CHEMICAL ENGINEERING

April 2010

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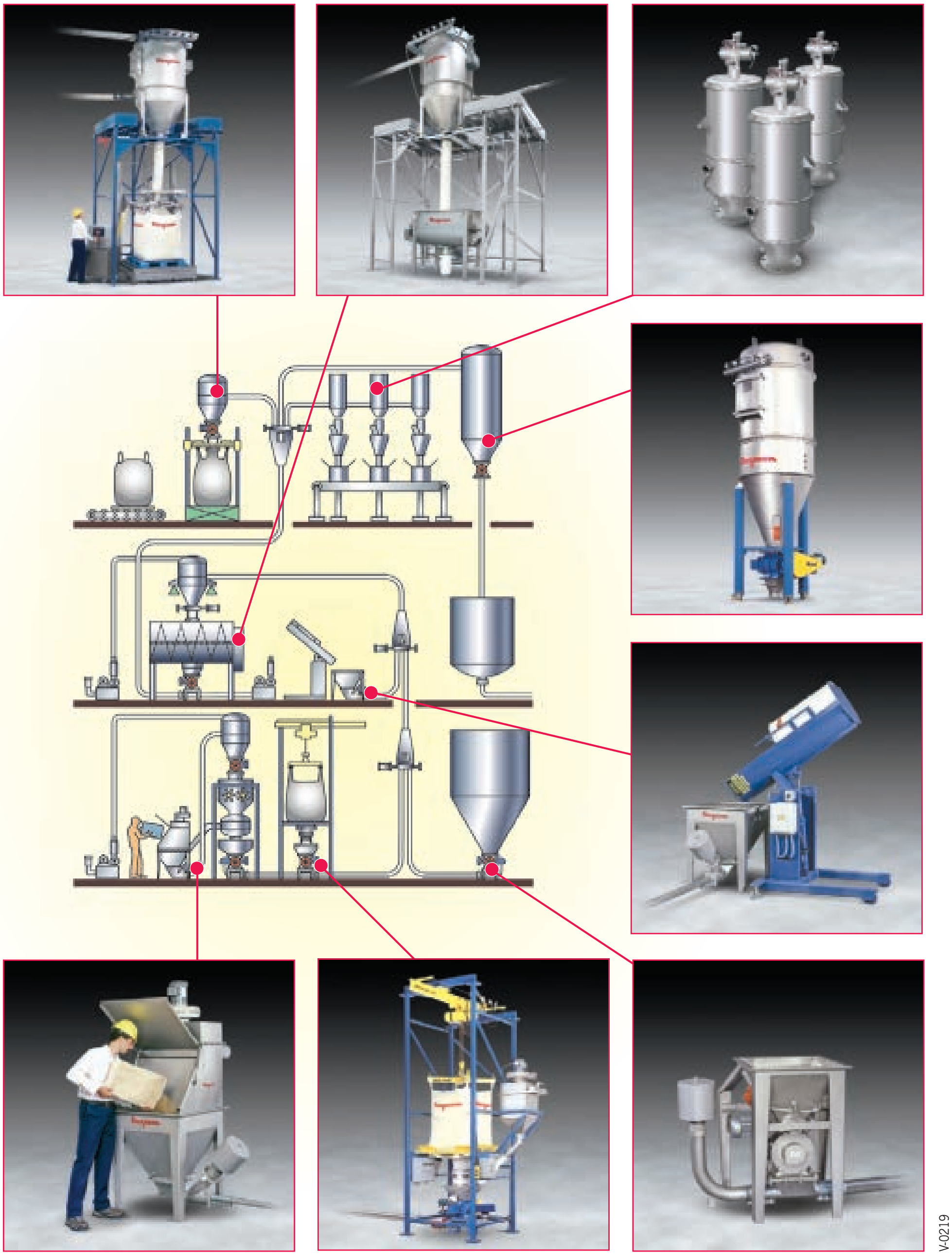

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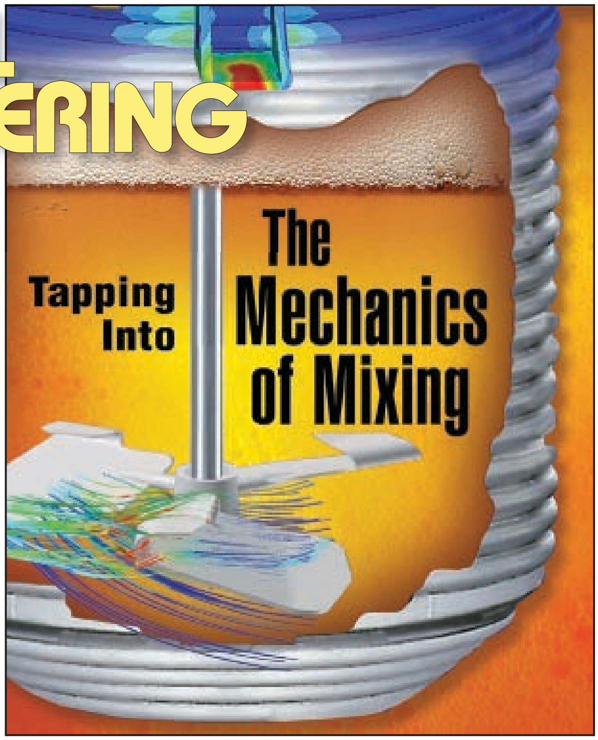

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Editor's Page

Help cultivate budding ChEs

Next month, on May 5th, the American Chemical Society (ACS; Washington, D.C.; www.acs.org) and more than 200 other private- and public-sector organizations representing more than 6.5 million science, technology, engineering and math (STEM) professionals will celebrate the first National Lab Day. At the most basic level, National Lab Day aims to inspire a wave of future innovators and foster U.S. competitiveness by improving the quality of STEM education in America. In a broader sense, though, the initiative is an acknowledgement of the greater prominence that STEM education and careers hold in some parts of the world and reminds all of us — regardless of nationality — of the value in engaging our children in the fascinating relevance of the chemical engineering profession.

As I am sure many of you can attest, children have a natural curiosity about science and how things work. Starting at a very young age, this appetite can either thrive or die, depending on how much (and how effectively) it is fed. What the traditional system has failed to realize is that the exciting flavor of this knowledge does not often come through in lectures or textbooks. According to this year's Lemelson-MIT Invention Index (Cambridge, Mass.; www.mit.edu/invent/), an annual survey that gauges American's perceptions about invention and innovation, two-thirds of teens chose hands-on projects as the types of classroom-based educational methods they enjoy most.

Therefore, National Lab Day is centered around hands-on learning throughout the year, culminating each May with special events. "We wouldn't teach football from a textbook," said John P. Holdren, President Obama's science advisor, at the National Lab Day announcement ceremony last November. "It is even more important that America's youth have the opportunity to learn math and science by doing." In this vein, volunteers are critical to the success of any efforts to support STEM education and careers. Therefore, ACS has solicited the help of chemists and chemical engineers to engage in activities that will strengthen laboratory experiences in their local communities or in outreach to other high-need schools. ACS suggests, for example, that volunteers might do one or more of the following:

- Install software or identify useful Web resources from the ACS Education Division and other sources
- Find, donate, or repair equipment
- Implement hands-on projects
- Start a fund-raising effort to buy needed supplies
- Help with science fairs
- Mentor a student
- Chaperone field trips
- Provide internship opportunities
- Donate materials
- Help with lesson plans
- Be an advisor for an after-school program like ACS ChemClubs

Your commitment could be as little as a few hours, though as ACS says for many volunteers, National Lab Day will be just the first step — if not the next step — in an ongoing involvement with local schools and teachers. The National Lab Day Website (www.nationallabday.org) provides a place to register as a volunteer and describe your ideas for participation.

As *Chemical Engineering* has pointed out in countless ways over the past 108 years, the solutions to the world's biggest problems continue to be solved at the hands of chemical engineers. An extension of that accomplishment is to make sure that there are enough inspired hands to accept the baton tomorrow. ■

Rebekkah Marshall

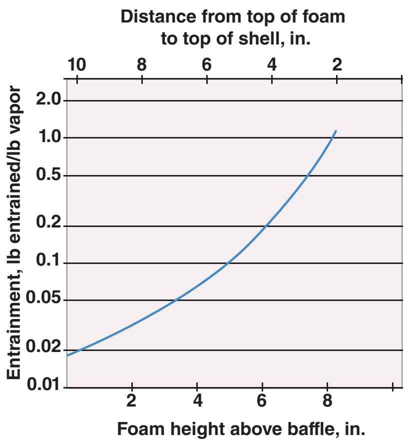
Letters

Entrainment in kettle reboilers

I read with great interest your article, Kettle Troubleshooting (February, pp. 26–33). The authors are to be congratulated on a very in-depth and timely presentation on the effects of boiling two-phase flow in kettle type reboilers. For over 45 years, I have been engaged in the refrigeration industry where refrigeration engineers are often challenged in designing evaporators to avoid liquid carryover. I was interested to learn that one criterion used in the design of kettle reboilers in the chemical process industries is to keep the top row of tubes in the bundle at least 12 in. or 1.3–1.6 times the bundle diameter (whichever is greater) above the liquid level. In refrigeration, we allow higher liquid levels without incurring liquid slopover, but this is likely because we do not have the high heat fluxes that were encountered in the article's example. On the other hand, I believe the typical range of overall heat transfer coefficients we calculate for design do not vary extensively from fluids with similar transport properties. I would appreciate more information about this and how it applies to the example.

Jon Edmonds
Edmonds Engineering Co., York, Pa.

Author replies: Many thanks for your kind comments on our work and for your valuable experience. The figure here, based on the Heat Transfer Research Inc. (HTRI) calculation, may shed light on your correct comment regarding the rule of thumb for the needed spacing above the liquid level. Entrainment is shown as a function of foam height above the kettle overflow baffle. As the foam approaches the outlet nozzle, entrainment exponentially rises. For the measured ratio of 0.46 lb entrained/lb vaporized in the 195 gal/min feed test, the foam was within 3 in. of the vapor outlet. Entrainment falls very rapidly as the foam height declines.



Difficulties in applying the calculation are estimating the foam height and accounting for the observed zoning in the kettle. For this reason, the rule of thumb, conservative as you correctly stated (we concur), keeps us on the safe side, at least in my experience with non-foaming systems.

Henry Kister
Fluor Corp., Aliso Viejo, Calif..

Postscripts, corrections

November 2009, "De-emphasize Capital Costs For Pipe Size Selection," pp. 41-43: In equations (1), (2A) and (2B), the addition signs in the equations should be division symbols. A corrected version of the article is available at www.che.com. ■

Calendar

NORTH AMERICA

Biopocess Training Academy. IBC Life Sciences (Boston, Mass.). Phone: 800-390-4078; Web: ibclifesciences.com.
Boston, Mass. **May 3–4**

BIO 2010, co-located with the 2010 Biosecurity Conference. Biotechnology Industry Organization (Washington, D.C.). Phone: 202-962-6655; Web: bio.org
Chicago, Ill. **May 3–6**

24th Coating and Drying Technology Seminar. Edgar B. Gutoff, Consulting Engineer. Phone: 617-734-7081; Email: ebgutof@coe.neu.edu
Waltham, Mass. **May 3–6**

12th International Symposium on Particles on Surfaces: Detection, Adhesion and Removal; and Process Cleaning Expo. MST Conferences (Hopewell Junction, N.Y.). Phone: 845-897-1654; Web: mstconf.com
Louisville, Ky. **May 4–6**

2010 PMA/CUMA Annual Meeting and Processing Techniques Seminar. Polyurethane Manufacturers Assn. (PMA; Milwaukee, Wisc.) and Candian Urethane Manufacturers Assn. (CUMA). Phone: 414-431-3094; Web: pmahome.org/annualmeeting.aspx
Las Vegas, Nev. **May 8–11**

ASME 18th Annual North American Waste-to-Energy Conference. American Soc. of Mechanical Engineers (ASME; New York, N.Y.). Phone: 973-882-1170; Web: asmeconferences.org/nawtec18/
Orlando, Fla. **May 11–13**

2010 Forum on Water Heating, Distribution, and Use Efficiency. American Council for an Energy-Efficient Economy (ACEEE; Washington, D.C.). Phone: 202-507-4035; Web: aceee.org/conf/10whforum/
Ontario, Calif. **May 12–14**

International Conference on Thermal Treatment Technologies and Hazardous Waste Combustors. Air & Waste Management Assn. (Pittsburgh, Pa.). Phone: 412-904-6004; Web: awma.org/it32010/
San Francisco, Calif. **May 17–20**

AATCC International Conference. American Assn. of Textile Chemists and Colorists (Research Triangle Park, N.C.). Phone: 919-549-3533; Web: aatcc.org
Atlanta, Ga. **May 18–20**

Techtextil North America Symposium 2010. Messe Frankfurt Group (Frankfurt). Phone: 770-984-8016, Ext. 424; Web: techtextilna.com
Atlanta, Ga,. **May 18–20**

RadTech UV & EB Curing Technology Expo and Conference 2010. RadTech Inernational (Bethesda,

Calendar

Md.). Phone: 240-643-0517; Web: radtech2010.com
Baltimore, Md. **May 24–26**

Coating Process Fundamentals Short Course. University of Minnesota (Minneapolis). Phone: 612-624-3492; Web: cce.umn.edu/coatingprocess
Minneapolis, Minn. **June 8–10**

103rd Annual A&WMA Annual Conference & Exhibition. Air & Waste Management Assn. (Pittsburgh, Pa.). Phone: 412-904-6020; Web: awma.org
Calgary, Alta. **June 22–25**

7th International Symposium on Contact Angle, Wettability and Adhesion. MST Conferences (Hopewell Junction, N.Y.). Phone: 845-897-1654; Web: mstconf.com
Danbury, Conn. **June 23–25**

A&WMA Second International Greenhouse Gas Measurement Symposium. Air & Waste Management Assn. (A&WMA; Pittsburgh, Pa.). Phone: 412-904-6020; Web: awma.org
Washington, D.C. **Sept. 8–10**

ChemInnovations 2010 Conference & Expo. Trade-Fair Group, Access Intelligence LLC. Phone: 713-343-1879; Web: cpievent.com
Houston, Tex. **Oct. 8–10**

EUROPE

45th Euchem Conf. on Stereochemistry. Stereochemistry Conference Committee, University of Geneva (Switzerland). Phone: +41 22 379 6062; Web: stereochemistry-buergenstock.ch
Brunnen, Switzerland **May 2–7**

18th European Biomass Conference and Exhibition. ETA Florence Renewable Energies (Florence, Italy). Phone: +39 055 5002174; Web: conference-biomass.com
Lyon, France **May 3–7**

Unconventional Gas 2010 Conference. Gas Technology Inst. (Des Plaines, Ill.). Phone: 847-768-0868; Email: gastechnology.org/gug2010
Amsterdam, The Netherlands **June 15–17**

ASIA & ELSEWHERE

7th Middle East Refining & Petrochemical Exhibit and Conference. Arabian Exhibit Management (Manama,Bahrain). Phone: +97 317 550 033; Web: mepetrotech.com
Manama, Bahrain **May 23–26**

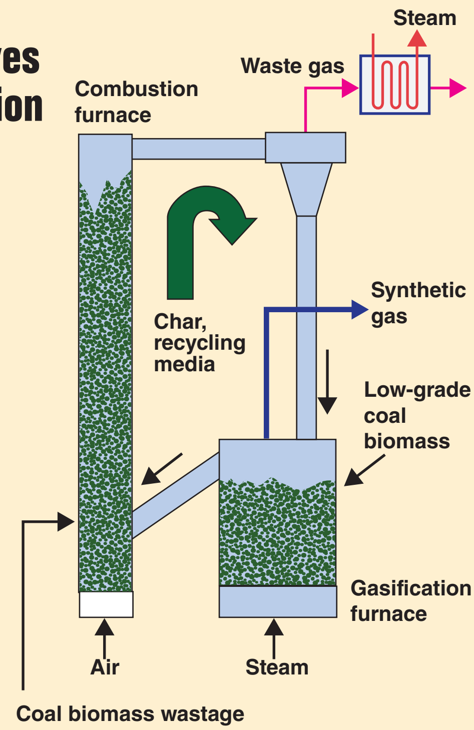
Cinte Techtextil China. Messe Frankfurt Group (Frankfurt, Germany). Fax: 852-2598 8771; Web: techtextil.messefrankfurt.com
Shanghai, China. **October 19–21** ■

Suzanne Shelley

A new gasification process moves a step closer to commercialization

Next year IHI Corp. (IHI; Tokyo, Japan; www.ihi.co.jp) plans to construct a demonstration plant in Indonesia that will gasify 50 ton/d of lignite (brown coal) into synthesis gas (syngas; predominantly hydrogen and carbon monoxide) using IHI's twin-tower, bubbling fluidized-bed gasification process. This process has been shown to produce 1,000 m^3 of syngas for each ton of low-grade coal at the firm's 6-ton/d test plant at Yokohama, Japan. Following a successful demonstration of the technology in the Indonesian facility, the company anticipates commercialization of units with capacities of 300 to 1,000 ton/d of coal, with the syngas used for making fuels, methane (synthetic natural gas) or chemicals such as methanol.

In the IHI process (flowsheet), lignite (coarse and dry) is pyrolyzed and gasified in a bubbling fluidized-bed reactor using sand (for heat transfer) and steam (as an oxygen source) at 800–900°C. Syngas emerging from the top is separated from solids by a cyclone, and the elutriated particles are returned to the reactor. Tars, unreacted char and cooled sand from the top of the bed are transported into an air-blown, pneumatic-riser furnace, where tars and char are completely burned into CO_2, and the sand is reheated by the heat of combustion.



IHI's technology has the advantage of operating at relatively low temperatures (compared to 1,400–1,500°C used by entrained gasifiers), and the use of steam instead of oxygen is said to increase the H_2 content of the syngas. The process also requires less feed preparation, using coarse coal particles instead of slurries or pulverized coal that is needed by other gasifiers.

