAL ENGINEERING

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photo: Tiger Tower Services

A powerful simulation resource for refiners

Bryan Research & Engineering introduces the latest addition to its simulation suite: ProMax Refinery Reactor Suite

For over 35 years, **Bryan Research & Engineering Inc.** (BR&E) has been committed to providing the energy industry with process simulation software that accurately and efficiently predicts the performance of gas processing, refining and petrochemical processes. Today, BR&E's ProMax simulator is used by engineers around the world to design and optimize processing facilities. Totally integrated with Microsoft Visio, Excel, and Word, ProMax is a comprehensive tool that offers incomparable flexibility.

The current version of ProMax contains a suite for modeling equilibrium, conversion, Gibbs minimization, and user-defined reaction sets. In addition to these features, BR&E is excited to introduce its newest simulation resource, ProMax Refinery Reactor Suite, which is a series of catalytic reactor models based on the concept of single event kinetics. This tool will allow the refiner to model reactors with little to no kinetic rate-based data. ProMax Refinery Reactor Suite accounts for differences in catalyst performance by providing the user with a calibration toolbox to tune single event kinetic parameters to predict plant performance. The first release of the Reactor Suite will include catalytic reforming, with future releases covering hydrotreating, hydrocracking, and fluidized-bed catalytic cracking (FCC).

ProMax is also widely known for its ability to model many aspects of a refinery. For instance, ProMax may be used to:

- model atmospheric and vacuum towers;
- model main fractionators, including FCC and coker;
- characterize crude oils;
- model gas and liquid sweetening;
- model sulfur recovery;
- study refinery changes on sour treating systems;
- simulate caustic treaters; and
- investigate preheat exchange and fouling.

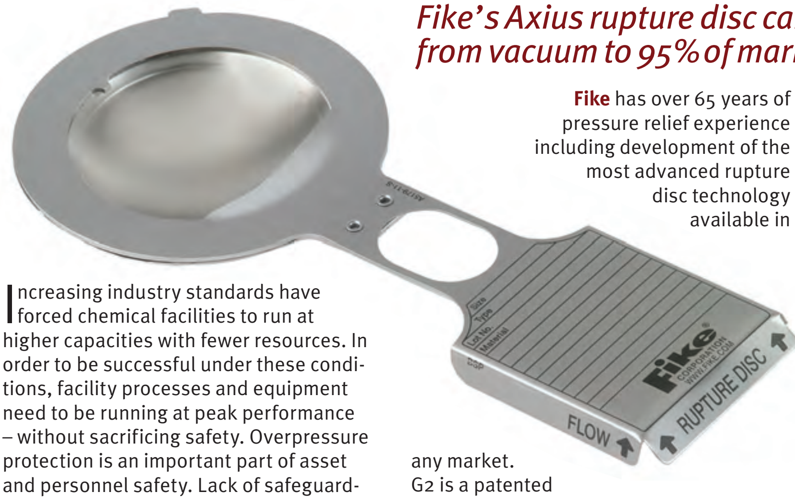
A ProMax license includes much more than just software. Bryan Research & Engineering is committed to providing unrivaled customer support. BR&E offers free training sessions around the world, provides timely customer support from a staff of knowledgeable and experienced engineers, and sets up free initial plant models for operating companies.

ProMax's advanced technology, including over 2,500 pure components and 50 thermodynamic package combinations, along with BR&E's exceptional client services unite to make ProMax the "must have" simulation resource.

www.bre.com

The right safety solution for your facility

Fike's Axius rupture disc can withstand 100,000 cycles from vacuum to 95% of marked burst pressure



Increasing industry standards have forced chemical facilities to run at higher capacities with fewer resources. In order to be successful under these conditions, facility processes and equipment need to be running at peak performance – without sacrificing safety. Overpressure protection is an important part of asset and personnel safety. Lack of safeguarding can cause mechanical damage, loss of product, environmental damage, personnel injuries and production downtime. Careful consideration is given to selecting the process equipment which will yield the desired results, and the same should be true for the overpressure protection of that equipment.

Fike has over 65 years of pressure relief experience including development of the most advanced rupture disc technology available in any market.

G2 is a patented Fike technology that creates rupture discs unrivaled in cycle life, performance accuracy, and manufacturing consistency.

Fike's Axius rupture disc is the direct result of this technology. Cyclic performance is derived from the absence of stress zones that can fatigue in rigorous applications. The manufacturing process used to produce the Axius utilizes millions of data points to provide product repeatability and precision. The bottom line, says Fike, is that the Axius does what it's supposed to, when it's supposed to, every time. The Axius has been cycle-tested to the worst-case scenario: from full vacuum to 95% of the marked burst pressure for over 100,000 cycles without failure. When burst, they measured well within stated tolerances. The Axius has also been successfully used for PRV/SRV protection.

All Fike pressure relief products are compliant with global code regulations and are designed to meet or exceed industry requirements for rupture disc performance, reliability, and quality. And the company's industry experts help customers to select the rupture disc most appropriate for their needs. Fike pressure relief products, including the top performing Axius rupture disc, are part of the critical path to lowering plant costs and helping to achieve higher profitability.

www.fike.com

Close coordination saves time and money

Tiger Tower Services garners support from the client and alliance partners to blind, open, clean, inspect and repair 114 vessels

Tiger Tower Services (The Tigers) specializes in vessel turnaround and repair – but it takes more than a lone specialist to complete a job under budget and under schedule.

For example, one of the nation's largest processors of natural gas and natural gas liquids chose The Tigers to participate in a turnaround involving 114 vessels (columns, drums and exchangers). Although The Tigers are highly professional and experienced, they cannot complete a project like this alone; they need cooperation from the client and from reliable partners... and it all begins by pre-planning.

For this time- and schedule-sensitive project, The Tigers and their client representatives performed extensive pre-planning including a site safety plan and blind lists for each item. The Tigers also coordinated with subcontractors during the pre-planning on such activities and preliminary schedules/logistics for scaffolding, insulation removal and replacement, chemical cleaning and steam cleaning, non-destructive testing activities, and exchanger bundle pulling and reinstallation.

The project scope also involved installing 776 blinds (some of 20 in. diameter) and blinding all 114 items and battery limits. All the vessels were opened and cleaned to allow API 510 inspection. Finally, all the vessels were closed, the blinds pulled and the plant area cleaned so normal production could begin again.