A hard biomaterial

Researchers at the Fraunhofer Institute for Manufacturing Engineering and Applied Materials Research (IFAM; Bremen, Germany; www.ifam.fraunhofer,de) have developed a granulate form of a biomaterial that may replace titanium used as screws and other hardware in medical applications. Although screws made of polylactic acid (PLA), for example, have already been used in the past for repairing broken bones, large holes remain in the bone after the PLA has degraded. IFAM's new material is a composite of PLA and hydroxylapatite — a ceramic component of natural bone. When screws of this composite degrade, the hydroxylapatite component promotes new bone growth into the implant. The new material can be processed using conventional injection-molding methods, without the need for any post-processing, such as

(Continues on p. 16)

Pilot plant to demonstrate advanced vapor-compression desalination nears completion

Researchers at Texas A&M University (College Station, Tex.; www.tamu.edu) are poised to complete assembly of a pilot project that seeks to demonstrate the commercial viability of advanced vapor-compression desalination, an updated version of a decades-old distillation technology first developed for naval vessels.

The pilot unit is nearing completion in Laredo, Tex., where it will produce 50,000 gal/d of potable water from the brackish groundwater of the region.

The technology was developed by Texas A&M chemical engineering professor Mark Holtzapple and research engineer Jorge Lara, and has been licensed to Terrabon Inc. (Houston; www.terrabon.com), which markets it as AdVE (advanced vapor compression evaporation) desalination.

Like its ancestors, AdVE compresses steam generated by heating salt water. The compression step allows the steam to give up its latent heat of vaporization, as it condenses to freshwater. The heat captured from the compressed steam is used to generate additional steam from the feedwater.

Process improvements developed by the Texas A&M team have made AdVE practical on a larger scale than its forebears. For example, Holtzapple developed a high-efficiency compressor that uses a gerotor-type (generated rotor) arrangement to process gases.

A key technology component is a novel "sheet-shell" heat exchanger that increases heat transfer coefficients dramatically. The heat exchangers are coated with a proprietary material that promotes dropwise condensation, rather than condensation in sheets. The heat exchanger, along with operation at elevated temperatures and pressure, allows heat transfer coefficients that are 20 times higher than conventional heat exchangers.

Capital costs and energy requirements for AdVE are similar to or less than reverse osmosis (RO) technology, and AdVE is more robust than RO, says Holtzapple. "AdVE isn't prone to random shutdowns, and it's less sensitive to water chemistry," he says.

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

A highly efficient microwave reactor continuously produces metallic nanoparticles . . .

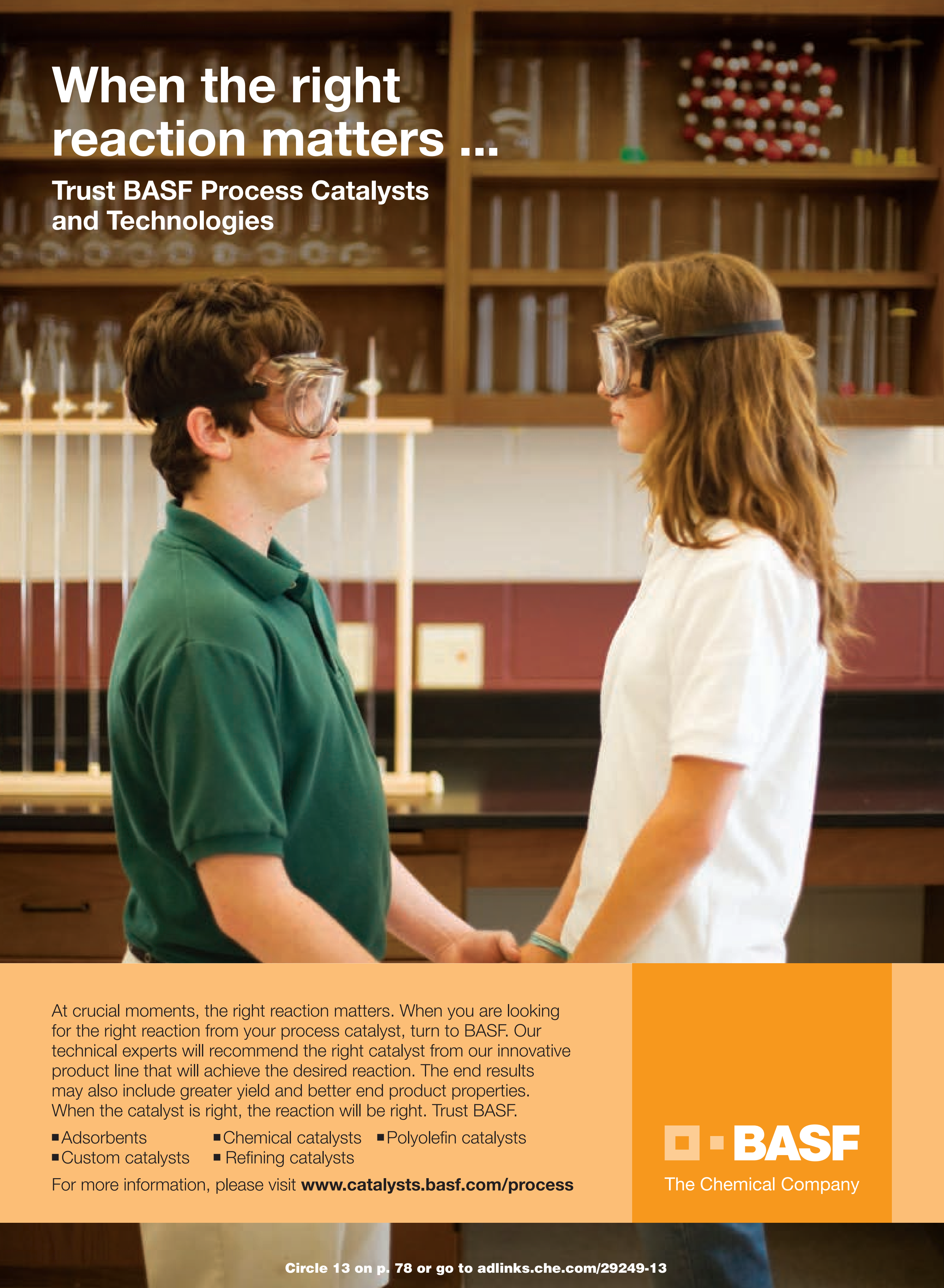
The process, developed by Masateru Nishioka at the Research Center for Compact Chemical Process, Institute of Advanced Science and Technology (AIST; Sendai; www.aist.go.jp) in collaboration with Shinko Kagaku (Koshigaya; www.shinkou-kagaku.co.jp), uses a microwave-assisted flow reactor developed by AIST and IDX Inc. (Tokyo, all Japan; english.idx-net.co.jp). The researchers found that they can uniformly heat the catalyst and reactants at the center of the vertical tubular reactor, and can control the reaction temperature by varying the frequency of the microwaves using a tunable, semiconductor microwave generator.

Using ethylene glycol as a solvent for the nanoparticle synthesis, the heating efficiency (conversion of microwave energy to thermal energy) of the system is more than 95%, compared to around 40% achieved by existing microwave heating devices. The system has been demonstrated for producing metallic nanoparticles from a wide range of feed materials. For example, gold particles with 10-nm dia. and narrow size distribution have been produced. The group is now developing a compact microwave generator for manufacturing processes. The technology is expected to be used for the production of nanoparticles as well as for performing organic synthesis reactions.

. . . and a microwave-assisted process makes nanoparticles underwater

Meanwhile, professor Tetsu Yonezawa at the Materials Science Div. of Hokkaido University (Sapporo; labs.eng.hokudai.ac.jp/labo/limsa/english/), in collaboration with Arios, Inc. (Akishima; www.arios.co.jp) and Suga (Hokuto, all Japan; www.suga.ne.jp), has developed a microwave-assisted device that can continuously generate a plasma under water. In the laboratory, Yonezawa has shown that underwater plasma can be used to synthesize various metallic nanoparticles, without the need for large devices such as a vacuum degasifier. Potential applications for the technology include the production of metal-supported catalyst and for performing organic reactions.

The plasma is generated by focusing microwaves through a tube onto an electrode chip submerged in water, which induces hot spots that cause sputtering of the metal substrate from the electrode. Only 1.5 kW of electric power — about twice that of a common household microwave oven — is required to create the plasma needed for the synthesis. As a result, the researchers believe the process is expected to cut plasma-generation costs to one third to one fifth of that needed by conventional high-pressure, pulsed-high-voltage plasma generators.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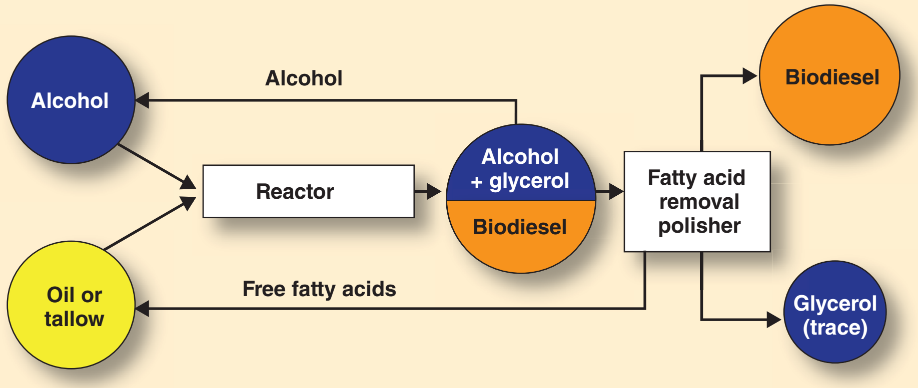
Catalytic process cuts the cost of biodiesel fuel



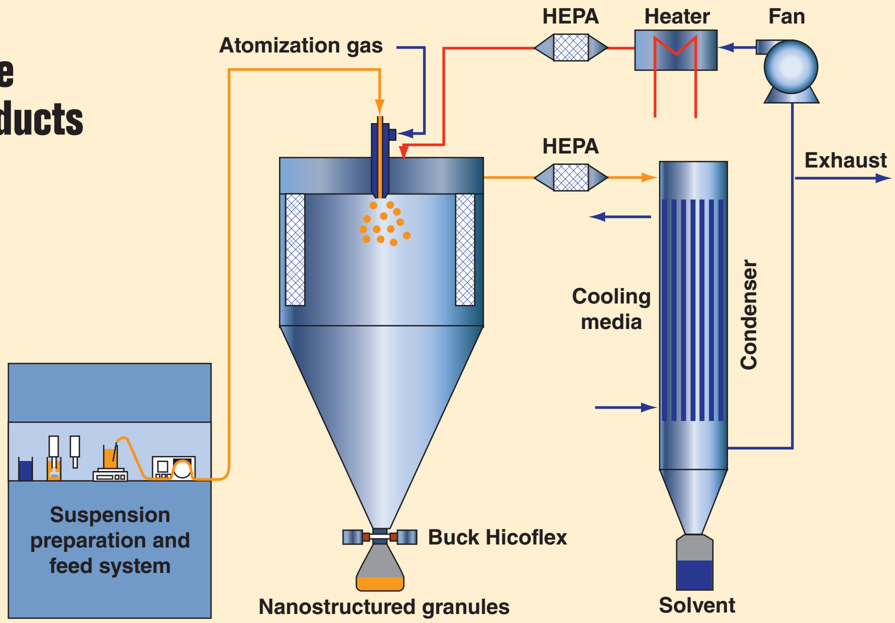
Biodiesel fuel is being produced for under $2/gal from product wastes in a process commercialized by Ever Cat Fuels (Anoka, Minn.; www.evercatfuels.com). This is comparable to the cost of diesel fuel obtained from petroleum, says Arlin Gyberg, a co-inventor of the process and a chemistry professor at Augsburg College, Minneapolis. Ever Cat is a new subsidiary of SarTec Corp. (Anoka, Minn.; www.sartec.com), which scaled up the technology.

The plant uses a continuous process to produce 4-million gal/yr of fuel from two 6-ft by 6-in.-dia reactors. The reaction takes about 6 s, versus about 6 h for a conventional batch process, says Gyberg. The feed is a mixture of waste corn oil from bioethanol plants and waste cooking oil, although about 40 feedstocks (animal fats and plant oils) have been successfully pilot-tested, he says. Preheated feed is introduced into the top of a catalyst-packed column and converted to biodiesel fuel under supercritical conditions at about 350°C and 200 psi.

Conversion is practically 100%, says Gyberg, since the process performs transesterification of triglycerides and esterification of free fatty acids. He notes that conventional processes do transesterification, but convert fatty acids to soap. Glycerol, an unwanted byproduct of traditional processing, is broken down in the reactor and the small amount produced is recycled, along with alcohol.

Ever Cat has been using a zirconia catalyst of 2-µm particles since the plant started up last fall. The catalyst is not degraded by the process (hence the name "Ever Cat"). If the column gets plugged, the catalyst can be heated to drive off the organics, says Gyberg, but so far this has not been necessary. He adds that the company will likely switch to a catalyst of titania particles developed by Rockwood Holdings Inc.'s Sachtleben operation (Duisburg, Germany). Titania has worked as well in tests and its cost is a fraction of that of zirconia, he says. Ever Cat plans to scale up production to 30-million gal/yr within two years by adding parallel reactors similar to those now in use.

A less risky way to manufacture and transport nanoparticle products



As producers continue to develop new applications for nanoparticles, the health, safety and environmental (HSE) hazards associated with these miniscule particles remain uncertain and controversial. To minimize the HSE risks for handling nanoparticles, GEA Niro, (Søborg, Denmark; www.niro.com) has developed a contained process that binds nanoparticles in a dust-free, micron-sized granular form. "The process is also expected to reduce costs, because it eliminated the large expenditure needed to set up a facility where operators can safely work, taking into account dust and the difficulty in handling due to the low density, poor flowability and electrostatic nature of nanoparticles," says Jesper Saederup Lindeløv, a research scientist at GEA. "Transportation costs are also lower for the granular form compared to common suspension form, which has the added weight of the liquid when shipping product to customers."

The heart of the new process (flowsheet), developed in cooperation with 21 partners within the EU-funded Saphir project (www.saphir-project.eu), is a spray dryer. Slurries of nanoparticles are injected through an atomizer into the drying chamber, where hot air dries the micron-sized droplets into granules. Unlike conventional spray dryers, which use an external bag filter to recover products (thus adding an extra chamber that has to be evaluated for confinement during the risk assessment), the new process recovers product through Niro's integrated Buck Hicoflex system — a containment interface for safe transfer of granules. Thus, everything "nano" is confined inside the spray drying system, says Saederup Lindeløv. The researchers have also devised a way to boost the feed's solids content to 37 wt.% through an educated selection of dispersion agents, pH, ionic strength and solvent type. Previously, the limit for atomizing viscous slurries has been 10 wt.% dry solids, he says.

Commercial production of spray-dried nano-hydroxyapatite has already occurred, and Niro believes that industrial units using the integrated filter configuration will be in commercial production within three years.

'Venus flytrap' — a new way to treat nuclear waste

The cleanup of nuclear waste could be simplified by a process being developed at Northwestern University (Chicago, Ill.; www.northwestern.edu) and Argonne National Laboratory (Argonne, Ill.; www.anl.gov). Nuclear waste consists mainly of non-toxic sodium ions, but this is mixed with a very small amount of highly radioactive cesium isotopes that have proved difficult to separate from the mix. Northwestern and Argonne have developed an ion exchange material that promises to solve this problem by selectively extracting the cesium, thereby producing a concentrated waste stream that can be more easily treated.

The new material is a rigid, porous structure of gallium and antimony sulfides. In laboratory tests, crystals of the material are stirred in an aqueous solution of surrogate cesium and sodium, potassium and calcium ions. Cesium is trapped in the crystals, but not the other ions, says Mercouri Kanatzidis, a senior scientist with Argonne and a professor of chemistry at Northwestern University.

Kanatzidis compares the capture mechanism to that of a Venus flytrap. The cesium reacts with sulfur atoms in the framework, causing the pores to narrow and trap the cesium. The other ions, in contrast to cesium, bond strongly to the water and are thus prevented from being trapped by the structure. Next, Kanatzidis plans to test the process in a packed column, using actual nuclear waste.

(*Continued from p. 11*)

milling. Prototype components have a compressive strength of 130 N/mm, which is comprable to real bone (130–180 N/mm).

Microreactor GTL demo

A 5–10 bbl/d demonstration gas-to-liquids (GTL) facility is to be up and running by early next year at the Petrobas Brasileiro S.A. (Rio de Janeiro) facility in Fortaleza, Brazil. The facility, which will incorporate a microchannel steam-methane reformer (SMR) and a microchannel Fischer-Tropsch (F-T) reactor based on technology of Velocys, Inc. (Columbus, Ohio; www.velocys.com), will be constructed by Toyo Engineering Corp. (Chiba, Japan; www.toyo-eng.co.jp), with support from Modec (Tokyo; www.modec.com). Fabrication of the SMR and F-T reactor will be carried out by Kobe Steel, Ltd. (Kobe, Japan; www.kobelco.co.jp). Following a successful demonstration, this technology is expected to be used by Modec, Toyo and Velocys to process gas, which is normally flared, into fuels on the floating production, storage and offloading vessels used in off-shore oil-and-gas fields.

Circle 16 on p. 78 or go to adlinks.che.com/29249-16

A quick way to tell when to pick cotton

An instrument called the Cottonscope, which automatically measures cotton maturity in 25 s, has been developed by CSIRO Cotton Research Unit (Melbourne, Australia; www.csiro.au).

The unit's leader, Stuart Gordon, says the instrument has been used to measure when a crop was mature enough to harvest. "The instrument will also be valuable in the spinning mill where it will enable more accurate prediction of nep (clusters of fibers) creation, dye uptake and overall quality control when cotton bales are laid down for processing at the mill," he says.

Cottonscope is a fully automated microscope that captures color images of cotton snippets on a glass slide. The color of each snippet is used to calculate the maturity ratio. The instrument combines the technologies of SiroMat and OFDA (optical-based fiber diameter analyzer).

SiroMat, also developed by CSIRO, is an automated version of the polarized light microscopy Standard Test Method (ASTM D1442.00). It uses a high-resolution color digital camera and intensive computing power to analyze images of mature and immature fibers. OFDA, from BSC Electronics Pty Ltd., (Western Australia), is an image processing instrument for rapid and accurate measurement of animal fibers such as cashmere and wool.

Commercial production of carbon nanotubes

This month, Showa Denko K. K. (Tokyo, Japan; www.sdk.co.jp) will begin marketing its carbon-nanotube (CNT) product, tradenamed VGCF-X. The company produces the CNTs in its new, 400-ton/yr production plant at its Oita facility, and plans to ramp up production to 1,000 ton/yr over the next five years. The company says world demand for CNTs will reach 2,000 ton/yr in 2011.

Making PE conduct heat

Scientists at MIT (Cambridge, Mass.; www.mit.edu) have found a way to transform polyethylene (PE) into a thermal conductor while maintaining its electrical insulating properties. The material is made by slowly drawing a PE fiber from solution using the finely controllable cantilever of an atomic-force microscope. The resulting fiber is 300 times more thermally conductive along the direction of the fiber than normal PE. This high, one-directional thermal conductivity, which is better than many metals (including iron and platinum), has implications for future polymers replacing metals in heat exchangers, solar-thermal collectors and electronics. The next step is to develop a way to make fibers on the macro scale.

A CO_2-to-fuel process demonstrated

Scientists at Carbon Sciences Inc. (Santa Barbara, Calif.; www.carbonsciences.com) have successfully demonstrated a CO_2-to-fuel process that proceeds under mild conditions using fluegas emissions as a carbon dioxide source and brackish water as a hydrogen source. The modular, three-step process is highly scalable, says Carbon Sciences chief technology officer Naveed Aslam, and depends on proprietary alkali-salt catalysts and auxiliary chemicals that are recoverable. The possibility exists that the carbon-negative CO_2-to-fuel process could allow a self-sustaining power plant that recycles its CO_2 from fuel combustion into more fuel.

In the first stage, CO_2 is hydrogenated at temperatures between 40 and 85°C and pressures of 0.5–10 bar in the presence of the catalyst and an auxiliary chemical. Bicarbonate forms, but is rapidly decomposed into a compound with lower oxygen content. The compound is recovered and converted to methane by stripping its oxygen in a second step. The third step involves synthesis of larger hydrocarbons such, as those found in gasoline.

Aslam says that the first step of the process succeeded in converting 30–45% of the CO_2 into the low-grade fuel product, a total he hopes will climb to 70–75% conversion as the process-optimization work now underway at Carbon Sciences moves forward. Among the chief strategies to improve process performance inolves nano-engineering, Aslam says — placing catalyst molecules inside a nanoscale structure.

Future plans for the process include generating additional data from the bench-scale demonstration project, then building a series of pilot plants, both in-house and with partners. Aslam says designs for a commercial-scale facility could begin in mid-2012. Since the process is modular, the company may commercialize individual steps along different timetables.

Carbon Sciences is also working on a separate CO_2-to-methanol process that works by utilizing biological enzymes encased in nanoscale polymer beads to recycle CO_2. ■

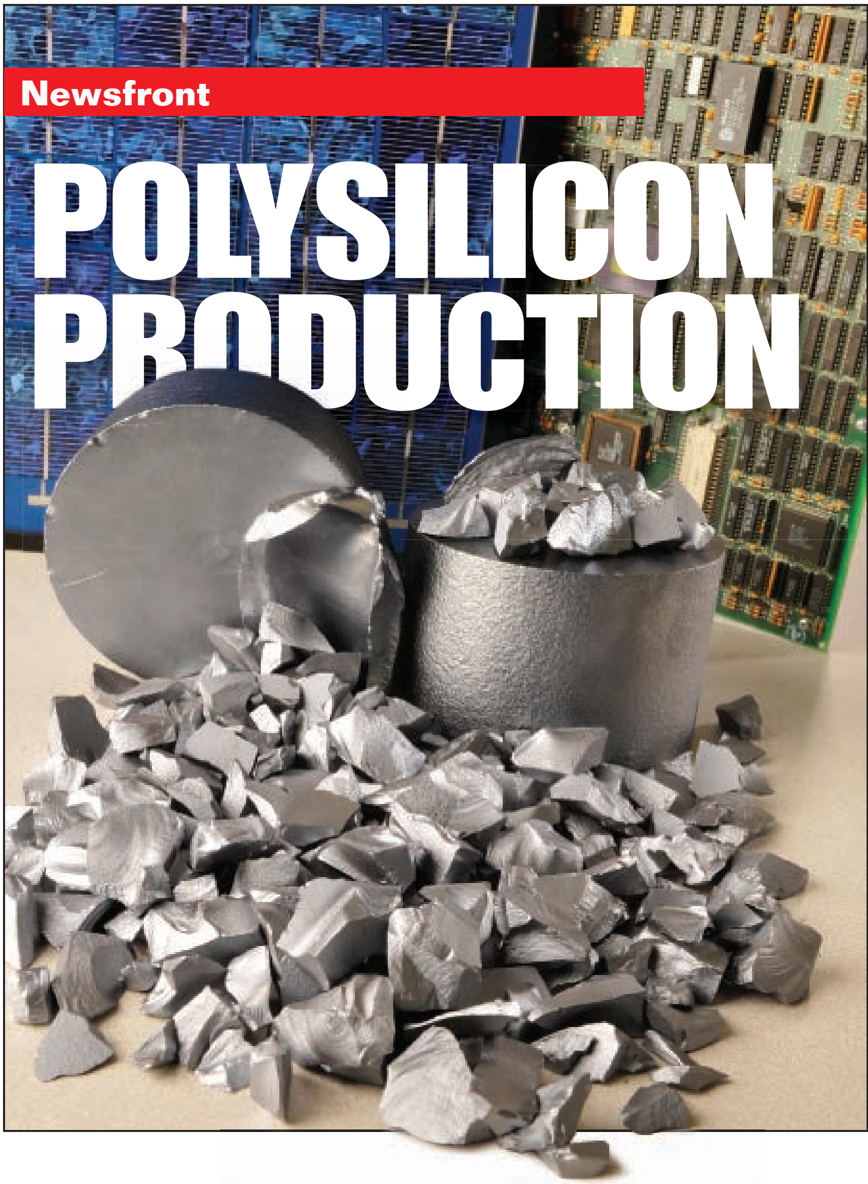
Monitoring gas bottles

Airgas Inc. (Radnor, Pa.; www.airgas.com) plans to market a wireless gas-cylinder monitoring system of Cypress Semiconductor Corp. (San Jose, Calif.; www.cypress.com). The system includes a Wireless Gauge Reader that clamps onto existing gas regulators, and wirelessly transmits pressure readings. The system collects gage data and enables consumption trending and analysis, historical tracking, excursion alarming and notification via e-mail or text messages.

The patent-pending technology can reduce the automation costs by 80% when compared with conventional approaches, which typically involve gas-cabinet or instrumentation upgrades. The system has a proven payback period of less than 18 months, says Cypress. ❏

Newsfront

POLYSILICON PRODUCTION



Hemlock Semiconductor

Facing over-capacity, polysilicon makers pursue opportunities in a solar-dominated future

FIGURE 1. Polycrystalline silicon producers, such as Hemlock Semiconductor Corp., are adapting to increasing demand from the market for photovoltaic cells. Polysilicon used in solar cells is expected to dwarf that used in electronics soon

A rapid and ongoing expansion of polysilicon production capacity will likely generate an oversupply for the next several years, driving polysilicon manufacturers to further innovate processes and reduce operating costs in preparation for an impending wave of new demand. Drastic price drops experienced in 2009 are expected to continue at a slower pace in 2010, yet polysilicon producers remain poised to supply high-purity product to a market increasingly dominated by solar photovoltaic (PV) cells.

By all estimates, demand for silicon for the solar-PV market has shot upward over the last decade. In 2000, demand for silicon for solar energy use was around 3,800 metric tons (m.t.), a total that grew to 42,000 m.t. in 2008. Forecasts put the number well above 100,000 m.t. by 2014. Analysts expect that while the semiconductor industry should grow at around 5–9%/yr over the next several years, growth in the solar market could exceed 40%/yr for multiple years, although the exact trajectory is uncertain.

For the time being, though, recent production-capacity increases appear to have overshot demand. Industry analyst Richard Winegarner of Sage Concepts Inc. (Healdsburg, Calif.; www.sageconceptsonline.com) is among those who think the capacity expansion, combined with the entry of new companies into the silicon production industry to serve the growing solar-PV market, will give rise to an over-capacity for silicon at least for the next several years.

Silicon expansion projects

The capacity increases include major players in the polysilicon production area, along with some smaller companies. Among the announcements was a 2009 expansion by leading silicon producer Hemlock Semiconductor Corp. (Hemlock, Mich.; www.hscpoly.com). The company began operations of a $1-billion, two-phase expansion at its Hemlock, Mich. headquarters that raised its capacity to around 36,000 m.t./yr Meanwhile, Hemlock is constructing a new polysilicon facility in Tennessee. Hemlock sales and marketing vice president Jim Stutelberg reports that construction is progressing on schedule for production to begin in 2012. Paralleling Hemlock's activities has been German specialty chemicals firm Wacker Chemie AG (Munich, Germany; www.wacker.com). Wacker also plans to open a polysilicon production site in Tennessee in a few years. Last year, Norwegian company Renewable Energy Corp. ASA (REC; Sandvika, Norway; www.recgroup) began operating a newly expanded polysilicon plant in Moses Lake, Wash., and Chinese solar wafer company LDK Solar (Xinyu City, China, www.ldksolar.com) began operating a 15,000 m.t./yr polysilicon plant in Xinyu.

Along with growing demand, tax credits have helped spur expansion of production capacity. In January, the U.S. government handed out $1.0 billion in tax credits to the solar industry for job creation investments. Hemlock and its majority owner, Dow Chemical Co. (Midland, Mich.; www.dow.com), received a total of $169 million in tax credits for expansion projects, while Germany's Wacker received $128.4 million for its new production facility in Tennessee. The U.S. arm of REC received tax credits worth $155 million for its recent expansion project at Moses Lake. Meanwhile, engineering companies such as Fluor Corp. (Irving, Tex., www.fluor.com) are having success constructing polysilicon sites. Fluor was involved with the construction of the facilities for LDK Solar, REC Group and others.

Price drops, but a sunny future

The fast-changing solar energy industry and the equally fast production ramp-up has impacted prices significantly. Prices for purified silicon rose sharply in 2007 and 2008 due to a shortage of the material — in 2008, prices for polysilicon peaked above $400/kg. Prices plummeted throughout 2009, however, falling to about $50–55/kg on average by year's end. Prices are expected to continue to drop over the next three years, although not as precipitously as in 2009. By 2012, some industry watchers think prices could hover around $40/kg.

Although the expansion in production capacity likely means a silicon oversupply for the next few years, the situation may change after that if solar-PV succeeds in establishing itself as an economically viable alternative to conventionally derived energy. Hemlock is among those taking the long-view regarding the capacity increases. Hemlock's Stutelberg views the growing capacity as essential to move solar energy toward "grid parity." Depending on a host of factors, grid parity for solar energy could be reached at electricity production costs of around $0.15/kWh.

There appears little doubt that polysilicon production will be dominated by the solar PV market in years to come. While the need for high-purity silicon in its traditional market — the semiconductor industry — remains, most silicon produced today is destined for the solar photovoltaic (PV) market. By 2008, the size of the market for silicon for the solar energy industry had overtaken that of the electronics industry. Industry analyst Winegarner estimates that, in 2010, 70% of the purified polysilicon produced will enter the solar market, versus 30% for semiconductors. The balance is likely to move to 90:10% in favor of solar in the next few years, he says.

Silicon production processes

To meet the needs of a solar-dominated future, high-purity silicon companies are exploring process improvements mainly for two chemical vapor deposition (CVD) approaches — an established production approach known as the Siemens process, and a manufacturing scheme based on fluidized bed (FB) reactors. It appears likely that improved versions of the two types of processes will be the workhorses of the polysilicon production industry for the near future.

Siemens process — The Siemens reactor was developed in the late 1950s and has been the dominant production route historically. In 2009, about 80% of the total polysilicon manufactured was made through a Siemens-type process. The Siemens approach involves deposition of silicon from a

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REC Group ASA

FIGURE 2. Polysilicon production capacity is in the midst of rapid expansion. An example is REC Silicon's facility in Moses Lake, Wash.

mixture of purified trichlorosilane or silane gas, plus excess hydrogen, onto hairpin-shaped filaments of high-purity polysilicon crystals. Silicon growth occurs inside an insulated "bell jar," which contains the gases. The filaments, which are assembled as electric circuits in series, are heated to the vapor deposition temperature by an external direct current. As the gases enters the bell jar, the high temperature (1,100–1,175 ºC) on the surface of the silicon seed filaments, with the help of the hydrogen, causes trichlorosilane to reduce to elemental silicon and deposit as a thin-layer film onto the hot seed filaments. HCl is formed as a by-product.

Temperature control is critical to the process — the temperature of the gas and filaments must be high enough for silicon from the gas to deposit onto the solid surface of the filament, but the temperature cannot be so high that the filament starts to melt. Further, the deposition rate must not be too rapid, or the silicon will not deposit in a uniform, polycrystalline manner, rendering the material of little use for semiconductor and solar applications.

Hemlock Semiconductor has a highly proprietary Siemens-type process that is capable of producing silicon of "11-nines" purity for the semiconductor industry and "9-nines" purity for the solar-PV market (see sidebar, p. 25). Hemlock is working hard to develop "a portfolio of innovations" on the process, Stutelberg says.

Fluidized bed process — Several companies are developing polysilicon production processes based on fluidized bed (FB) reactors. The FB approach to polysilicon production has its origins in a 1980s-era program sponsored by the U.S. Department of Energy whose goal was to devise less energy-intensive methods for making silicon. FB approaches to polysilicon production offer the ability for continuous production, as opposed to the batch production of the Siemens route. In addition, FB polysilicon reactors consume less energy. REC Solar, for example, says their fluidized-bed polysilicon process consumes only around 10% of the energy required to run a Siemens-type process.

In an FB process, tetrahydrosilane or trichlorosilane and hydrogen gases are continuously introduced to the bottom of the reactor at moderately elevated temperatures and pressures. High-purity silicon particles are inserted from the top and are suspended by the upward flow of gases. When the reactor operates at high temperatures (750 ºC), the silane gas reduces to elemental silicon, which deposits on the surface of the seed particles. As the seed crystals grow, they fall to the bottom of the reactor, where they are removed continuously. To compensate for the removal of silicon granules, fresh seed crystals are injected into the top of the reactor.

MEMC Electronic Materials (St. Peters, Mo.; www.memc.com), a silicon wafer manufacturer, has been producing granular silicon from silane feedstock using a fluidized bed approach for over a decade. Several new facilities will also feature variations of the FB. Wacker Chemie is expected to announce the operation of a fluidized bed reactor facility using trichlorosilane as the working fluid in mid-2010. The plant, located in Burghausen, Germany, is designed specifically to make solar-PV material. Several major players in the polysilicon space, including Wacker and Hemlock, are developing FB processes, while at the same time continuing to produce silicon using the Siemens process as well.

New feedstock for FB process

A development-stage company called Peak Sun Silicon Corp. (Albany, Ore., www.peaksun.com) is working on an FB process using tribromosilane (TBS) as the feedstock, rather than either silane, or trichlorosilane. While TBS costs more than its bretheren, Peak Sun's process uses less, so the feedstock costs are even. The inclusion of massive bro-

POLYSILICON PURITY COULD ELEVATE PHOTOVOLTAICS

Metallurgical-grade silicon, produced from sand, is about 99% pure. According to generally accepted guidelines regarding silicon purity, electronic grade material suitable for the semiconductor industry requires at least 99.9999999% pure material (known as "9-nines" purity), which translates to impurity concentrations of 0.0005 ppm. Polysilicon producers of electronic grade material routinely achieve 11-nines purity. At present, the purity requirement for the solar-PV market is somewhat less stringent. The prevailing opinion is that silicon with a purity of 99.9999% (6-nines) is the lower limit for a viable solar cell. Research in the area suggests, however, that the efficiency with which solar cells convert sunlight into electricity is correlated with material purity.

"We see more and more crystalline photovoltaics companies pushing for higher-quality material," says Hemlock Semiconductor group vice president Jim Stutelberg notes. Substantial R&D throughout the solar industry will validate the correlation between polysilicon purity and PV cell performance, Stutelberg remarks.

The purity-performance correlation may not be the only driver toward higher-purity material. In the face of silicon oversupply, prices are expected to fall throughout 2010 and the following two years to around $40/kg. One effect the price drop may have is to make lower-purity versions of the material obsolete. Companies may opt for the highest-purity material possible if prices are comparable, Sage Concepts' Winegarner suggests. ❑

mine atoms in the feedstock compound offers several key advantages.

"Using tribromosilane in the process allows different operating parameters," says Scott Schumacher, vice president of sales and marketing at Peak Sun. "We have a much wider tolerance of temperatures and pressures" than the tight control that must be exerted in other processes, says Schumacher. TBS processes also operate at lower temperatures, which enables energy savings.

The TBS-FB approach also helps avoid formation of submicron-diameter amorphous silicon dust through a homogeneous nucleation route, a significant challenge encountered by silicon reactor operations that use silane or trichlorosilane as the feed gas.

Homogeneous nucleation can occur when materials move from vapor to solid phase and reach a "critical nucleus" of solid-phase material. At certain values of "n" atoms, the thermodynamics of the system favors self-nucleation, rather than deposition on the surface of a seed particle. The phase-change energy barrier is overcome more readily at higher values of n, since surface area-to-volume ratio decreases as particle diameter increases. Silane and trichlorosilane have a natural propensity for self-nucleation when overcoming the phase-change energy barrier. By virtue of its relatively large molecular size, TBS requires a greater n value to achieve critical nucleus, and molecules perfer to transition to solid phase by nucleating on an existing silicon surface. The result is that TBS deposition favors growth on the surface of crystalline seed particles over formation of low-value amorphous silicon dust.

When completed, the Peak Sun project will be the first demonstration of a FB silicon unit using TBS. Peak Sun claims that its process will have lower capital costs and 25% lower operating costs than a Siemens process unit.