Tiger Tower Services devoted 14,642 total man-hours to the project with no recordable injuries. Despite running one day over schedule during the discovery phase, the project was still completed under schedule and under budget. That's the value of coordination, cooperation and getting the right people on your turnaround team, says the company.

Tiger Tower Services recently completed a 114-vessel project for a natural gas processing plant – on time and on schedule

www.tigertowerservices.com

Manage risks and increase visibility

The DeltaV SIS Process Safety System from Emerson is integrated with the control system for maximum reliability

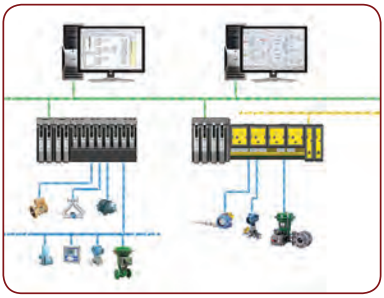
Manufacturers need to ensure process safety while at the same time reduce costs and improve operational efficiency. The DeltaV SIS process safety system from **Emerson Process Management** can help manage operational risks by increasing visibility into the process. This is especially true when used with the DeltaV automation system for process control. Used together as an integrated control and safety system (ICSS), the DeltaV and the DeltaV SIS systems have an integrated but separate architecture, providing one common user environment.

The DeltaV SIS system is integrated with the DeltaV engineering, maintenance and operations environment. However, the DeltaV SIS power supplies, communications channels, hardware and real-time operating systems are physically separate and independent of the DeltaV basic process control system (BPCS). Together they automatically monitor, control and collect both process and safety-related data. This "integrated but separate" architecture provides many advantages, including:

- single view of all process information;
- common engineering tools;
- no interfaces or mapping required;
- reduced lifecycle cost with simplified architecture.

With a common interface, operators are able to control both systems through one portal, providing earlier warnings of potential hazards. The integrated engineering environment enables management of all aspects of system configuration – hardware, control strategies, and safety loops – and includes built-in change management and history. This integrated approach also eliminates the need for expensive data mapping and handshaking logic that is common in disparate solutions.

The DeltaV SIS process safety system complies with IEC 61511 standards for independence. When used with the DeltaV BPCS, DeltaV SIS maintains this compliance with physical separation, while still delivering all the benefits of total integration. The DeltaV SIS integrated but separate architecture does not mean the same hardware for control and safety, nor does it require an interface and data mapping. Integrated but separate architecture is unlike any other – providing a single set of tools for operators and engineers, which improves efficiency and helps manage risks.



Integrated yet separate: DeltaV SIS uses the same tools as its process control sibling, while retaining safety integrity

www.DeltaVSIS.com/Integrated

Check critical water and wastewater parameters

Myron L Company manufactures hand-held and fixed instruments for testing the quality of process water and effluent

Myron L Company manufactures reliable cost-effective handheld instruments and monitor/controllers for managing critical water quality parameters in process control and for influent and effluent screening. The company's latest digital handheld, the Ultrameter III 9P, is based on the tried and tested design of the Ultrameter II. The 9P adds the ability to perform in-cell alkalinity and hardness titrations either as stand-alone measurements or as part of an LSI calculation. Alkalinity, hardness, pH and temperature values can be manipulated in the LSI calculator to predict the effect of changes on water balance. Measurements are extremely accurate, and the 9P is simple to operate and maintain.

The 9P is packaged as part of the AHL Titration Kit whose hard foam-lined carry case contains: the 9P; 9P cell extender; required reagents for in-cell alkalinity, hardness and LSI titrations; standard calibration solutions for all parameters; storage solution to protect the pH/ORP sensor; and pipette for precision dispensing with additional tips. Sensors are internal and included.

All-in-one: a comprehensive kit accompanies the new Ultrameter III 9P

High performance features include:

- fast, one-touch measurements for conductivity, resistivity, TDS, ORP, free chlorine, pH and temperature;
- intuitive prompts step users through alkalinity, hardness, and LSI titrations;
- convenient LSI Calculator accepts both grains and ppm hardness units;
- easy keypad calibration;
- stable four-electrode conductivity cell eliminates polarization, increasing accuracy with minimal maintenance;
- powerful microprocessor-based surface mount circuitry;
- unique pH/ORP glass sensor construction;
- versatile solution modes for accuracy in diverse water quality applications;
- efficient design features auto-off that minimizes power consumption – one 9 V battery lasts up to 1 year/5000 readings;
- advanced proprietary temperature compensation and TDS conversion algorithms.

The 9P is also capable of wireless communication with the bluDock option installed. The bluDock uses Bluetooth technology to transfer data wirelessly to a personal computer and comes with user-intuitive software that makes it easy to analyze saved water sample data. **www.myronl.com**

Your global source for high-temperature fabrics

Hi Temp Products produces FM-approved high-temperature materials for hot-work operations – with safety in mind

As a manufacturer of welding pads, welding blankets and welding curtains with more than 20 years' experience, **Hi Temp Products** has developed a patented silicone elastomer coating and a proprietary manufacturing technology that sets it apart from all others. This unique combination has resulted in products that lead the industry in performance and affordability, especially among FM-approved materials. Hi Temp products can also boast the only FM-approved welding blanket made with a fiberglass base fabric, and the highest temperature rating of a fiberglass base fabric.

FM approval is extremely important because ANSI, the American National Standards Institute, adopted the FM standard as ANSI/FM 4950. This is currently the only recognized standard specifically for evaluating welding pads, welding blankets and welding curtains for use in hot-work operations. Hi Temp Products is one of the few manufacturers that have FM-approved materials in all three product categories.

Tools for the job: Hi Temp products offer superior protection for hot work

The Hi Temp product line includes the following FM-approved materials:

- Welding Pad: for horizontal use to protect against heavy molten metal splash;
- Welding Blanket: for horizontal use to protect against the sparks, and splatter produced during welding, cutting, grinding and other hot work operations;
- Welding Curtain: for vertical use to contain sparks by forming enclosures around areas where hot work is being performed. These materials are designed to protect personnel and equipment from intense heat and flame, welding, sparks, and metal splashes.

When using welding pad, welding blanket or welding curtain material, it is important to make sure the fabric is ANSI/FM4950 approved and that it is used for its intended purpose: material approved as a welding curtain should not be used as a welding blanket, the company notes.