Other advantages to the Peak Sun TBS-FB process include the formation of dense metallic beads with a narrow particle size distribution. Silicon beads formed by the TBS-FB process tend to have less surface oxidation and less gas molecule inclusions, which gives the silicon better melt properties.

Crystallization technologies

Another key process in the manufacture of high-purity silicon involves a recrystallization step that converts polycrystalline material to monocrystalline silicon. The process is more important at present for semiconductor-grade silicon, since polycrystalline silicon is suitable for PV cells.

Manufacturers typically use some variation of the so-called Czochralski process, in which a seed crystal is introduced to a silicon melt and slowly withdrawn to generate a long mass of monocrystalline silicon.

An alternative is a float-zone process, in which impurities are segregated during a transition that occurs as a mass of polysilicon passes through a radio-frequency heating coil, which creates a localized molten zone from which the pure crystal grows.

UMG may be on the outs

One technology approach to polysilicon production that appears to be waning is upgraded metallurgical grade (UMG) silicon. UMG is produced by melting metallurgical grade silicon and slowly and directionally recrystallizing it. The approach would offer a less expensive route to material, but the 5-nines or 6-nines purity UMG can achieve wouldn't be viable in an environment where higher-purity methods are cost-competitive. For example, metals firm Timminco Ltd. (Toronto, Canada, www.timminco.com) reportedly suspended its UMG-silicon operations in March as a result of low prices and lack of demand for UMG material for solar cells.

Stutelberg explains that the solar industry as a whole seems to be gravitating toward higher purity silicon. "Next-generation solar components may demand higher levels of purity" than UMG can offer, he says. ■

Scott Jenkins

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Newsfront

THE ROAD TO RECOVERY

EPCs sense a slight uptick in activity due to interest in biomass and renewables projects, as well as revamp projects in sectors that are still thriving

FIGURE 1. Fluor is providing EPC services in China for LDK Solar, whose world-class polysilicon facility is expected to produce 15,000 metric tons of polysilicon annually (for more on polysilicon, see story on pp. 21–26)

Like most other businesses, engineering, procurement and construction (EPC) firms have felt the pinch of the economic downturn. While EPCs that specialize in building processing plants are optimistic that recent global interest in renewable and bioprocessing projects to create alternative fuels, power and chemicals may fill some of the void, most say they will continue to pursue work in markets where they are already established for a variety of reasons. Among the concerns are the high-risk profiles and technical challenges associated with biomass and renewable projects and the continued need for other types of processing and power facilities.

"EPCs obviously have to push forward in renewable and other emerging fields, but also keep a focus on conventional industries," says John Derbyshire, senior vice president of technology with KBR (Houston) who says his firm is tentatively looking at increased interest in renewables as a new source of business while continuing its work in "bottom of the barrel" upgrading for its refinery customers because conventional technologies will continue to dominate the world energy map. "If you look at the percentage of contribution for renewable forms of energy over the next 10 to 20 years, it is only a couple percent, even in the best outlook, of our total energy needs," says Derbyshire.

Rob Smith, senior vice president of the energy division with CH2M Hill, Inc. (Englewood, Colo.) agrees that renewables and bioprocessing are not replacement areas. "However, it is an area of science that is opening up and creating some new opportunities for us on top of our traditional business," he says.

Opportunity in new fields?

However, the question remains whether more EPC opportunities will arise as awareness in this new sector gains momentum around the world with interest especially strong in the U.S. and Europe, where environmental issues are the driving force, and in areas such as China and the Middle East, where biomass and renewables are viewed as potential power sources.

EPCs say they are fielding more questions than ever about making products such as plastics, polymers, synthetic fibers, biofuels and chemical intermediates from a multitude of bio-based sources. There's also much interest in power projects using biomass or ones that use biomass in conjunction with renewable sources such as wind or solar power.

Although the rising cost of energy as well as environmental interest have been the driving source of current projects, the market is still not as strong as EPCs had hoped. "There have been some government stimulus packages that have helped companies get projects into the pipeline and increased the amount of companies moving along with these projects from a handful about three years ago to maybe 50 currently," says Smith. However, he quickly adds that there have been "mixed signals" due to the recession, financial difficulties obtaining funding and indecision in government policy, all of which have created uncertainty for the project flow that was ex-

pected in the areas of renewables and bioprocessing.

"What we see is a 'say-do' ratio that is pretty low in these areas right now," says Derbyshire. By that he means that throughout the Middle East, China, Europe and the U.S., EPCs are hearing about a lot of planned projects, but many developers and companies are still seeking finance or waiting to find out what requirements new government mandates will bring forth before actually moving forward.

"EPCs have to look for the right combination of technology, local conditions such as availability of feedstocks, and local economic conditions to make a project viable," says Derbyshire.

EPCs everywhere agree that the current economic climate is one of the greatest challenges to moving these projects beyond the planning stage. A lot of developers in the marketplace have an idea for a laboratory-scale technology that they would like to ramp up, but funding is a key aspect of a project's success, says Warren Kennedy, vice president of sales and marketing with Burns & McDonnell (Kansas City, Mo.). The U.S. Dept. of Energy (DOE; Washington, D.C.; www.energy.gov) has freed up some money to support kick starting projects such as these, but capital is still tight. "From an EPC perspective, most of these developers don't have much in the way of balance sheets, so they are looking for the EPC to take an equity or cost risk position in the project," notes Kennedy. "When you're used to working with a large integrated petroleum-oil or chemical company, that is a significant risk structure."

Many EPCs agree, saying that even if the technology is proven, the plants are expensive to build and the product may not be cost competitive with traditional fuels, power or chemicals. And while the government may make subsidies available for the first few years, there are no guarantees that they will continue to provide funding or legislation for future subsidies.

"As EPCs get into detailed engineering and buying of equipment, we have to make sure there's sufficient funding to go through those stages of a project. We can't afford to put ourselves out in front of the client to do that," explains Bill Wingate, vice president, marketing and business development with SNC-Lavalin Engineers and Constructors (Houston). "Assurance of payment is critical, particularly where a new company without much of a track record is involved." He adds that his firm, like other EPCs, is watching its risk profile carefully.


CH2M Hill

FIGURE 2. CH2M Hill is providing EPC services at the Mitsubishi polysilicon plant in Alabama

And, for the projects that secure enough funding to move along, finding the right technology and staffing mix can be an added hurdle. Though most bio-based projects employ chemical engineering units and material handling operations familiar to EPC staffs and the design aspects are transferable from other projects in their repertoires, the challenge here lies in staying current with the latest technology developments.

"We need to determine which of the multiple technologies out there are proven and which can be scaled up to a viable commercial level," says Jim Davis, senior director midstream services with SNC-Lavalin. "A lot of the available technologies look fantastic in the laboratory or demonstration plant making 1–2 gal/d, but when you scale up to 10,000 or 20,000 gal/d, there's bound to be unique challenges."

He says the engineers at SNC-Lavalin spend a lot of time trying to figure out which viable technology will best satisfy the owner's requirements and minimize the impact of scaleup, complexity, cost, operating problems, insufficient yields or energy inefficiencies.

The other side of the equation is finding the appropriate mix of staff for new project categories. Because there are enough skilled process and mechanical engineers available and the technology is not that different from what's already in existence within the refining and chemical industries, there won't need to be a massive retraining of people, explains Davis. "I liken it to a pilot that's flying a two-engine propeller plane learning to pilot a two-engine jet," he says. "He needs some retraining, but he already knows how to fly."

Instead, what is needed for many biomass and renewable projects is a "re-bundling" of skilled engineers. In many cases there are engineers from a variety of departments working together who may have never done so before. In the past EPCs might have had one group of engineers who worked on technologies related to greenhouse gas reduction, another group familiar with energy conservation, another that looks at waste minimization, as well as process engineers who specialize in chemical production. With these new projects, EPCs have to tie these component pieces together in a different way so they can respond to clients interested in renewables and bioprocesses in a more holistic fashion.

"That's a change for us in that before, each of these groups didn't usually work on the same project team for the same client to solve the same problem," notes Smith. "Today we see more merging of complex issues as clients look for a strategy to deal with a variety of issues in a holistic way."

As an example, Smith points to the possibility of a developer looking to grow food in the Middle East. "He may be looking at a solar-powered desalination facility that can be used to grow food in an geography that historically has never done this," he says. "In the old days, they would need one company that specializes in desalination, another in solar and one in agriculture. Now they are looking for one company that can solve all their problems, so we have to start taking experts from different divisions and bundling them together to solve a variety of problems on one job."

Slow but steady

Because of the many variables related to renewable and biomass projects, EPCs say that while they are pursuing projects in these new categories, they are reluctant to ignore projects in traditional industry, which is just beginning to show signs of a slow rebound in certain markets.

"We see clients on the fringe of rethinking their spending plans and looking at projects that will obtain the best ROI," says Smith. "We are seeing a slight rebound in proposal activity that will hopefully lead to more work in the coming months."

Some of the areas seeing a bit of activity include pharmaceutical revamps in the U.S. and Europe, petrochemical project prospects in the Middle East and China and projects that will boost energy efficiency and reduce processing costs all around the globe.

Jeff Rozelle, associate, biotech core team leader with Clark, Richardson & Biskup Consulting Engineering (CRB) (Kansas City, Mo.), which does about 85% of its business in life sciences, says vaccine processing is in the midst of an upswing as it's been bolstered by H1N1 and other targeted infectious diseases and that biogenerics are becoming an emerging industry as consumers are looking to reduce their pharmaceutical costs.

Many of the projects in the life sciences are retrofits and facility modifications/modernizations, which can be a challenge for EPCs as there are strict controls in place to protect products, as well as personnel. "It's critical to the success of the project to make sure there is limited downtime and that the plants are back up and operating safely and effectively according to schedule," notes Rozelle.

Globalization is another issue in these retrofit projects. "In the past when we designed a facility, we designed for the U.S. market and its regulations, but now during a retrofit our clients want it designed so the products will be in compliance with other regulating bodies as well," says Rozelle.

Because of the multitude of compliance issues, as well as patent expiration issues and frequently changing pipelines, flexibility must also be designed into new and existing life science facilities. "New technologies such as disposables have helped us find a way to provide the additional flexibility in a process or building while staying within the current budget constraints," he adds. (For more on disposable equipment, see: *CE*, March, pp. 21–24)

In the Middle East and China there has been more petrochemical project discussion than there was just 6 to 12 months ago, says Ivor Harrington, senior vice president with Fluor Corp. (Irving, Tex.). "Right now we see a lot of feasibility studies in major petrochemical facilities in China and the Middle East, which we see coming into the EPC phase in the latter part of 2011," notes Harrington. He says that due to the geography of this activity, Fluor has been ramping up its global procurement capabilities for these areas, meaning that the firm has invested in key suppliers to gain access

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to materials in an effort to reduce the timeline and cost of these projects for its foreign clients.

And everyone, everywhere seems interested in projects that will help lower the cost of their goods, which often includes energy efficiency projects. The need is especially prominent in food processing and life sciences. For this reason, CRB has developed a process called "Future Facility," which employs a mindset intent on closing processes, shrinking the size of facilities, planning for flexibility and reducing energy. "If you can reduce the size of a facility and reduce energy use, you ultimately reduce the cost of goods, thereby allowing your client to be more competitive," notes Rozelle. Examples of Future Facility planning includes rethinking cleanrooms, which normally require a lot of energy use due to the air handling, heating and cooling requirements. But, if you can provide better control over processing systems through employment of closed operations and ultimately reduce the cleanroom space, opportunities to reduce capital and operating expenses can be realized.

Similarly in the food and consumer good industries, which have weathered the economic storm better than most, there is interest in reducing product price per unit through energy efficiency and sustainability projects. As a result, EPCs like Burns & McDonnell, find themselves developing sustainability plans, working on projects to reduce carbon footprint and to use green energy where it makes sense to reduce the cost of production for clients in these markets.

While projects are currently few and far between compared to just a few years ago, EPCs remain hopeful that bioprocess and renewable projects will create a new market that will compliment and bolster their existing areas of expertise. And in the meantime, they are honing their knowledge so that it may be applied to both traditional and new project categories in the best possible way. "In all cases, we have to be aware of how to use technology to bring costs down and satisfy government regulations around the world," says KBR's Derbyshire. "We must lead with technology, but all the while we must make sure we aren't trying to force technology where it flat out doesn't fit." ■

Joy LePree

INTERNATIONAL Powder & Bulk Solids 35TH ANNIVERSARY


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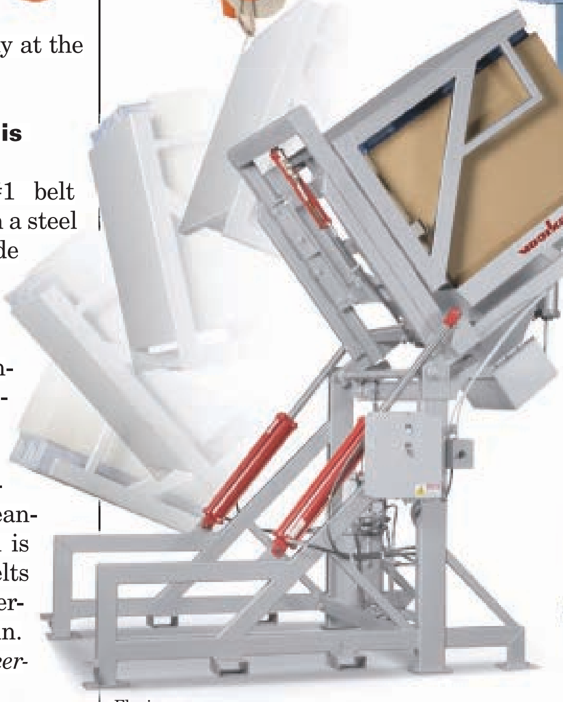
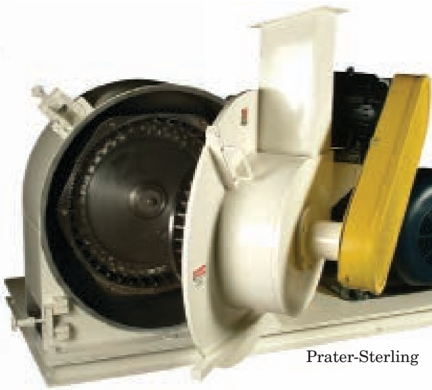

Flexicon


Prater-Sterling

The International Powder and Bulk Solids / Process Technology for Industry International (PTXi) 2010 conference and tradeshow will be held May 4–6, 2010 at the Donald Stephens Convention Center in Rosemont, Ill. The event will showcase products from more than 300 exhibitors and will offer educational seminars covering a wide range of solids-processing topics. Attendees at the show are invited to visit *Chemical Engineering* staff at Booth 2819. Among the products and services on display at the meeting are the following:

Minimize downtime with this conveyor-belt cleaner

The Performance Duty QC#1 belt cleaner (photo) is designed with a steel rib that allows "one-pin" blade replacement to minimize labor and downtime. The cleaner features a steel mainframe, a low-maintenance spring tensioner and a high-volume urethane blade that contains 20% more urethane than competing blades. The extra material extends life while maintaining cleaning performance. The PDQC#1 is suited for applications on belts from 18 to 72 in. wide and operating speeds of up to 900 ft/min. Booth 2245 — *Martin Engineering Co.; Neponset, Ill.*
www.martin-eng.com

Use these cartridge filters in process temperatures up to 5,000 °F

High-efficiency pleated cartridge filters from this company (photo) can be used for industrial air filtration baghouses with process temperatures up to 5,000 °F. The filters are said to increase system throughput by up to 25% compared to alternative filters of similar diameter. The filters feature membranes made of expanded polytetrafluoroethylene (ePTFE) and construction using a new potting technology based on molten aluminum. The membrane material is designed to increase filtration efficiency, provide better product capture and lower emissions. Booth 1400 — *W. L. Gore & Associates Inc., Newark, Del.*
www.wlgore.com

This box dumper creates a dust-tight seal

The Tip-Tite box dumper (photo) creates a dust-tight seal between boxes and the containment hood. The device can pivot the container to 45, 60 or 90 deg beyond horizontal, and can discharge bulk material through a chute at controlled rates. Boxes of size 36–48 in. on a side and 39–44 in. high can be

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

Kice Industries

Admix

Magnetic Products

accomodated. Booth 1005 — *Flexicon Corp., Bethlehem, Pa.*
www.flexicon.com

A bag packer for high fill-accuracy applications

The MT Series valve bag packers (photo, p. 32D-1) are said to be ideal for low-capacity applications requiring an extremely high degree of fill accuracy. The packers feature a three-stage filling cycle, and can deliver ±1-2 oz per bag at rates up to 200 bags per hour. MT packers are suited to bags of weight 20–110 lb, and are combined with one of six possible product dosing systems. Booth 2821 — *Cordano Packaging Engineers LLC, Cumming, Ga.*
www.cordanopackaging.com

Double inline powder delivery with this feed system

A new model in the Fastfeed powder induction and dispersion product line (photo) is designed to double inline powder delivery capabilities, offering controlled feedrates from 3–400 lb/min. The new Fastfeed model consistently delivers powders into liquid mixtures even as viscosity and solids levels increase. Design features promote fast dispersal, prevent plugging and fouling and provide the shear forces needed for modern ingredients. Fastfeed allows processors to add dry ingredients to mix vessels in an ergonomic fashion, reducing operator injuries. Booth 3035 — *Admix Inc., Manchester, N.H.*
www.admix.com

Combine grinding and air classification with this mill

CLM Series classifier mills (photo, p. 32D-1) combine two-stage, closed-circuit grinding and air classification in one unit. The mill can handle difficult-to-grind products and those requiring a narrow particle size distribution. Oversized particles that fail to meet specifications are rejected by the classifier and directed to a separate part of the grinding rotor, where they are reground and then reclassified. The large access door allows for inspection and cleaning of the main rotor as well as the classifier rotor. Booth 1405 — *Prater-Sterling, Bolingbrook, Ill.*
www.prater-sterling.com

Handle large air volumes with this filter

CR Filters (photo) are designed to handle large volumes of air ranging from 15,000–50,000 ft^3/min. The filter features a pre-separator that can remove 80% of large dust particles prior to entering the bag housing, so the filter bags never come into contact with this material. Also, internal baffles evenly distribute the air and small dust particles throughout the bag chamber, which lengthens filter bag life. Booth 2045 — *Kice Industries Inc., Wichita, Kan.*
www.kice.com