All materials are available in rolls, precut sizes, and constructed pads. Custom sizes can be made to order for blankets, pipe wraps and welding pads.

Hi Temp Products was founded in 1989. The Canadian headquarters is in Edmonton, Alberta. The US headquarters is in La Conner, WA, with sales offices and distribution centers strategically located in Canada, the United States, Europe and China. **www.hitemp.ca**

Delivering results for chemicals and polymers

Mustang provides highly experienced process engineers and project managers for all types of process projects, including automation and control

Mustang has wide-ranging experience on chemical and polymer projects, with a project management team whose members have worked together for more than 30 years. Similarly, Mustang's process engineers average more than 20 years on these types of process industry projects. Behind the scenes, the company boasts superior support teams and the latest 3D modeling techniques, including laser scanning, to streamline projects and reduce costs.

©ISTOCKPHOTO.COM/PATTIES

Mustang has completed more than 11,000 engineering projects worldwide

Mustang can manage its client's projects from conception through to operations. With its proven processes and focus on safety, it executes projects that come in with predictable results – on budget, on time and with flawless startup. Mustang personnel have experience in most of the licensed petrochemical, chemical and polymer processes used today and can assist clients with the introduction of "first of a kind" or licensed technologies. Mustang offers comprehensive technical and economic studies, technology evaluation, experimental program design, pilot plant programs, and acquisition of physical and chemical property data.

Mustang's Automation and Control group adds still another dimension to Mustang's total project capabilities on behalf of its clients. An experienced team with extensive process knowledge provides a vendor-independent approach with cost-effective and workable solutions for complex IT, automation and control projects. Front-end definition is a forte of the team, combined with innovative tools and methodologies that allow Mustang to be a full service provider of automation integration services, including advanced process control and abnormal condition management.

Mustang supports its projects with extensive front-end planning, established procedures and proven best practices. The company uses its own stage gate process (Stage COACH) and a proprietary project management tool (PACESETTER) to ensure that projects are successful from start to finish.

Founded in 1987, Mustang has more than 4,000 employees with offices around the globe and has completed over 11,000 projects for more than 350 clients.

www.mustangeng.com

A one-stop resource for inspection and testing

PetroChem Inspection Services provides safe, reliable, and affordable inspection and testing services in refineries, storage facilities and chemical processing plants

Clients rely on **PetroChem Inspection Services** for all their inspection needs – Advanced, Onstream, Turnaround, Quality Assurance, capital projects, and more.

PetroChem Inspection Services has served the refining and petrochemical industries for over 30 years. In addition to on-stream and turnaround API inspection capabilities, PetroChem offers a complete array of non-destructive testing such as ultrasonic, magnetic particle, radiographic, and eddy current. Technicians are fully trained and certified in accordance with SNT-TC-1A and have advanced certifications for many of the inspection techniques. All technicians are certified professionals with both the American Petroleum Institute (API) and The American Society of Non-Destructive Testing (ASNT). A specialist in advanced technology, PetroChem was the first U.S.-based service provider for guided wave ultrasonics.

Services include:

- mechanical integrity programs

TÜV SÜD

PetroChem

- on-stream resident inspectors
- turnaround inspectors
- NDE services – all disciplines
- Tank inspection and calibration
- computerized radiography
- guided wave ultrasonic inspection
- helium mass spectrometer leak testing
- ACFM
- API 510, 570, and 653 certified inspectors
- NACE coating inspectors
- vendor quality assurance and QA/QC inspectors.

With their combined expertise in both management and technical areas of inspection of storage terminals including their associated piping and equipment, PetroChem delivers outstanding results with the highest quality inspections and safety performance.

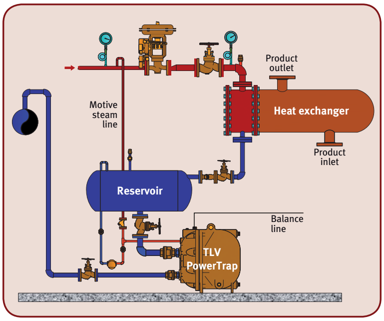
PetroChem's parent company, TÜV SÜD America Inc., is a leading testing, inspection and certification organization, itself a subsidiary of TÜV SÜD AG (Munich, Germany), which has over $1.5 billion sales and 16,000 employees at over 600 locations worldwide. This strong foundation gives PetroChem the experience and resources to support both locally and globally operating companies with its wide range of services in the US and worldwide.

www.petrochemintl.com

Stop wasting valuable MP steam for heating duties

Back-pressure often restricts the use of cheap low-pressure steam—a problem solved by the PowerTrap combined steam trap and pump from TLV Corp.

Many refineries and petrochemical plants use costly medium-pressure (MP) steam for low-temperature heating duties, notes **TLV Corp.**, when they could instead be using cheaper and more readily available low-pressure (LP) steam. Alternatively, plants may use LP steam for heating, but waste energy by sending the condensate to drain. TLV's PowerTrap, a combined steam trap and pump, avoids both these problems by returning LP condensate to the boiler house even against significant back-pressure.



Steam power: TLV's PowerTrap works at line pressures up to 200 psig

LP steam is a versatile heat source that is so abundant on many process plants that it is frequently vented to atmosphere, wasting its valuable energy content. MP steam, on the other hand, is scarcer and more expensive to produce, sometimes to the point where MP steam demand is made up by letting down high-pressure steam—a very wasteful operation.

So why is MP steam often used for low-temperature heating duties in reboilers, exchangers, jacketed vessels and preheat coils? A common reason is that if there is significant back-pressure in the condensate return system, the pressure of the LP steam is too low to drive condensate through a steam trap and into the condensate main. Instead, the system stalls: condensate backs up in the equipment and impedes heat transfer.

The typical way around this problem is either to use MP steam for heating, or to use LP steam and dump the condensate to drain. Either way, energy is wasted.

A much better way to use LP steam for heating when back-pressure is high is to install a TLV PowerTrap, a combination of a steam trap and a steam-powered condensate pump.

The PowerTrap optimizes process heating equipment performance by ensuring continuous drainage of condensate from equipment at steam pressures between vacuum and 200 psig.

It reduces energy costs by allowing plentiful LP steam to be used for process heating, avoiding the need to dump condensate or use costly MP steam instead.

The PowerTrap also improves the availability and reliability of process systems. It reduces channel head gasket damage, and eliminates cavitation or seal leakage issues often experienced with electric pumps, says the manufacturer.

www.tlv.com

Blast resistant modules and storage units

Founded in 1998, A Box 4 U is the industry leader in the manufacture of blast resistant modules and storage units

A Box 4 U originally manufactured storage units, but quickly saw the need for worker safety in the petrochemical, chemical processing and construction industries.

Now, A Box 4 U specializes in blast resistant modules (BRMs) in both standard and custom designs. The company's strengths include an innovative approach, rapid response, and flexible financing which allows customers to purchase, lease, or lease-to-own their BRMs.

A BRM from A Box 4 U has roof and wall panels strengthened with steel tube stiffeners. To demonstrate its performance, a standard BRM from A Box 4 U was field tested at a blast overpressure of 5 psi and a duration of 500 ms. The module survived without any structural damage. All components of the BRM were found to have suffered damage within or below the "low medium" range. Damage to non-structural components such as conduit pipes, light fixtures, HVAC unit and interior sheathing was minor or non-existent.

A Box 4 U engineered blast resistant modules and buildings provide safety for offices, conference rooms, equipment and sensitive storage as well as an industry exclusive, new Tool Cribs. A Box 4 U also offers custom designed and engineered blast resistant modules and buildings to meet just about any customer requirement.

The company's latest offerings include new Multi-Section BRMs, effectively doubling the width of a standard 12-ft BRM to 24 ft or more. All the usual A Box 4 U features are standard, including the company's world renowned blast resistance. With the only Multi-Section on the market with open design floor plans, A Box 4 U is able to custom design and engineer any number of specialized, safe, work environments.

The new QUAD POD two-story BRMs are the answer to limited space in the workplace. The Quad Pod features a standard A Box 4 U BRM with a second BRM stacked on top. QUAD PODS are available in all the company's standard leasing sizes: 8 ft x 20 ft, 8 ft x 40 ft, and 12 ft x 40 ft. The QUAD POD is engineered to meet or exceed API 753 and is designed for ease of installation and teardown without welding on the job site.

www.abox4u.net

Only A Box 4 U blast resistant modules (BRMs), like the new Multi-Section BRM shown above, are field tested and proven blast resistant

The expert source for rental energy solutions

Aggreko supplies rental equipment and services for temporary process cooling, climate control, power generation, and compressed air

Cooling towers and generators are among the equipment available

Aggreko's proven experience and innovation have made it the premier resource for rental energy solutions for the petrochemical and refining industries. Drawing on vast industry-specific knowledge, the company develops custom solutions to meet the challenges of turnarounds, shutdowns and general maintenance, including process, operational and environmental constraints.

Aggreko Process Services (APS) consists of an experienced process engineering team. It can design and install process enhancement solutions within a matter of weeks, rather than the months required for a typical capital project. This enables customers to capture short-run market opportunities. APS specifically targets process limitations caused by high ambient temperatures and fouled or under-performing equipment.

To address the demands for emergency or supplemental cooling at refineries, factories or other plants, Aggreko Cooling Tower Services (ACTS) was created. It provides 24-hour availability of the largest fleet of modular cooling towers in the industry, and enables operations to keep running smoothly during emergencies or maximize production while reducing the risks inherent in process cooling. Additional benefits of ACTS include:

- maximize production during hot summer months or peak demand times;
- maintain production while repairing or maintaining existing cooling tower;
- reduce costly downtime after disaster strikes; and
- meet or exceed customers' own environmental and safety standards.

Whether providing rapid emergency response to equipment failures or vessel cooling services to increase production, Aggreko is committed to delivering the highest performance standards 24/7/365. Aggreko keeps production and profitability flowing while delivering valuable time and cost savings, thanks to its experience, skill and specialized equipment.

www.aggreko.com/northamerica

Heat transfer fluids for the oil and gas industry

Therminol heat transfer fluids from Solutia are widely used in refining, gas processing, oil and gas pipeline operations, and reprocessing used lube oils

Therminol heat transfer fluids from **Solutia** are commonly used in offshore and onshore oil and gas processing, fractionation, refining, transportation, and recycling operations. Therminol 55, Therminol 59, Therminol 62, Therminol 66 and Therminol VP1 have successfully demonstrated low-cost, reliable, and safe performance in these applications for decades. Therminol fluids are selected because they provide lower capital and operating costs, and better temperature control, than other heat transfer options.

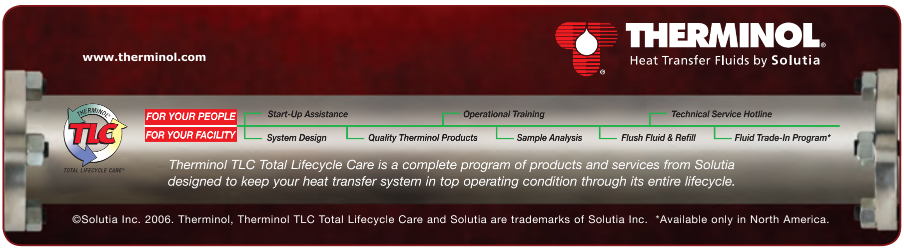
In gas processing and fractionation, Therminol fluids are frequently used to heat gases for regenerating solid desiccants (such as molecular sieve) in gas dehydration beds; to reboil liquid desiccants (such as glycols) used for gas dehydration; to regenerate liquid solvents (such as amines) used for gas sweetening; to heat gas stabilization and NGL fractionation reboilers; and for other gas processing operations.

In oil processing and refining, Therminol fluids are often used to enhance oil/gas/water/sediment/salt separation and for other processing and refining operations such as low-sulfur gasoline production, solvent extraction, and sulfur recovery.

Therminol heat transfer fluids have applications in transportation too. Pumping stations along oil and gas pipelines often require heating to control the viscosity of oil streams, and to prevent condensation of components from gas streams. Therminol heat transfer fluids have proven capable of meeting these requirements in virtually any environment.