Magnetic separator for metal contaminants in low-density systems

The Round Spout Pneumatic-Line Magnet (RSPLM) magnetic separator (photo) removes inbound tramp-metal contaminants from high-speed material streams in low-density, high-air systems. Typical applications include powder or granular materials being transported in large-diameter lines. Unlike conventional drawer magnets, which are traditionally placed horizontally in gravity-fed flows, the RSPLM is situated vertically. The orientation extends magnet dwell time. The RSPLM also features three internal magnets, rather than one, providing a greater gap space between magnets which allows more product to come into contact with the magnets. Booth 1023 — *Magnetic Products Inc., Highland, Mich.*
www.mpimagnet.com

This solids conveyor system offers enclosed transfer

The "No-Tip Unloader" Vacuum Conveyor (photo, p. 32D-3) offers enclosed and sanitary product transfer. De-

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Show Preview

Volkmann

signed with a smaller footprint, the No-Tip Unloader eliminates material flow issues involved when transferring powders, granules, pellets, tablets and other bulk materials via unloading methods that require tipping of the raw material container. This vacuum transport can supply packaging lines, mixers, filling machines, tablet presses or other process equipment. The system features a unique lifting column that guides the product suction device while initially holding the product repository liner bag in place, and then lifting it to exhaust maximum product in the final suction periods. Booth 2237 — *Volkmann Inc., Hainesport, N.J.*
www.volkmannusa.com

This size reduction system allows high flexibility

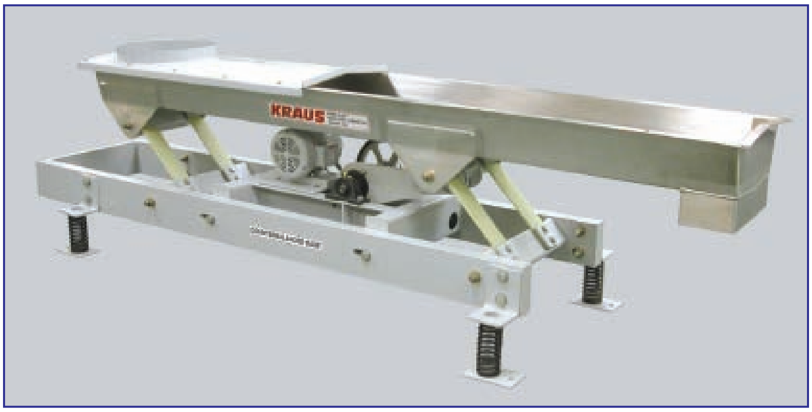
The Universal Mill size reduction system is designed for maximum grinding flexibility and can generate coarse material down to ultrafine particles. It can work with four types of rotors (turbo, pin, disk and cross), and has seven production sizes. With a standard 10-bar design, the equipment meets common standards for explosion pressure containment. It is available in carbon or stainless steel. Booth 1805 — *Bauermeister Inc., Memphis, Tenn.*
www.bauermeisterusa.com

Use this conveyor for feeding lighter density bulk materials

Specially designed to isolate the counter-

Posi-flate

Dynamic Air



acting forces produced in a conventional vibratory conveyor, the Stedi-Flex vibratory conveyor (photo) is said to be ideal for feeding lighter density bulk materials. The low-cost Stedi-Flex conveyor features a simple design and construction. The company is also displaying an air-operated vibratory feeder. Booth 1304 — *Dynamic Air Inc., St. Paul, Minn.*
www.dynamicair.com

These butterfly valves are designed for severe applications

Series 585 (photo) and 586 are new heavy-duty, inflatable seated butterfly valves that are designed for the most severe applications, including high operating temperatures and pressures. The company is also introducing the VMAX linear air-operated vibrator, which is designed for low noise and high force output. Booth 1012 — *Posi-flate, St. Paul, Minn.*
www.posiflate.com

Minimize downtime with this powder flow tester

This instrument, designed to deliver quick and easy analysis of power flow behavior, is ideal for manufacturers seeking to eliminate the downtime

and expense that occur when hoppers and silos fail to discharge. Users can perform quality control checks on incoming materials, quickly characterize new formulations and adjust composition to match the flow behavior of established products. The flow tester features options such as flow function, time consolidation, wall friction and bulk density. Booth 2644 — *Brookfield Engineering Laboratories Inc., Middleboro, Mass.*
www.brookfieldengineering.com

A dryer that can be used in mercury recovery

The Turbo Heat Treater has a proprietary, continuous-tray-dryer design (photo) that consists of a stack of rotating cicular trays in a sealed enclosure. Material to be dried is fed onto the top tray and is wiped onto successive lower trays after each revolution. Internal turbo-fans circulate heated gas in the enclosure to provide the drying medium. The Turbo Heat Treater is the the first thermal processor to be used commercially in a patented mercury recovery process. Mercury is recovered from powdered activated carbon used to remove mercury from flue gas. Booth 1000 — *Wyssmont Co. Inc., Fort Lee, N.J.*
www.wyssmont.com

Wyssmont

Reduce energy costs with this pneumatic conveyor

The MiniVac pneumatic conveying system (photo, p. 32D-7) has an integral regenerative blower that is said to reduce energy costs by up to 30%, as well as eliminate the need for plant air supply. The equipment features side-door access for filter changes and cleaning that does not require tools. The company also offers flexible screw and tubular drag conveyors, as well as a range of products for bulk solid conveying. Booth 3553 — *Hapman, Kalamazoo, Mich.*
www.hapman.com

Bottle labels can be inspected from any angle

The CI Vision bottle inspection system

Hapman

allows bottle labels to be inspected from any angle, eliminating the need to orient the product.The 360-deg, full-view bottle inspection system produces a seamless and complete image of full or empty bottles of plastic or glass in various sizes up to 1.5 L at line speeds of up to 400 bottles per min. This company is also showcasing a new serialization solution for pharmaceuticals, as well as a metal detector for inspecting tablets and capsules. Booth 2673 — *Mettler-Toledo, Solon, Ohio*
www.mt.com

A filler that combines high output rate with weighing accuracy
The model 4192 Twin Auger open-mouth bag filler is designed to provide high output rates while maintaining effective product control and weighing accuracy. It can achieve filling rates of 7–10 50-lb bags per minute and accuracies of ±0.2 lb from the target weight. The 4192 can handle a wide range of materials from fine and aerated powders to sticky, hard-to-feed solids. The filler offers the ability to execute dribble or bulk feeds through PLC and VFD control of the augers. Booth 1636 — *Chantland MHS, Humboldt, Iowa,*
www.chantland.com

An initiative to supply sustainable filter technology
This manufacturer has established a sustainability initiative to help customers implement their own sustainability program. The company's environmental engineers will provide technical expertise and innovative filter technology to its customers to redesign production processes. The campaign is designed to increase participation in sustainable practices, and to raise money for nonprofit organizations that fight climate change. Booth 1038 — *Midwesco Filter Resources Inc., Winchester, Va.*
www.midwescofilter.com

Manage multiple-cell scales with this fast weighing system
The iQUBE2 is said to be the fastest available commercial equipment for managing multiple-cell weighscale systems, boasting the ability to update up to 500 times per second. The iQUBE2 is billed as an intelligent digital junction box that can be used to help ensure accuracy and reproducibility, monitor drift, test for linearity and identify noise. A key component is a load-cell emulation feature that allows the iQUBE2 to calculate accurate weights in the event of a malfunctioning cell. Calculations are based on comparisons to functioning cells, making it suitable for "mission-critical" applications. Booth 2629 — *Rice Lake Weighing Systems, Rice Lake, Wisc.*
www.ricelake.com

5X faster blending with this alternative to ribbon mixer
The OptimaBlend fluidizing paddle blender (photo, p. 32D-8) offers mixing five times faster than ribbon blenders. The blender is designed to balance mixing speed and efficiency with low equipment cost and consumed power. The blender is suitable for traditional ribbon blender applications and can handle diverse ingredients with high efficiency. Units are available in carbon steel, stainless steel and sanitary construction for a wide variety of solids to solid and solids-to-liquid blending applications. Booth 3541 — *American Process Systems, Gurnee, Ill.*
www.apsmixers.com

American Process System

Eurus Blowers

Mesh laminates that optimize stability, flow and filtration

This line of multi-layer woven wire-mesh laminates is designed to achieve an optimum combination of stability, fine filtration capabilties, flowrate and backwash properties. The mesh laminates are diffusion-bonded and sintered, and are appropriate for chromotography bed supports as well as other applications, such as aeration beds, air-gravity conveyors and more. They are available in square sheets of 48 in. per side. Booth 2010 — *G. Bopp USA Inc., Wappingers Falls, N.Y.*
www.bopp.com

Combustible dust hazard training is online

These online training modules are designed to train employees on important concepts in identification and remediation of situations involving combustible dust clouds in process vessels, dust collectors and powder transfer equipment, as well as possible ignition sources, such as electrical sparks, static electricity and friction. The online training system automatically tracks employees' progress and quiz scores. Booth 2531 — *Chilworth Global Online Training, Plainsboro, N.J.*
www.chilworth.com

Accomplish test sieving in less time with this analyzer

The CPA 2-1 photo-optical particle size and shape analyzer is designed for laboratory use, measuring dry, free-flowing, non-agglomerating particles. The CPA 2-1 performs an analysis in an average of 3–5 min, compared to 15–20 min on a traditional test sieve and shaker apparatus. The CPA 2-1 is also capable of accurate, realtime counting of individual particles, rather than relying on calculating percentages of a representative sample. Its accompanying software correlates raw particle count data with the sieving distribution curve. Booth 4034 — *W.S. Tyler, St. Catharines, Ontario, Canada*
www.wstyler.com

These feeders are approved for hazardous environments

This line of small vibratory feeders feature a unique electromagnetic drive circuit that is approved for Class II, division I, groups F and G hazardous environments. They also are designed for tool-less removal of covers and screen inserts for trays. Other feeders are available for Class II hazardous environments. Booth 1629 — *Eriez, Erie, Pa.*
www.eriez.com

These blowers have high-efficiency intake filters

Available in bi-lobe and tri-lobe packages, these blowers (photo) are equipped with a high-efficiency integrated intake filter/silencer and feature oversized cylindrical roller bearings, piston-ring air seals, and washable polyurethane filter media. Both the bi-lobe and tri-lobe series are rated for pressures of 15 psig and provide air flows up to 3,950 ft^3/min. Both series have integral-shaft ductile iron impellers and vibration dampeners. Booth 1223 — *Eurus Blowers, Suffolk, Va.*
www.eurusblowers.com

A cleaner that fits most cartridge filters

The Green Filter Cleaning Machine is a standalone cleaner that adjusts to fit most cylindrical cartridge-filter sizes. It cleans by releasing shop air through a rotating air jet that is driven up and down in a spiral motion inside the filter cartridge. The fully automated cleaning cycle lasts for five min. The equipment can accommodate filters with inner diameter sizes from 6–14 in. Booth 3504 — *Diversi-Tech Inc., Lachine, Quebec, Canada*
www.diversitech.ca

Improved pressure and flow from this blower system

The new IQ blower delivers pressures to 15 psig, vacuum to 16 in. Hg and air flows from 200–1,400 ft^3/min. The 50–100 hp blower features a sound-reducing design, digital monitoring, a removable discharge silencer and a variable frequency drive for optimizing efficiency. Booth 1721 — *Gardner Denver Inc., Quincy, Ill.*
www.gardnerdenver.com ■

Scott Jenkins

Retsch

POWTECH 2010

KMPT

Brabender Technologie

Frewitt

Nearly 700 exhibitors and 15,000 visitors are expected to participate in Powtech 2010 — The International Trade Fair for Mechanical Processing Technologies and Instrumentation (Nürnberg, Germany; April 27–29; www.powtech.de). Decision-makers from around the world use this forum to learn the latest innovations in size reduction, milling, screening and mixing. Simultaneously and at the same venue, is TechnoPharm 2010, the International Trade Fair for Life Science Process Technology (www.technopharm.de).

In addition to the exhibition, visitors can also participate in a number of additional activities during the show, including the World Congress on Particle Technology, supported by Partec. Several events related to explosion issues, with updates on current knowledge and source information about innovations in safety and explosion protection will also be offered. These include the seminar "Industrial explosion protection and tests to the German Health & Safety Act — Practical Examples," organized by the VDI Wissenforum (www.vdi.de/explosion), and the Index Safety Congress, which is devoted to industrial explosion protection (www.ind-ex.info). What follows is a selection of some of the products being exhibited at Powtech.

Finding the optimal mill parameters without trial and error

Thanks to the introduction of a new generation of conical sieve mills (photo) and a technical center with an analytical laboratory, this firm has done away with trial-and-error methods for mill optimization. This conventional method has been replaced with statistical design of experiments, which makes it possible to look for patterns in the available data. The results of this analysis have been incorporated into a guideline, which is available for users to meet their product and process specifications as close as possible to the specifications and process variables chosen in the preliminary phase of product development. Hall 9, Stand 320 — *Frewitt S.A., Granges-Paccot, Switzerland*
www.frewitt.com

Bulk metering-and-discharging systems for food products

Along with its comprehensive product line for powder and bulk metering and discharging, this firm will be launching the new gravimetric metering feeders from the company's Food Line (photo). Developed in close cooperation with a leading food company, the new product line comprises hygienic designs of a variety of well-known metering feeders, including the FlexWall Plus Feeder, with its paddle-agitated flexible hopper, loss-in-weight scales with screw feeders, vibrating-tray loss-in-weight feeders and weight-belt feeders. Thanks to this diversity, the Food Line offers suitable metering feeders for virtually all bulk ingredients commonly metered in the food industry. Hall 7, Stand 164 — *Brabender Technologie KG, Duisburg, Germany*
www.brabender-technologie.com

A combined cone and bell dryer for laboratory applications

The new 4-L laboratory-scale Type BD 4-L dryer (photo) extends the existing BD Series, which combines the advantages of a cone dryer and a bell dryer. Suitable for small amounts of product, the 4-L Series can be used for design tests at a user site or in this firm's test center. The dryer features a patented combination of a cone dryer with hemispherical base and an efficient agitator design, which means the drive shaft undergoes small deflection with a close clearance. The removable drive shaft offers a high degree of flexibility by selecting various agitator designs that are customized to the product characteristics. A glass lid allows the course of the process to be monitored. Hall 9, Stand 242 — *KMPT AG, Vierkirchen, Germany*
www.kmpt.com

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

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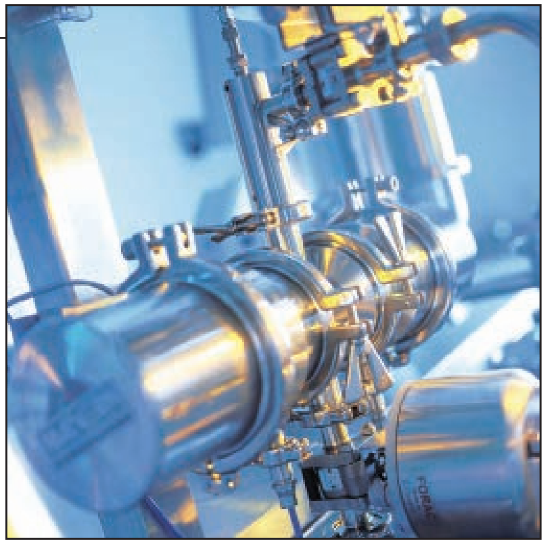
GEA Niro



Malvern Instruments

A new mill for different and difficult tasks

The new SM 300 cutting mill (photo; p, 32I-1) combines powerful size reduction with easy handling. Its variable speed (700 to 3,000 rpm) and very high torque enable the mill to be adapted to many different and difficult tasks, including grinding heterogeneous sample mixtures. The grinding chamber is easy to access for cleaning; its housing is simply folded back and the push-fit rotor removed, without tools. The mill can be equipped with a range of accessories, including a version for heavy-metal-free sample preparation. Hall 7, Stand 340 — *Retsch GmbH, Haan, Germany*
www.retsch.com

Water and organic solvents can be used in this spray dryer

This firm will be exhibiting one of its smallest spray dryers, the SDMicro (photo). This laboratory-scale spray dryer is equipped with a two-fluid nozzle for atomization that can be used for both water- and organic-solvent-based formulations. The system is designed with the smallest possible spray-drying chamber that allows for retaining the same air flow pattern as a large-scale spray dryer. This makes it possible to conduct realistic tests at a very small scale and produce small quantities of powder for product and concept evaluation. Hall 1, Stand 115 — *GEA Niro, Søborg, Denmark*
www.niro.com

A split butterfly valve for contained transfers

The Müller Containment Valve (MCV; photo, p. 32I-4) is a stable and robust split butterfly valve that is also pressure tight, making it suitable for transferring highly potent or toxic substances. The seal around the valve disk has been made very small to reduce costs, and the valve disk can be exchanged in less than 5 min. The MCV is suitable for OEB 4 (OEL 1–10 μm/m^3), is GMP compliant and is available in sizes of DN 100, 160, 200 and 250. The valve is dust and liquid tight at pressures up to 2 barg, with higher pressures possible upon request. Product-contacted components are in AISI 316L stainless steel (or Hastelloy upon request), with a PTFE seal. Hall 9, Stand 316 — *Müller GmbH, Rheinfelden, Germany*
www.mueller-gmbh.com

Haver & Boecker OHG

This particle analyzer delivers data in realtime

Laser-diffraction-based Insitec particle analyzers (photo) are designed specifically for use in the process setting. The realtime data they deliver transform process control and enable manufacturers to operate plants at optimal performance: better capital utilization, lower energy consumption and reduced waste. In cement production, for example, the installation of Insitec systems drives down specific energy consumption and improves product quality and consistency, thereby enabling greater use of cost-efficient, environmentally benign, replacement materials. Hall 9, Stand 306 — *Malvern Instruments Ltd., Malvern, U.K.*
www.malvern.com