And the reprocessing of used lubricating oils involves operations at very high temperatures and high vacuum, for which Therminol heat transfer fluids are ideal. A variety of Therminol fluids are available with low vapor pressure, high thermal stability, and good heat transfer performance, supporting process needs at virtually any temperature.

www.therminol.com



Improved wash water service from new pumps

Gulf Coast refinery replaces maintenance-intensive positive-displacement pumps with Wood Group SPS surface pumps

Reciprocating positive-displacement (PD) pumps are often used for wash water service in refineries. They can be costly to operate, frequently leak and require constant monitoring and maintenance in order to comply with environmental and safety standards. They suffer repeated valve, packing and drive train failures requiring costly rebuilds. In this Gulf Coast refinery, wash water PD pumps cost approximately $250,000 annually to maintain and repair. The refinery operator needed more reliable and economical technology for wash water pumping applications.

Wood Group Surface Pumps replaced the PD pumps with an economical SPS Surface Pumping System. Two model TJ-7500, 64-stage tandem SPS units with 400 HP motors (producing 250 GPM at 1,842 psig) were installed. One SPS unit served as the primary pump, with the second system in place as a backup. The SPS units feature easily replaceable multi-stage horizontal centrifugal elements. They were designed for improved abra-

SP1000 pump installation at Texas refinery for wash water service

sion resistance, reduced wear and higher efficiency, and feature a single mechanical seal that operates at suction pressure.

The bearing frame/thrust chamber is supplied as a replaceable module and is interchangeable with other SPS units. The thrust chamber features a very low number of rotating parts for long, trouble-free life and minimal maintenance. It includes an oil-ring lubrication system for optimum oil dispersion and reduced operating temperatures, plus a thermocouple to provide periodic or permanent temperature monitoring/shutdown protection.

After installation of the SPS units, pump fluid losses, leakage and environmental issues were eliminated. There has been 100% up-time, 24/7 run reliability with no failures. Only minimal change in controls and operating procedures were required to adapt to the new pumps. The SPS pumps are very quiet with minimal vibration. Maintenance requires only quarterly change of the thrust chamber lubricant and routine vibration measurement. Maintenance personnel now focus their efforts on non-pump issues and opportunities at the refinery. The new units have supplied a dependable flow of wash water at design rates, which helped reduce fouling of the exchangers and provided more stable unit operation.

www.woodgroupsurfacepumps.com

Process simulation, turbocharged for speed

A performance boost allows CHEMCAD from Chemstations to avoid the compromise between speed and rigor in both dynamic and steady-state recycle simulations

CHEMCAD, the flagship process simulation software suite from **Chemstations**, is now capable of delivering rigorously calculated results for dynamic simulations and steady-state recycle loops even faster than before. A new feature known as Thermo Acceleration, which can effect significant gains in calculation speed, has been incorporated for use in CHEMCAD simulations.

Thermo Acceleration is a unique and proprietary solution introduced by the CHEMCAD development team, originally to address dynamic simulations used in conjunction with operator training and real-time performance monitoring systems.

These systems demand a very short calculation and response time from process simulation. This has often meant giving up rigorous calculation for pure speed; in many cases, a lack of rigor meant that the overall system was incapable of providing the required project value. These systems are often characterized by a large number of chemical components, very non-ideal thermodynamics requiring activity-coefficient methods, and, often, aqueous electrolytes. Chemstations set out to solve this dilemma, and Thermo Acceleration was the key to delivering a process simulation that meets both the rigor and the speed requirements.

After months of development, internal testing showed 30% to 90% reductions in calculation time for established test cases. More importantly, in actual use in the field, these results were borne out in a large-scale operator training project.

Once the concept was proven, the development team began the next phase of Thermo Acceleration by applying the same concepts to recycle calculations in steady-state simulations. Again, similar improvements in calculation time were achieved, this time with difficult-to-converge recycle loops. Considering that the vast majority of simulation work is steady-state, this development has wide applicability and potential to reduce the time spent working with the simulator.

Thermo Acceleration will be turned on automatically for all new simulations starting with the release of CHEMCAD 6.4 later this year. Users retain the choice to use or disable this feature via an easy-to-access setting. Steady-state simulations that do not incorporate recycle loops will not be affected by the Thermo Acceleration setting.

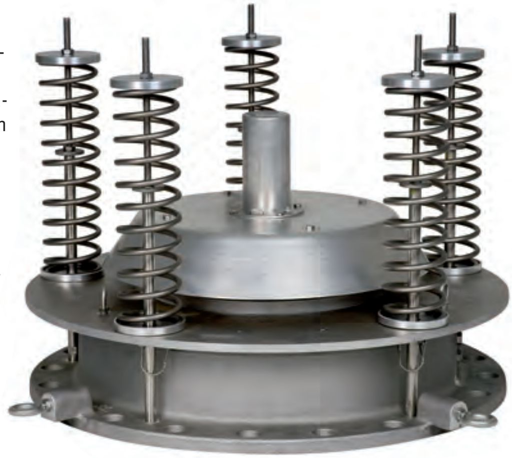
www.chemstations.net

A versatile range of emergency relief vent valves

These new manway pressure and pressure/vacuum relief vents go well beyond the performance of normal pressure relief systems, says manufacturer Valve Concepts

The new VCI 8900 Series from **Valve Concepts, Inc.** (VCI) provides the versatility that comes with innovative design and modular construction. Available in both top-guided (spring-loaded) and hinged (weight-loaded) configurations, 8900 Series relief vents feature a one-piece flange base with an integrated bolting pad to accommodate the hinged design. The modular design allows the valves to be converted from a pressure/vacuum vent to a pressure-only vent or vice versa.

"The design also permits the pressure pallet assembly to be easily removed for unobstructed access to the tank for cleaning, inspection or repairs," says Aaron Brantley, VCI product engineer. "Plus, the flange base incorporates a set of integrated lifting lugs for easier removal or installation."



Modular design makes the VCI 8900 a versatile pressure/vacuum relief valve

Unlike competitive emergency pressure relief vents that use an O-ring for sealing, 8900 Series units utilize a flat diaphragm, which forms around the seat to provide a tighter seal and improved reliability. "The pressure pallet assembly provides an effective vapor-tight seal when the tank is not under emergency conditions," Brantley continues, "and after the excess pressure is relieved, the pallet assembly will reseat to again provide a vapor-tight seal."

Relief pressure on the hinged Model 8930 pressure relief vent and Model 8940 pressure/vacuum relief vent can be adjusted to <0.5 psig by adding or removing lid weights and counter-balance weights in any combination. The top guided Model 8910 pressure relief vent and Model 8920 pressure/vacuum relief vents can be adjusted from 0.5 to 15 psig by simply tightening or releasing spring pressure. All models are available with 20-inch or 24-inch ASME and API flanged bases, with other designs on request.

VCI, a division of Cashco, Inc., is headquartered in Ellsworth, Kan. Cashco manufactures a broad line of throttling rotary and linear control valves, pressure reducing regulators and back pressure regulators. **www.cashco.com**

The industrial website for today's engineer

Global sealing products manufacturer Flexitallic has revamped its website to provide easy and rapid access to the information engineering professionals need

Dynamic tools: Flexitallic's new website

The profile of today's engineer is changing the landscape of industrial marketing and how companies are reaching prospects and customers. The **Flexitallic Group** (Flexitallic), an international market leader in industrial static sealing products, has listened to this need and has created an interactive industrial website that is designed specifically for the research and buying needs of engineers in 2011.

"Creating this next-level website speaks directly to our markets and to our customers," says Jim Lenahan, Marketing Manager of Flexitallic. "It is important that our website model align with the demand of our industry engineers to understand their needs for researching, selecting and making buying decisions online."

Today, online methods dominate the stages of the buying cycle. 2010 reports from engineering portal Global Spec demonstrate that engineers have significantly reduced their reliance on traditional channels, preferring to use supplier websites, online catalogs and other online resources that help educate, improve decision making capabilities, and increase their confidence level in making final purchase decisions. "Next-generation engineers have stepped up the demand of what they expect from their industrial suppliers online," adds Lenahan. "They expect tailored solutions."

"Most industrial websites are just a little more than a brochure, with many companies still not on board with the changes that have taken place in the market," says Keith Miller, VP of Sales, Marketing & Engineering for Flexitallic. Intuitively structured, the Flexitallic website provides easy and rapid access to product information, online training, specifications, decision-making tools and live technical and customer service.

"Increased web capabilities brings the elements of technology together with information and dynamic tools for engineers who require real time information and response," adds Miller. "This helps them make intelligent research and buying decisions, resulting in shortened sales cycles in our business."

The Flexitallic Group is an international market leader in the manufacture and global supplier of high-quality, high-value industrial static sealing products. Flexitallic has manufacturing locations in 15 countries and over 600 stocking distributors worldwide.

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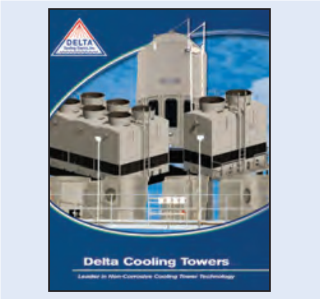

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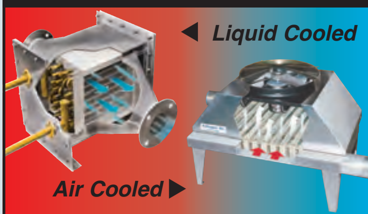
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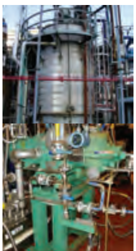

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BUSINESS NEWS

PLANT WATCH

Evonik builds surfactants plant in China

March 30, 2011 — Evonik Industries AG (Essen, Germany; www.evonik.com) is building an integrated production plant for organic specialty surfactants at its site in Shanghai, China. With an investment in the upper double-digit million euro range, the production network is scheduled to begin operation in mid 2013.

... and a new catalyst plant in Argentina

March 29, 2011 — Evonik Industries AG plans to build a new facility to produce alcoholates to be used as catalysts for the manufacture of biodiesel in Argentina. Construction work on this plant, which will have capacity of over 60,000 metric tons per year (m.t./yr), is expected to be completed by the end of 2012. The project is still contingent on the approval of the relevant authorities.

Dow and Binhua announce new JV for PCE production in China

March 29, 2011 — The Dow Chemical Co. (Midland, Mich.; www.dow.com) and Befar Group Co. (Binhua) have announced a memorandum of understanding (MoU) for a new 50–50 joint venture (JV) to produce perchloroethylene (PCE). The two companies will explore development of a new, PCE manufacturing facility in Binzhou, Shandong Province, China, which would have an initial capacity of 40,000 ton/yr, with the ability to double production soon thereafter. Assuming the terms and milestones of the MoU are met and subject to customary government approvals, Dow and Binhua estimate production would begin in 2014.

BASF Chongqing MDI project has been approved

March 25, 2011 — BASF SE (Ludwigshafen, Germany; www.basf) has received approval from the Chinese authorities for a 400,000 m.t./yr diphenylmethane diisocyanate (MDI) project in Chongqing, China. The investment will total approximately €860 million. The facility, which will produce a core component mainly used for polyurethane foams, is expected to start up by 2014. This facility will consist of an MDI plant, a nitrobenzene plant and an aniline plant. It will form the center of an integrated chemical -production complex operated by the Chongqing (Changshou) Chemical Industry Park.

AkzoNobel boosts cellulose-derivatives capacity in China

March 23, 2011 — AkzoNobel (Amsterdam, the Netherlands; www.akzonobel.com) is to invest more than €60 million in boosting production capacity for its Bermocoll cellulose derivatives (paint and building material thickeners). As well as constructing a new facility at its Ningbo multi-site in China, the company will also debottleneck the existing manufacturing site in Örnsköldsvik, Sweden. The two projects will increase capacity to close to 40,000 ton/yr. The debottlenecking project in Sweden is due to be completed by the end of this year. The new plant in Ningbo should be on stream in early 2013.

UOP technology for detergents production in China

March 22, 2011 — Technology from UOP LLC (Des Plaines, Ill; www.uop.com), a Honeywell company, has been selected by Great Orient Chemical for a new petrochemicals complex in China that will produce the key ingredient for biodegradable household laundry detergents. Great Orient Chemical expects the new complex to produce up to 100,000 m.t./yr of linear alkylbenzene (LAB). The project is expected to come on stream in the 2nd Q of 2012. Great Orient Chemical Pte. Ltd., wholly owned by the Singapore GOC Pte. Ltd, is a JV between Indonesian Salim Group and Korean ISU Chemicals focused on expanding detergents capacity in China.