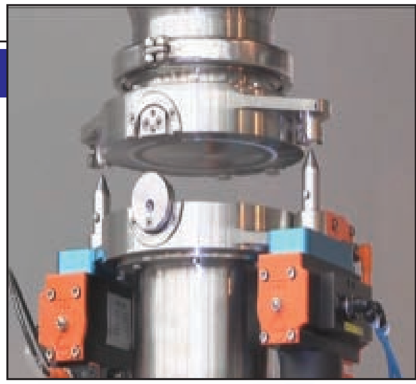
Inline particle analysis, even in hazardous areas

This firm is presenting its latest development, the Inline Particle Probe IPP 70-SLe (photo, p. 32I-4). The probe adds to its Series of ATEX-certified probes, enabling particle measurements in Zone 0 through Zone 20. The new probe is especially suited for applications in mixing and granulation processes in the chemical and pharmaceutical industries. As with all probes in the IPP Series, this latest version covers the measurement range from 50 to 6,000 μm. Hall 7, Stand 551 — *Parsum GmbH, Chemnitz, Germany*
www.parsum.de

Measure particle concentration and size with this analyzer

The new welas digital 2000/3000 light-scattering spectrometer system (photo; p. 32I-8) determines particle concentration and particle size precisely and reliably. For particle size measurement, up to four measurement ranges can be selected from a single device, covering the measurement range from 0.2 to 105 μm. Particle concentration can be measured from less than 1 particle/cm^3 up to 106 particles/cm^3. The sensor operates at temperatures from –90 to 70°C, with options to handle 250°C and pressures to 10 bar. The fiber-optics-based system uses a 35-W Xenarc lamp, incorporates a 20 MHz

Parsum



Müller

Hosokawa Micron

digital processor and a USB interface. — *Palas GmbH, Karlsruhe, Germany*
www.palas.de

This combined classifier and mill is designed to save energy

The Mikro ACM SD air-classifying mill (photo) is said to save not only power, but also costs, space and maintenance. Only one motor is used in combination with a spring-pulley belt drive. The motor shaft drives belt pulleys for both air classifier and mill. The speed of the air classifier is infinitely variable; for the ACM size 40, it is from 820 to 3,500 rpm. In the regenerative operation of the classifier, the energy gained is thus made available for the milling. As a result, electricity consumption, manufacturing costs, and space and maintenance are reduced. Hall 7, Stand 360 — *Hosokawa Micron GmbH, Cologne; a branch of Hosokawa Alpine AG, Augsburg, Germany*
www.hosokawamicron.de

Convert products into dust-free pastilles with this process

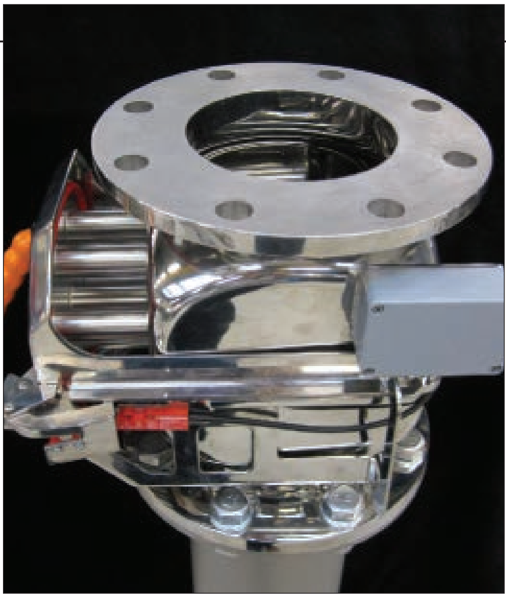
Each of the nine members of the Rotoform family of steel-belt pastillation systems has been designed to meet specific process requirements in the oil, chemical, plastics and food industries. At the heart of the system is a special drop depositor — the Rotoform itself — that feeds droplets of the molten product onto a continuously running steel belt. The product is rapidly solidified as the belt is cooled by water from beneath, then discharged in the form of dry, uniform, free-flowing and dust-free pastilles. The highly flexible process handles molten product at temperatures of up to 320°C and viscosities up to 50,000 cP. Depending on the system used, pastilles can be produced with diameters of 1 to 30 mm. Hall 7, Stand 425 — *Sandvik Process Systems, Div. of Sandvik GmbH, Fellbach, Germany*
www.sandvik.com

The latest developments in particle-size standards

A new silver-coated opaque particle standard covers the size range from 19 to 190 microns. It has been analyzed within the Quality Audit Scheme of independent company LGC Standards, and has produced the best ever repeatabilities seen by laser diffraction analyzers, says the manufacturer. The firm's managing director will be discussing the latest trends in particle size standards during the World Congress on Particle Technology, which takes place alongside Powtech. — *Whitehouse Scientific Ltd., Waverton, U.K.*
www.whitehousescientific.com

Cyclone separation gets even more efficient

Mechanical ReCyclone Systems consist of batteries of Hurricane Cyclones and particle separators (recirculators)



Goudsmit Magnetic Systems

located downstream of the cyclones. The recirculator reintroduces the fine, non-captured particles into the cyclone. The tangential gas stream becomes enriched with particles while the axial gas-stream exhausted to the stack is clean. A ReCyclone MH is said to reduce emissions of a stand-alone Hurricane Cyclone by 40–60%, says the manufacturer. The Hurricane (photo, p. 32I-8) is claimed to be the most efficient cyclone on the market for the same pressure drop. Hall 6, Stand 202 — *Advanced Cyclone Systems, S.A., Porto, Portugal*
www.acsystems.pt

A 'clever' measurement system for bulk solids flow
The C-Lever direct (photo, p. 32I-7) achieves an optimum accuracy in measuring bulk flow — regardless of density, friction, particle type and flowrate. The device has no mechanical parts and offers up to ±0.2% of the volumetric range with a turndown ratio of five-to-one. Bulk materials can be viewed through the unit's window, and an exhaust air-cleaning system can also be retrofitted. The C-Lever direct permits easy cleaning in case of product change, such as color pigments or other problematic materials. Hall 6, Stand 240 — *Rembe GmbH Safety + Control, Brilon, Germany*
www.rembe.de

Standard and customized piping components on display here
This firm will demonstrate the variety and possibilities provided by its easy-to-install, modular pipework system. Serial and connection options for diameters of 60 to 800 mm are available. Additions to the product range on display include two-way distributors, shutoff valves, pipe regulators and gates, and also an innovation regarding system components that are certified shock-explosion-proof to 10 bar overpressure. The complete modular range includes wall thicknesses of 1 to 3 mm, and alternative surface options, including conductive powder coating, galvanized or stainless steel. Hall 6, Stand 222 — *Fr. Jacob Söhne GmbH & Co., Jacob Pipework Systems, Porta Westfalica, Germany*
www.jacob-rohre.de

Save time, space and money with this modular filtration system
ProJet mega is a standardized filtration system based on prefabricated components and modular design for applications with capacities of 2-million m^3/h. The cleaning system is combined with the most modern filtration media and handles filter bags of 8 m and longer. ProJet mega can be adapted to all the local standards, systems and processes, and requires less space for installation. The system is also designed to reduce transportation costs and minimize installation costs. Hall 9, Stand 105 — *Intensiv-Filter GmbH & Co. KG, Velbert-Langenberg, Germany*
www.intensiv-filter.com

Removing iron from powders gets cleaner with these magnets
Both the standard and rotating cleanflow magnets do not include welded seams in the new design, which allows for a very smooth finish and excludes the formation of bacteria. Ra values between 0.05 and 0.3 ensure that even the finest iron dust will be removed from powders. The door construction has also changed to include a quick release between the extractor and magnets, as a result of which the former will always be pulled outwards as well. A new seal makes it possible to work with a high overpressure, which is an important factor for filling pressure-sensitive bags. Hall 9, Stand 322 — *Goudsmit Magnetic Systems B.V., Waalre, the Netherlands*
www.goudsmit-magnetics.nl

Circle 57 on p. 78 or go to adlinks.che.com/29249-57

This conveyor is easy to access and maintain

The ProClean Conveyor permits easier maintenance and filter replacement via its freely accessible cover; there's no need to disassemble connections. For the first time, it is possible for operators to observe the filling level directly through a sight glass in the housing cover. A vacuum/pressure display simplifies parameter settings in order to achieve the desired conveying modes from dilute phase to plug conveying. An additional inlet at the cover permits contamination-free addition of further products via the same connection. Hall 9, Stand 431 — *Hecht Technologie GmbH, Pfaffenhofen, Germany*
www.hecht-anlagenbau.de

This machine puts powder into lots of PE bags

The Integra and Rotoseal packaging systems meet the demands for higher speeds, cleanliness, weighing accuracy, high-level product protection and ease of operation and maintenance. Now it is also possible to fill powder-type chemicals into water-tight polyethylene (PE) bags (photo; p. 32I-2) using the new Adams and Benjamin packaging machines. The Adams is a rotating, high-speed system equipped with eight or ten filling spouts, which allow packaging speeds of up to 1,200 bags/h. The Benjamin has one to four spouts, making it suitable for medium-sized capacities. Hall 9, Stand 526 — *Haver & Boecker OHG, Oelde, Germany*
www.haverboecker.com

Rembe

A reactor-dryer system for high-temperature applications

When products have to be heated indirectly, the maximum achievable temperature with thermal oil is about 400°C. In cooperation with a major chemical group, this firm has designed a high-temperature reactor/dryer that uses special electrical heating pads wrapped around the drum for heating up to 600°C. The tailor-made heating elements with redundant heating circuits provide an even and controlled heat transfer. The completely closed system can be operated under vacuum or under pressure. Hall 9, Stand 314 — *AVA-Huep GmbH + Co. KG, Herrsching, Germany*
www.ava-huep.com

Palas

Advanced Cyclone Systems

A single packaging machine that does it all

The latest FFS (Form-Fill-Seal) packaging systems will be presented at Powtech. The machinery program includes three machines for different bulk-goods applications and variable output levels up to 2,400 sacks/h. The substitution of FFS process for premade paper or plastic sacks is gaining importance, says the manufacturer. Inline bag making, filling and sealing offers considerable advantages in terms of cost and handling when compared with traditional, separate processes of bag production, storage, transport, filling and sealing. Packaging produced by the FFS is also said to excel with high functionality, such as improved product protection, attractive goods presentation and extended shelf life. Hall 9, Stand 454 — *Windmöller & Hölscher KG, Lengerich, Germany*
www.wuh-group.com

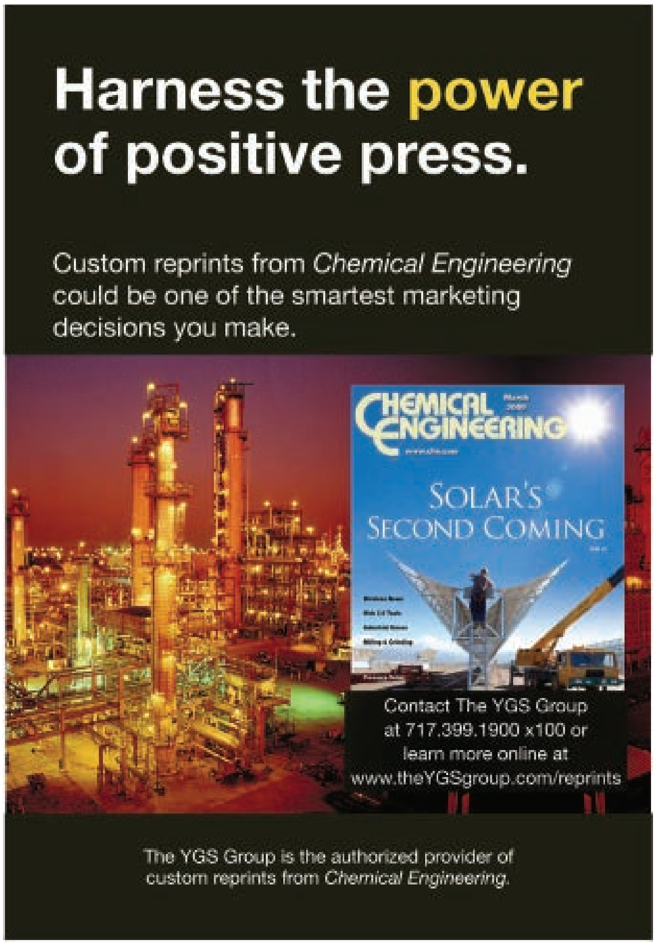
Manage inventories with this cable-based level transmitter

The newest edition of the TM-MM-SMU Inventory Management System is designed to handle some of the most harsh and dynamic conditions. The level transmitter incorporates state-of-the-art sensors, a wide choice of operator interfaces, auxillary outputs and displays, and a unique remote/vendor managed inventory solution. The device measures the level of materials in bins, silos and tanks up to 150 ft in height, and the sensor is suitable for use with a variety of powders, granules, slurries and liquids. Hall 6, Stand 230 — *Techmark GmbH, Munich, Germany*
www.techmark.de

A new instrument for surface characterization

The Belsorp-max is a static volumetric sorption instrument for measuring the physisorption and chemisorption of vapors. It can be used for measurement of the smallest micropores up to macropores because of the wide, relative pressure range handled. Water vapor sorption is integrated into the standard unit, and chemisorption can be integrated as an option. Standard analyses include specific surface area (BET), pore size distribution, vapor adsorption and chemisorption. Hall 6, Stand 451 — *Rubotherm GmbH, Bochum, Germany*
www.rubotherm.de ■

Gerald Ondrey



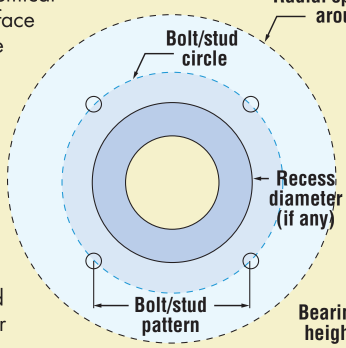
CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

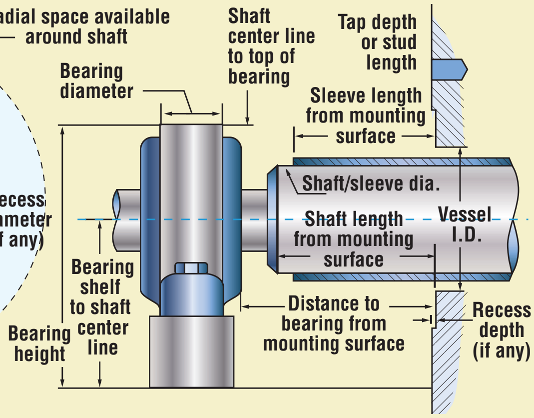
Measurement guide for replacement seals

Mechanical seals play a pivotal role in the chemical process industries (CPI). As the sealing interface between rotating process equipment and the materials contained inside, these devices prevent product leakage and fugitive emissions, while permitting process machines, pumps and compressors to operate at ever-increasing pressures, vacuums, temperatures and speeds. Even the most basic mechanical seal is a complex assembly.

Correct measurement of the machinery for replacement seals can be an underappreciated aspect of maintenance planning.

The following steps outline basic procedures and considerations involved in measuring machinery for replacement seals.





MEASURING FOR SHAFT SEAL REPLACEMENT

Step 1. Shaft diameter
Measure the shaft diameter (ø) where the replacement seal will be installed. It's important to actually take a measurement of the shaft and sleeve, rather than relying on dimensions from the machinery's blueprints.

The shaft diameter can vary slightly at different points along its length, so take the measurement where the seal will be positioned. This may mean removing the existing seal, or at least sliding it out of the way.

The shaft may be worn or fretted, so obtain an average measurement of the shaft. This can be accomplished by taking several measurements with a micrometer or caliper, then averaging them. An alternate way to get an average measurement of the shaft is to use a diameter-reading tape measure. These are precision tapes with a vernier scale, which allows you to measure shaft diameters to within 0.001 in.

After taking the most precise measurement possible of the shaft and the sleeve, if any, it may be useful to take a photograph of the shaft if it is fretted or worn. Your seal supplier can be a resource for more information.

Step 2. Radial clearance
Using a rule or tape measure, measure the radial clearance around the shaft and identify the nearest radial obstruction. If more than one obstruction exists, measure and mark all on a sketch.

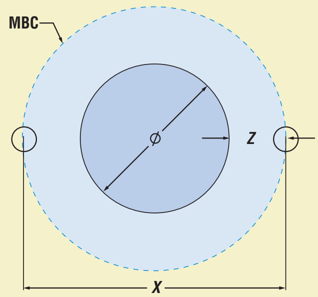
Step 3. Axial clearance
Measure the axial clearance to the first obstruction. This is usually the distance from the seal mounting point to the bearing or drive assembly. There may, however, be other closer obstructions, such as shaft couplings. A sketch can be helpful in communicating your needs.

Step 4. Seal mounting
Determine how the existing seal is mounted. For example, are there bolts or studs fastening it in place? If so, how many are there, what size are they, and how are they distributed around the diameter of the shaft?

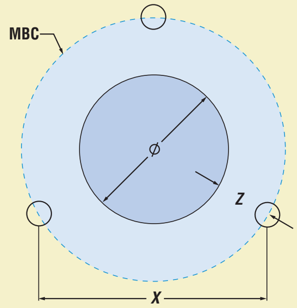
Start by measuring the distance between the centers of each pair of adjacent bolts (X). Take this measurement for every pair of bolts — bolt spacings may not be equal around the circle.

See the accompanying illustrations for how to convert common bolt patterns to a mounting bolt circle (MBC). You can check your work by measuring from the shaft outer diameter to each bolt center. Twice this distance, plus the shaft diameter, should also equal the MBC dimension. Careful attention is important here because the shaft may not be centered exactly within the bolt circle.

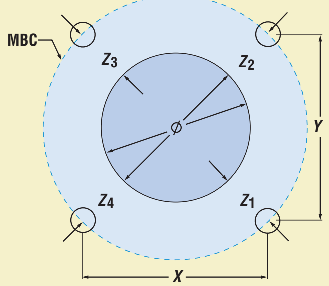
If studs are used for fastening, determine their lengths. Measure lengths and provide details of thread length, as well as whether or not the studs are welded onto or threaded into the machine.



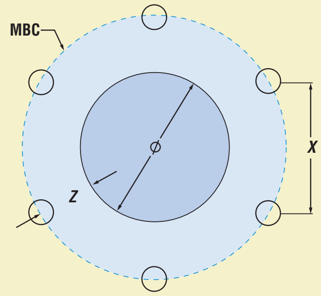
MBC = X
Verify MBC = $Ø + 2(Z)$



MBC = X / cos 30 deg
Verify MBC = $Ø + 2(Z)$



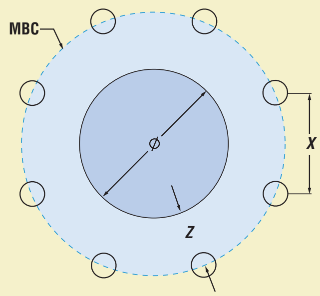
MBC = $\sqrt{X^2 + Y^2}$
Verify MBC: if $Z_1 = Z_2 = Z_3 = Z_4$
then MBC = $Ø + 2(Z)$



MBC = $2(X)$
Verify MBC = $Ø + 2(Z)$

Step 5. Mounting surface
Check the surface on which the seal will be mounted. Is it flat or perpendicular to the shaft? Use a straightedge and a machinist's square to verify this information, which will be important when mounting a new seal.

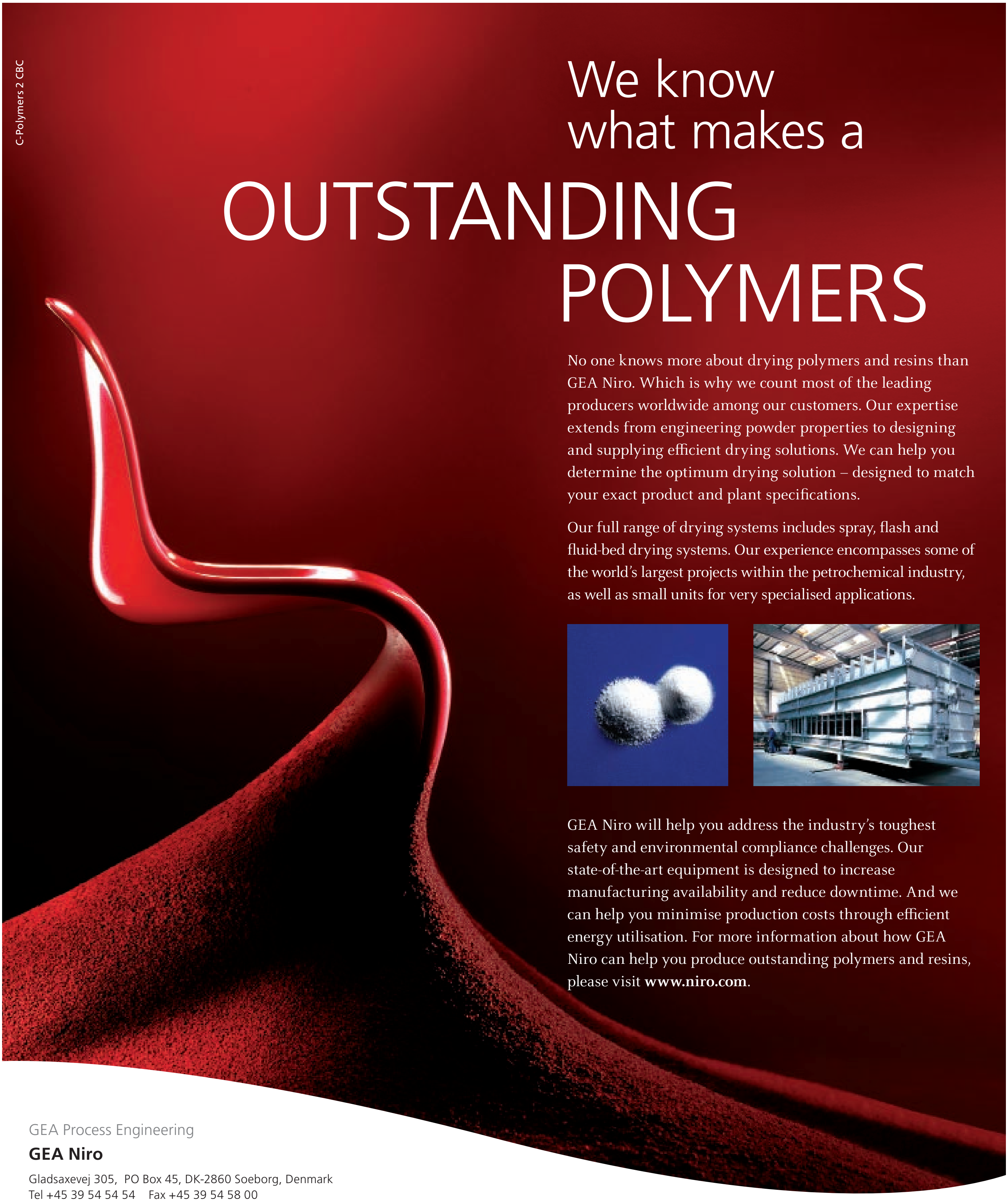
Note that some equipment has a machined recess around the shaft cutout, where a boss on the seal is intended to fit for centering purposes. If there is such a recess, measure both the diameter and the depth.



$$\text{MBC} = 2(X)\left(\frac{\sin 67.5 \text{ deg}}{\sin 45 \text{ deg}}\right)$$
Verify MBC = $Ø + 2(Z)$

ACKNOWLEDGEMENTS

Material for this month's Facts at Your Fingertips was provided by Woodex Bearing Co. (Georgetown, Maine; www.mecoseal.com) general manager Starkey Steuernagle, and seal designer Matt King.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POLYMERS
No one knows more about drying polymers and resins than GEA Niro. Which is why we count most of the leading producers worldwide among our customers. Our expertise extends from engineering powder properties to designing and supplying efficient drying solutions. We can help you determine the optimum drying solution – designed to match your exact product and plant specifications.
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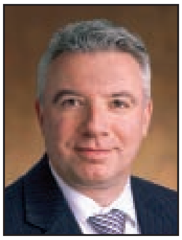
WHO'S WHO


Seale


Stello


Goerck


Neumann


Yarosh

Richard Seale is promoted to president of the Automation and Control business unit of **Mustang** (Houston).

Mike Mason, executive vice-president of the Fisher Div. of Emerson Process Management has been elected chairman of the **Valve Manufacturers Assn. of America** (Washington, D.C.).

Michael Rosenberg is now vice-president of business development for **OPX Biotechnologies** (Boulder, Colo.), a renewable biochemical and biofuel company.

Matcor, Inc. (Doylestown, Pa.), a cathodic protection and corrosion-prevention firm names *Jeffrey Stello* president and CEO.

BASF Catalysts (Iselin, N.J.) names *Rui-Artur Goerck* group vice-president, mobile emissions catalysts, and *Hans-Peter Neumann* group vice-president, process catalysts and technologies.

EagleBurgmann USA (Houston), a maker of mechanical seals and packings, names *Dow Secrest* global key account manager, and *Andy Martin* communications manager.

Joerg Riesmeier is named managing director and chief operating officer of **Direvo Industrial Biotechnology GmbH** (Cologne, Germany).

Ken Yarosh, global service line manager for Dow Corning's Specialty Chemicals Business, has been elected vice-chairman of the board of directors for the **American Soc. of Testing and Materials** (Washington). ■

Suzanne Shelley

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Mechanical Design Aspects for

High-Performance Agitated Reactors

An understanding of the mechanical design helps in specifying, maintaining and revamping agitated reactor systems

M. Stadtaus, **H.-J. Weiss**, **W. Himmelsbach** and **J. Smith**
Ekato

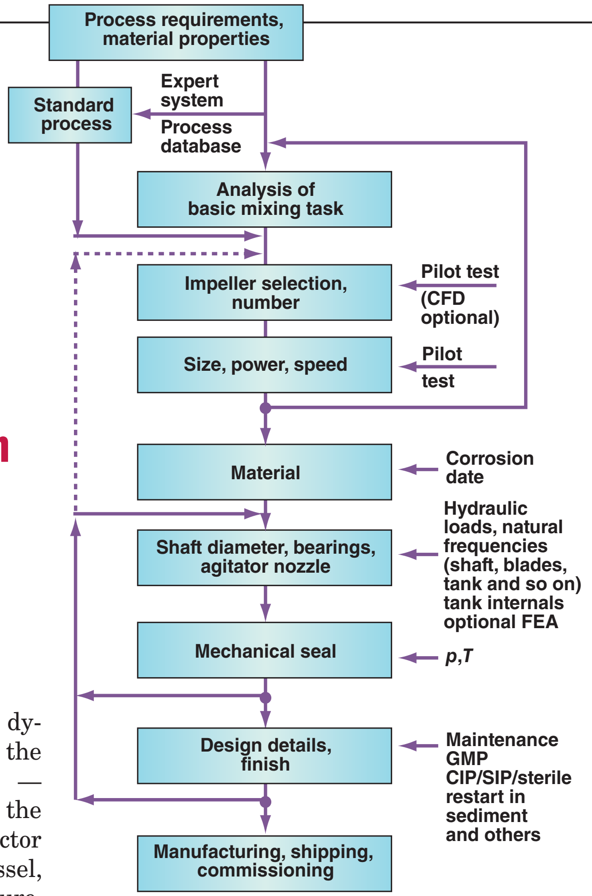

FIGURE 1. Many factors are involved with designing an agitator system for a given application

The stirred tank reactor with rotating mixers remains the backbone of the chemical process industries (CPI). While mixing is considered a mature technology, it is clear that continued technological development is necessary to achieve the state-of-the-art design demanded by ever-increasing efficiency needs.

As worldwide competition forces the CPI to increase the profitability of their production plants, it is even more important for process developers and plant design engineers to understand the mechanical design aspects of agitated reactors. Process design is often an interactive procedure of chemical and thermodynamic requirements on the one hand, and plant or mechanical restrictions on the other. Chemical and mechanical engineers work together to reach the common goal of optimum reactor design. And, this knowledge is also important for plant operators and maintenance engineers. Often there is a need to boost the plant capacity and process efficiency by revamps and modifications of the reactors. Only an awareness of the mechanical conditions in the existing reactor will prevent expensive failures.

This article gives an overview of the mechanical design aspects of agitated, high-performance reactors that will help in endeavors to specify, maintain and also retrofit equipment. The article is addressed to process developers, plant designers, plant operators and maintenance engineers. First, the agitator and its components are illustrated, and then the dynamic forces created by the agitator are explained — those forces that act on the agitator itself, on all reactor internals and on the vessel, including its steel structure. In addition, the article explains resonance and vibration phenomena and how these are considered. Mechanical seals play a critical role, resulting in safe and economic operation of pressurized reactors. Their detailed description, however, would exceed the scope of this article (for more on mechanical seals, see Mechanical Seals, *Chem. Eng.*, December 2004, pp. 36–42).

Process intensification

Higher productivity in the CPI can be defined as higher output per plant volume, less energy and raw material consumption together with reduced wastes, and better product quality. In addition to these points, focus is also being given to reducing investment and maintenance costs. Bigger plants for bulk chemicals provide economies of scale, and a more sophisticated design of the equipment leads to reduced maintenance. Apart from these needs, specialty chemicals producers also expect high flexibility in production for faster time to market. The solutions of the equipment manufacturers to fulfill these requirements of the process industry can be summarized as "process intensification".

Considerable progress in process intensification for mixing has already been achieved and is still ongoing [*1*]. One example is in agitated gas-liquid reactors [*2*]. Bulk chemical reactors often convert gases with inert components, such as oxidizers with air, and require large reactors with a capacity in excess of 1,000 m^3. Their continuous operation requires precise tuning of the interaction between agitation hydrodynamics and the superimposed liquid- and gas-feed and outlet streams with the reaction kinetics for optimum process results.

For a successful reactor design, consideration has to be given to the relationship between all relevant parameters. This includes not only the operating conditions, such as temperature, pressure and fluid properties, but also tank size and shape, all internal components (such as baffles, feed and outlet pipes, spargers, and heating-and-cooling equipment) and structural components (such as steady bearings), as well as power input or agitation intensity. Agitation not only defines the process results, but is also the source of all dynamic loads that must be considered for the design of the reactor unit. It is obvious that the

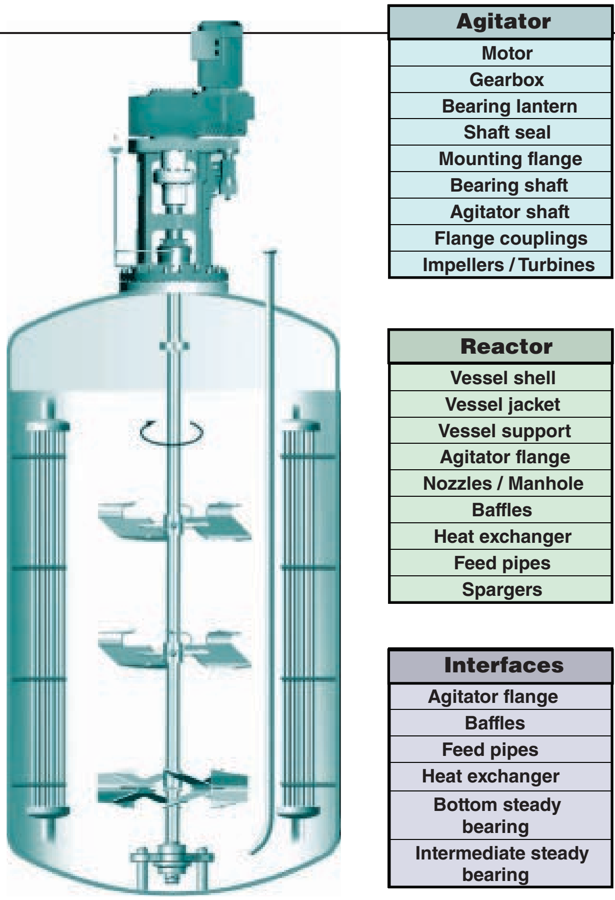

FIGURE 2. This overview of a general reactor layout shows the main components of agitated reactors and their interfaces

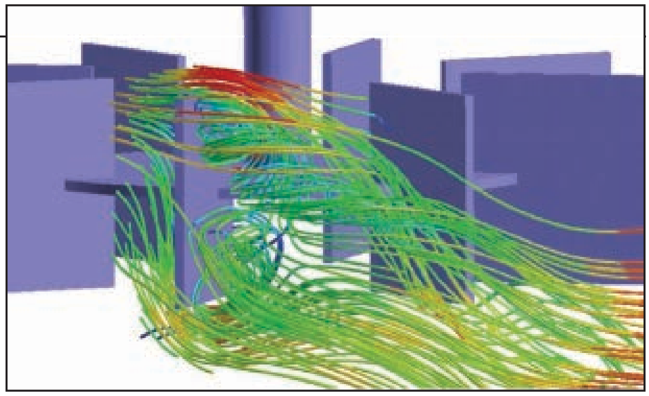

FIGURE 3. CFD can be used to calculate the flow patterns and velocities around a flat-blade disc turbine

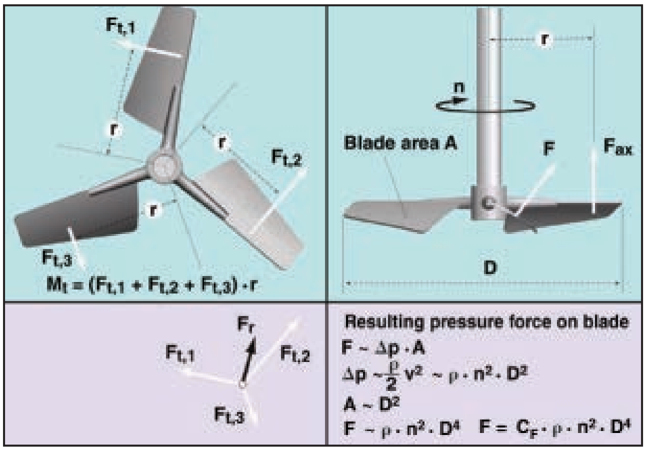

FIGURE 4. Torque (M_t) and hydraulic radial force (F_r) are functions of the tangential forces ($F_{t,i}$, left). Derivation of the hydraulic force (F) is shown on the right

conditions of intensified processes need a new, integrated approach for reactor design, which considers the agitator and vessel as one unit.

Design of agitated reactors

The design of agitators and reactors starts by defining the process performance and operating conditions (Figure 1). The results are the basic engineering data for the reactor and agitator including the main dimensions of all components, impeller type, number of impellers, size and speed or power input respectively as described in detail in several references [*1–3*]. These data are the input for the design work of the mechanical engineers.

The next step is to find the ideal balance between the process requirements and an economical, mechanical solution of the vessel-agitator system. As the agitator is connected via the agitator mounting flange, the vessel and agitator cannot be treated as separate units because their designs mutually influence each other. Figure 2 shows an overview of the general reactor layout and lists its key components.

In addition to these key agitator components, a variety of ancillary equipment also needs to be considered. For example, vessel supports could take the form of a skirt, bracket or leg design. Heat exchangers can be divided into external and internal types. The design of an internal heat exchanger can be classified as plate, coil or tube bundle. There are many more aspects to be considered. If the diameter of the manhole is restricted by mechanical or structural needs, for example, this would have a direct impact on the impeller design to ensure that the impellers could be inserted into the reactor. If the manhole is too small, the impeller hubs can be of a split-clamped design or the blades may be bolted.

Computer-aided engineering

The use of computers for engineering purposes has developed rapidly over the last two decades and has now become an indispensable tool for the mechanical design of agitated reactors and internal components. Therefore, the use of numerical simulations, for example computational fluid dynamics (CFD) and finite element analysis (FEA), has become mandatory (see box, p. 40).

The complex flow pattern in agitated reactors can be computed and visualized with CFD calculations. Not only does this facilitate the understanding of hydrodynamic mechanisms, but CFD data can also be used for the determination of the heat transfer coefficients of complex heat exchangers. Hydraulic loads, such as pressure distributions and forces based on local flow velocities, are calculated by CFD and then used as input for FEA.