Wacker expands its polysilicon production in Germany

March 14, 2011 — Wacker Chemie AG (Munich, Germany; www.wacker.com) is expanding its production facilities for hyperpure polysilicon at its Burghausen and Nünchritz sites in Germany. By taking debottlenecking measures, it will increase annual quantities at each site by 5,000 m.t. First volumes from these expansion measures are expected to be available in 2012. The debottlenecking involves investments totaling some €130 million.

Huntsman to expand polyurethane production in India

March 9, 2011 — The Polyurethanes Div. of Huntsman Corp. (Everberg, Belgium; www.huntsman.com) plans to expand its polyurethane (PU) production capabilities with a $10-million investment over the next year for the construction of a systems house in Pune, India. The new facility, which is scheduled to be operational by the end of the 1st Q of 2012, will replace Huntsman's existing system house in Thane, India.

Oxea to build new carboxylic-acids unit in Germany

March 8, 2011 — Oxea GmbH (Oberhausen, Germany; www.oxea-chemicals.com) will build a new carboxylic-acids unit in Oberhausen, Germany. The new unit will boost Oxea's global carboxylic-acids production capacity by an additional 40% on top of the already announced capacity expansion projects becoming effective at the end of 2011. Subject to approval by the relevant authorities, the new carboxylic acids unit is planned to come on stream by late 2012.

MERGERS AND ACQUISITIONS

Berkshire Hathaway to acquire Lubrizol for $9.7 billion

March 14, 2011 — Berkshire Hathaway Inc. (Omaha, Neb.; www.berkshirehathaway.com) and The Lubrizol Corp. (Wickliffe, Ohio; www.lubrizol.com) have announced a definitive agreement for Berkshire Hathaway to acquire 100% of outstanding Lubrizol shares for $135 per share in an all-cash transaction. The transaction, which was unanimously approved by the board of directors of each company, is valued at approximately $9.7 billion, including approximately $0.7 billion in net debt. The transaction is subject to the approval of Lubrizol's shareholders and the satisfaction of customary closing conditions, including the expiration of waiting periods and the receipt of approvals under the Hart-Scott-Rodino Antitrust Improvements Act and applicable non-U.S. merger-control regulations. Berkshire Hathaway and Lubrizol expect the transaction to be completed during the 3rd Q of 2011. After the close of the transaction, Lubrizol will operate as a subsidiary of Berkshire Hathaway. Lubrizol will remain located at its Wickliffe, Ohio, headquarters and will continue to be led by its current management team.

Lanxess buys Syngenta's Material Protection business

March 1, 2011 — Lanxess AG (Leverkusen, Germany; www.lanxess.com) has agreed to acquire the Material Protection business of Syngenta AG (Basel, Switzerland; www.syngenta.com). The transaction will be financed from existing liquidity and was expected to close in April 2011. Both parties have agreed not to disclose the acquisition price. ■

Dorothy Lozowski

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May 2011; VOL. 118; NO. 5

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Economic Indicators

2009 2010 2011

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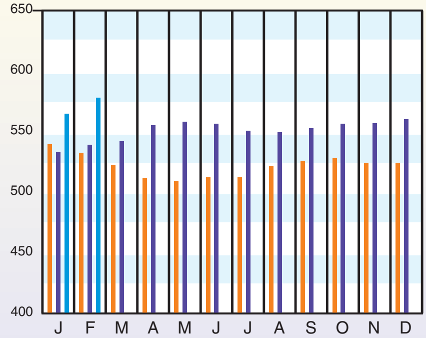
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Feb. '11 Prelim.	Jan. '11 Final	Feb. '10 Final
***CE* Index**	577.9	564.8	539.1
Equipment	701.8	681.9	641.1
Heat exchangers & tanks	668.8	635.8	587.3
Process machinery	653.5	643.7	610.3
Pipe, valves & fittings	868.3	859.2	796.1
Process instruments	440.8	431.1	420.5
Pumps & compressors	892.6	876.5	903.4
Electrical equipment	498.0	495.2	468.4
Structural supports & misc	732.1	707.4	660.0
Construction labor	325.0	326.6	330.2
Buildings	509.9	505.5	500.5
Engineering & supervision	334.9	334.8	342.4

Annual Index:

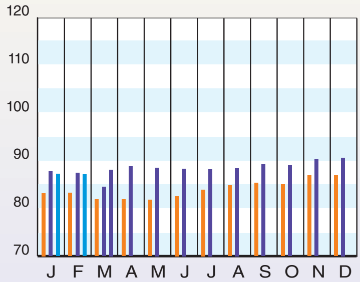
2003 = 402.0
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8



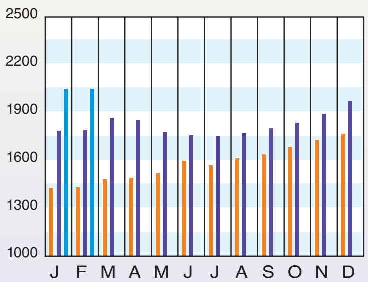
CURRENT BUSINESS INDICATORS

	LATEST			PREVIOUS						YEAR AGO		
CPI output index (2007 = 100)	Mar. '11	=	88.1	Feb. '11	=	87.1	Jan. '11	=	87.2	Mar. '10	=	84.5
CPI value of output, $ billions	Feb. '11	=	2,049.7	Jan. '11	=	2,046.4	Dec. '10	=	1,974.3	Feb. '10	=	1,789.6
CPI operating rate, %	Mar. '11	=	75.9	Feb. '11	=	75.0	Jan. '11	=	75.1	Mar. '10	=	72.0
Producer prices, industrial chemicals (1982 = 100)	Mar. '11	=	312.9	Feb. '11	=	304.2	Jan. '11	=	291.4	Mar. '10	=	273.1
Industrial Production in Manufacturing (2007=100)	Mar. '11	=	90.7	Feb. '11	=	90.1	Jan. '11	=	89.6	Mar. '10	=	85.1
Hourly earnings index, chemical & allied products (1992 = 100)	Mar. '11	=	157.4	Feb. '11	=	154.6	Jan. '11	=	156.4	Mar. '10	=	150.0
Productivity index, chemicals & allied products (1992 = 100)	Mar. '11	=	113.7	Feb. '11	=	113.4	Jan. '11	=	114.0	Mar. '10	=	111.2

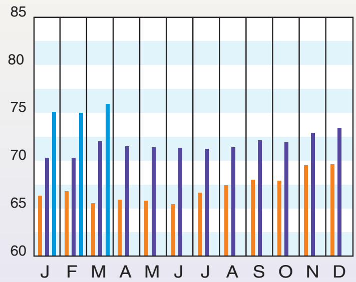
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



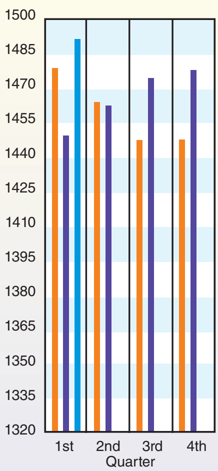
Current Business Indicators provided by Global Insight, Inc., Lexington, Mass.

MARSHALL & SWIFT EQUIPMENT COST INDEX

(1926 = 100)	1st Q 2011	4th Q 2010	3rd Q 2010	2nd Q 2010	1st Q 2010
M & S INDEX	1,490.2	1,476.7	1,473.3	1,461.3	1,448.3
Process industries, average	1,549.8	1,537.0	1,534.4	1,522.1	1,510.3
Cement	1,546.6	1,532.5	1,530.0	1,519.2	1,508.1
Chemicals	1,519.8	1,507.3	1,505.2	1,493.5	1,481.8
Clay products	1,534.9	1,521.4	1,518.3	1,505.6	1,496.0
Glass	1,447.2	1,432.7	1,428.5	1,416.4	1,403.0
Paint	1,560.7	1,545.8	1,542.1	1,527.6	1,515.1
Paper	1,459.4	1,447.6	1,444.5	1,430.1	1,416.4
Petroleum products	1,652.5	1,640.4	1,637.0	1,625.9	1,615.6
Rubber	1,596.2	1,581.5	1,579.3	1,564.2	1,551.0
Related industries					
Electrical power	1,461.2	1,434.9	1,419.2	1,414.0	1,389.6
Mining, milling	1,599.7	1,579.4	1,576.7	1,569.1	1,552.1
Refrigeration	1,827.8	1,809.3	1,804.8	1,786.9	1,772.2
Steam power	1,523.0	1,506.4	1,502.3	1,488.0	1,475.0

Annual Index:

2003 = 1,123.6 2004 = 1,178.5 2005 = 1,244.5 2006 = 1,302.3
2007 = 1,373.3 2008 = 1,449.3 2009 = 1,468.6 2010 = 1,457.4



CURRENT TRENDS

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Ethylene Glycol Specialist — JRE29683

Qualification: B. Sc. in Chemical Engineering, an additional degree in Business Management would be an added asset.

Experience: The candidate must possess a verifiable record of over 15 years professional working experience in a developed Petrochemicals environment in the EG derivatives; must have proven experience in technical and plant operations and a working knowledge of operation in an international market environment.

Poly Olefin Specialist — JRE29682

Qualification: B.Sc. in Chemical Engineering. An additional degree in Business Management would be an added asset.

Experience: The candidate must possess a verifiable record of over 15 years professional working experience in a developed Petrochemicals environment preferably in the polyolefin derivatives; must have proven experience in technical and plant operations and a working knowledge of operation in an international market environment.

Fertilizer Specialist — JRE30260

Qualification: B.Sc. in Chemical Engineering. An additional degree in Business Management would be an added asset.

Experience: The candidate must possess a verifiable record of over 15 years professional working experience in a developed petrochemicals environment in the cracking derivatives; must have proven experience in technical and plant operations and a working knowledge of operation in an international market environment.

Extruder Specialist — JRE30270

Qualification: B.Sc. in Chemical / Mechanical / Plastic Engineering.

Experience: The candidate should have minimum of 15 years experience in a plastics compounding including: extrusion/compounding equipment technology and troubleshooting, mixing/ blending equipment, solids handling, pelletizing equipment, classification and packaging processes and equipment. The candidate should have knowledge of computerized process control, PLC, or DCS systems. International experience traveling and providing compounding support for Europe and Asia compounding operations is required. Experience with PI, ASPEN, SPC. SAP is an added advantage.

Fired Heaters & Boilers Specialist — JRE30283

Qualification: B.Sc. in Mechanical / Chemical Engineering. Candidates with an M.S. Degree is preferred.

Experience: The candidate should have minimum of 15 years professional experience in fired heaters and boilers with broad experience in design check, performance enhancement, troubleshooting, and failure analysis of fired heaters and boilers. Good experience in refractory design and installation is desirable.

Ethane/Naphtha Ethane/Naphtha Cracking Specialist — JRE30284

Qualification: B.Sc. in Chemical Engineering. An additional degree in Business Management would be an added asset.

Experience: The candidate must possess a verifiable record of over 15 years professional working experience in a developed petrochemicals environment preferably in the Ethane/Naphtha cracking derivatives; must have proven experience in technical and plant operations and a working knowledge of operation in an international market environment.

Distillation/Separation Specialist — JRE30286

Qualification: B.Sc. in Chemical Engineering. An additional degree in Business Management would be an added asset.

Experience: The candidate must possess a verifiable record of over 15 years professional working experience in a developed Petrochemicals environment in the separation technology; must have proven experience in technical and plant operations and a working knowledge of operation in an international market environment.

Unfired Heat Transfer Equipment Specialist — JRE30287

Qualification: M.Sc. / B.Sc. in Mechanical / Chemical Engineering.

Experience: The candidate must have a minimum of 15 years professional experience in the Heat Transfer discipline with a focus on the oil and gas industry. The Heat Transfer Specialist is expected to have a sound background in engineering, as well as knowledge in the field of heat transfer and physics of transport phenomena and fluid flow. The candidate should have experience in troubleshooting and de-bottlenecking of (unfired) heat transfer equipment in operating plants, heat transfer equipment operating data analysis and interpretations, preparation of heat transfer equipment design (thermal, hydraulic, and mechanical), capital project support and quality assurance, training, technology development and guidance on design practices and procurement standards.

APPLICATION PROCESS: Candidates may send CVs to **oildxb@jvi-global.com**
Processing preference will be given to CVs received at **www.jerryvarghese.com/applyonline**
Please select your source of CV as "Print Advertisement" quoting the above Job Title and Ref. No. (JRE). To view complete job details, please visit **www.jerryvarghese.com/sabic**

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