The mechanical behavior of a structure, such as natural frequencies, stresses and deformations, can be ascertained with FEA. The general advantages of numerical simulations include the following:

- Reduced development time, for faster time to market
- Application specific dimensioning of vessels and their components for savings in time, energy and money
- Improvement of plant safety
- Increased reliability and operational safety; better planning of shutdown and maintenance intervals
- Prevention of potential safety and environmental risks at an early stage

CFD AND FEA

Computational fluid dynamics (CFD) and finite element analysis (FEA) are important simulation tools that enable fast, economical and innovative design and development of vessels, agitators and their interfaces. Compared to a traditional approach based solely on experiments, simulation offers a number of advantages including the following:

- Numerical simulation improves the understanding of important process details and their mutual influences
- Parameter studies are facilitated, as numerical solutions reduce the number of tests needed
- Trial and error calculations are reduced
- Numerical simulation allows an extrapolation of experimental experience and empirical data
- Numerical simulation makes inaccessible process steps transparent and allows innovative developments in virtual reality, saving material, manpower and energy

These numerical simulation tools should not be used alone, but should be combined with experiments for validation. ❑

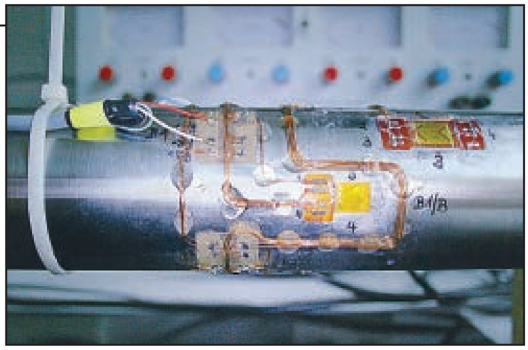

FIGURE 5. Force coefficients are determined in pilot tests with a laboratory-scale shaft equipped with strain gauges

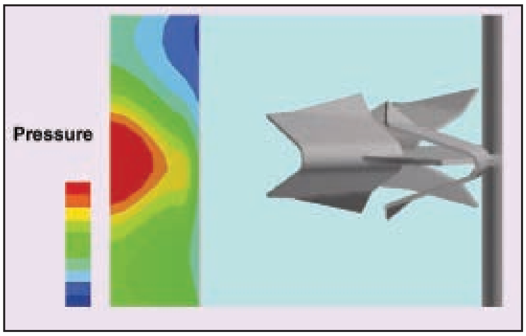

FIGURE 6. Local pressure distribution on a baffle section due to turbulent flow is indicated by color

Loads acting on the system

Every mechanical design starts with the evaluation and definition of the relevant loads acting on the structure. This is especially true for mixing, a highly dynamic process in which, besides the static loads, considerable dynamic forces can also have significant effects on the vessel structure.

Fundamental for a reliable design is the exact knowledge of the number and nature of the static and dynamic forces and momentums acting on the vessel and its internal components (baffles, heat exchangers, feeding devices, and so on) and on the agitator itself. Typical static loads are weight, vessel pressure and the reactor temperature with its thermal expansion.

The dynamic hydraulic forces are generated by the agitator itself, actually at the impeller blades. Depending on the blade geometry, which defines the flow direction, there are three major groups of impeller types:

- Those with axial flow direction
- Those with radial flow direction
- Those with both axial and radial flow direction

Figure 3 shows a CFD-calculated snapshot of the flow pattern around a flat-blade dis turbine. To understand the dynamic nature of mixing, consideration has to be given to the fact that the turbulent flow characteristic is a function of time and is not rotationally symmetric; or in other words, the forces acting on each individual blade are not identical.

The result of this unequal flow is shown on the left side of Figure 4 for a three-bladed impeller. The difference of the tangential forces ($F_{t,i}$) at each blade (at time t) leads to a resulting radial force (F_r). With the known lever of radial force (l), which is the distance between impeller and shaft bearing, the bending moment (M_b) can be calculated by the following equation:

$$M_b = F_r \cdot l \quad (1)$$

The sum of all tangential forces in turn generates a torque (M_t) around the agitator shaft:

$$M_t = \Sigma F_{t,i} \cdot r \quad (2)$$

For axially pumping impellers, an axial force ($F_{ax,i}$) arises at each blade, leading to an overall axial thrust defined as the following:

$$F_{ax} = \Sigma F_{ax,i} \quad (3)$$

The results from a laboratory-scale force measurement, using appropriate scaleup criteria or CFD are then used as the input for the subsequent analysis of the full-size design.

Figure 5 depicts a laboratory-scale impeller shaft, which is equipped with strain gauges for bending moment and torque measurement. The force coefficients can be obtained by using dimensionless coefficients.

The force coefficients (C_F) are individual for each impeller type and quantify the magnitude of axial, tangential and radial forces, independent of the impeller diameter. It is common to use the following terms:

- Radial force coefficient (C_r)
- Axial force coefficient (C_{ax})
- Tangential force coefficient (C_t)

Radial force and torque are the primary input data for the calculation of the shaft diameter.

Large shaft diameters, as well as large and expensive mechanical seals, bearings and other items may be required in the case of long and overhung agitator shafts, depending on the properties of the structural material. To eliminate these disadvantages, the use of a bottom steady bearing — which is an additional bearing at the shaft end in the tank, lubricated by the process fluid — can be considered.

The cost advantages of a bottom steady bearing are illustrated in Table 1. For example, for a 10-m-long shaft, the manufacturing costs for the complete agitator can be reduced by approximately 35%. Savings can be achieved by the reduction of the shaft diameter from 240 mm to 180 mm, compared to a 5-m shaft which would only provide a 10% saving. The applications that easily benefit from steady bearings include both large and tall reactors, such as bulk chemical reactors, bioreactors and large slurry storage tanks.

While a bottom steady bearing offers commercial advantages for the equipment cost there are other aspects to consider, including the following:

- A bottom bearing is a wearing part
- Higher cost of ownership (maintenance, spare parts and so on)
- Wearing part material selection has to be carefully considered
- The vessel design must withstand the induced forces
- A high level of precision is required for the alignment of the bearing to the agitator shaft axis

The vessel shell and the reactor internals are exposed to considerable hydraulic loads. In turbulent conditions these forces can be calculated by the following equation:

$$F = ½ \, c_w \cdot \rho \cdot v^2 \cdot A \quad (4)$$

Where c_w is the drag coefficient, ρ is the liquid density, A is the projected area of interest (baffle, feed pipe or other) and v is the flow velocity. The determination of v is conducted by measurements together with CFD computations. Figure 6 illustrates the pressure distribution on a baffle section calculated from the velocity field. The results of such calculations and experiments are the basic input for the subsequent mechanical dimensioning of a vessel's internal components.

The hydraulic forces acting on all reactor components are primarily generated by the agitator. Excessive vibrations, stresses and deformations of internal components and their supports can be caused by a weak vessel structure and by insufficient sizing. The following topics discuss opportunities to reduce these risks.

TABLE 1. SUMMARY OF COST SAVINGS ACHIEVED BY INSTALLATION OF A BOTTOM STEADY BEARING FOR TWO VESSEL-AGITATOR DESIGNS

		Design 1	Design 2
Reactor diameter (T)	mm	5,000	5,000
Reactor height	mm	5,000	10,000
Length of agitator shaft (L)	mm	5,000	10,000
Number of impellers	–	2	4
Impeller diameter (D)	mm	2,500	2,500
Motor power (P_{Mot})	kW	130	260
Shaft speed (N)	rpm	53	53
Shaft torque (M_t)	Nm	23,400	46,800
Material of construction	–	316 L	316 L
Vessel pressure (p)	bar	10	10
Shaft diameter (d_S)	with bottom bearing	160 mm	180 mm
	overhung	180 mm	240 mm
Relative agitator price for each layout	with bottom bearing	90%	65%
	overhung	100%	100%
Cost savings		10%	35%

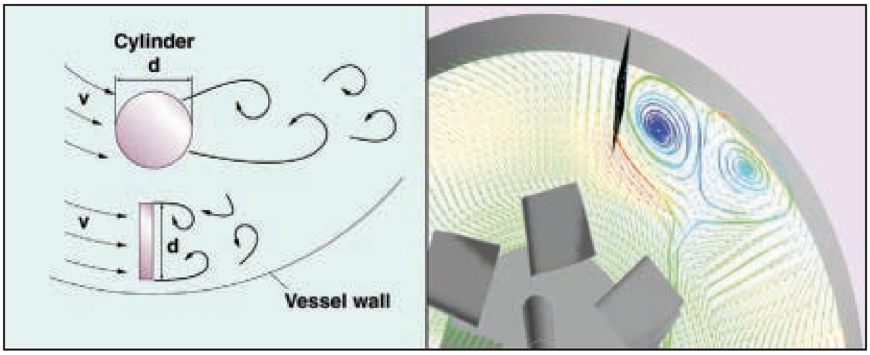

FIGURE 7. Distinctive vortices around vessel internals (baffles) can be seen as a schematic (left) and as calculated, flow velocity fields (right)

Vibration and resonance

When existing reactors are upgraded to reach higher productivity, it is critical to ascertain the resonance-free dimensioning of the vessel-agitator system for a high level of operational safety. Careless modifications can shift the natural frequencies into the critical range and result in operational problems. First the relevant excitation spectra must be clearly known, as excitation can be caused either by shaft speed, passing blades or a turbulent vortex spectrum. Resonance effects are often the reason for noise and unacceptable vibrations that lead to structural damage of components. This can result in costly, unplanned plant shutdowns and could also have an impact on health, safety and environmental issues.

Blade passing frequencies are defined by impeller type and shaft speed. The vortex excitation frequencies, the so-called Karman vortex detachment frequencies (f_k; Figure 7, left) are far more difficult to determine. The vortex frequency is described by the Strouhal number (S) in Equation (5).

$$f_k = S \cdot d \, / \, v \quad (5)$$

Pilot-scale measurements can, once again, provide data for the local velocities (v), but CFD simulations give a more comprehensive and differentiated picture of the entire flow pattern, as shown in Figure 7 (right).

Even if the excitation frequencies are well known, the design engineer has to decide which type of excitation is relevant or dominant for a specific component. This decision has to be made on a case-by-case basis, with care to avoid any resonance caused by coincidence of excitation with natural frequencies.

Vibrations, which are caused by the dynamic nature of the mixing process, are inevitable and not detrimental as long as they do not exceed the calculated, acceptable intensity level. This is ensured when the system's natural frequencies are sufficiently distanced from the relevant excitation spectra. The difference between the natural frequency and excitation frequency is Δf. In the field of machine dynamics an acceptable margin is $\Delta f > \pm 15–20\%$ [4, 5].

If this condition is not fulfilled, resonance ($\Delta f = 0\%$) or resonance effects amplify even small dynamic forces drastically. The most important natural frequency for agitators is the 1st bending mode of the agitator shaft, which is the critical shaft speed (N_c).

For a free overhung shaft with one single impeller, the shaft length (L) and the impeller mass (m) are the dominating parameters influencing the shaft critical speed:

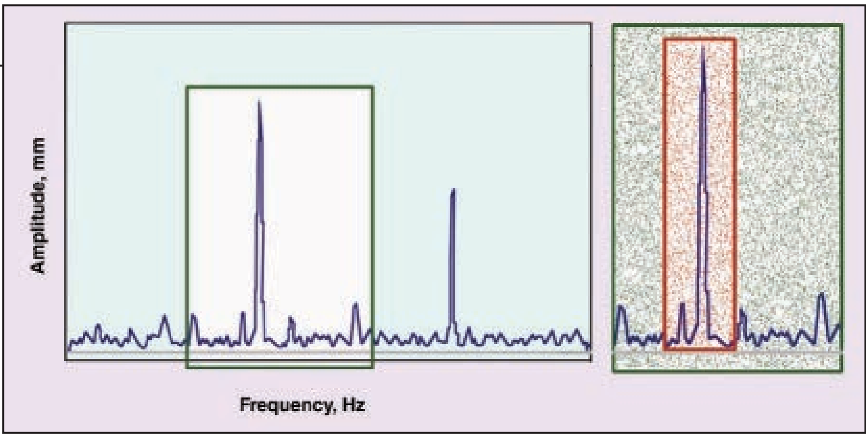

FIGURE 8. In measured natural frequencies of a heat exchanger, peaks indicate critical frequencies that must be avoided for a reliable operation

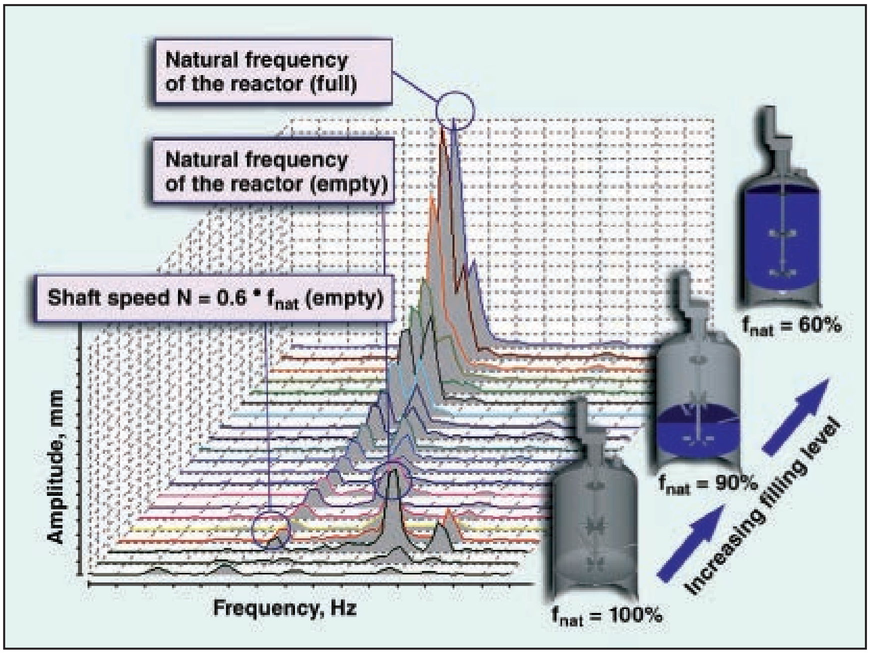

FIGURE 9. The decrease of the vessel's natural frequency during the filling process could lead to resonance effects with the shaft speed

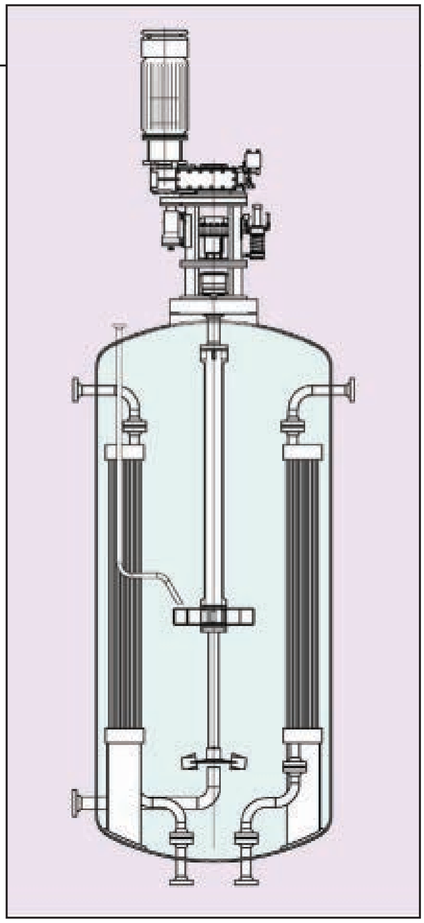

FIGURE 10. This sketch shows a typical, 50-m^3 continuously operated hydrogenation reactor

$$N_c \propto \sqrt{\frac{1}{m \cdot L^3}} \quad (\mathbf{6})$$

Correlation (6) shows that even minor changes to the shaft length or impeller position can lead to a dramatic change of the shaft's natural frequency. Far more sophisticated calculation methods are required to determine the exact N_c when designing complex shaft systems, such as multiple impellers, multi-shouldered or stepped shafts, and bottom-bearing or hollow shaft sections.

Operating below or above the shaft critical speed is possible. An overcritical operation is technically feasible because the dynamic force decreases again after passing through the critical speed. An agitator designed to operate above its shaft critical speed expands its operating range, which results in increased productivity. When overcritical operation is required, it must be ensured that the critical speed is passed through very quickly. This is achieved when using a standard 3-phase-a.c. motor with appropriate power margins.

The shaft critical speed is only one of a large number of natural frequencies that are present in agitated vessels. The whole vessel-agitator system, including internal components, has to be considered with regard to resonance. Figure 8 shows measured natural frequencies of a heat exchanger. The indicated peaks, or "critical" frequencies, must not be excited by the agitator.

The natural frequencies are numerically determined when using FEA, however the accuracy of the results is totally dependant on the accuracy of the input data. The numerical model must take all different operating conditions into account. For example, during a mixing operation, a vessel is filled with the material to be mixed. Depending on the filling level, this can significantly decrease the vessel's natural frequencies by up to 40% (Figure 9).

The same principle applies to internal components when they are submerged by liquid or simultaneously carry fluid. This is the case with heating and cooling coils, and feed pipes, where a significant decrease of natural frequencies can be expected and a purely structural, mechanical approach would fail. Such operating conditions are considered by fluid-structure interaction (FSI) analysis, based on the wave equation of acoustics [7]. All relevant factors influencing the vibration behavior can be taken into account by this type of multiphysical approach.

If scaling or product particles accumulate on the surface of an internal component, the overall mass of this component will increase. This mass increase leads to a decrease of the natural frequencies, which can change the operating conditions during production over a period of weeks or months.

Table 2 shows the influence of different operating conditions that result in the decrease of natural frequencies for individual components.

Natural frequencies and relevant excitation spectra must be calculated accurately to avoid any resonance effects. In conjunction with safety factors, any inaccuracies can lead to a restriction of the operating speed range, which could lead to process inefficiency.

Fatigue-proof design

At least 90% of failures in mechanical engineering are due to fatigue, and only 10% are due to static overload. This means that mechanical breakdowns can occur even though the static strength of the component, or the yield strength, has not been reached. The common cause for this type of failure is microcracking, which is caused by cyclic loading. The overall stress level will not cause a component to fail, but a frequently repeated, stress intensity range — which can be caused when operating in resonance conditions — will.

Dynamic loads are induced as a result of agitator rotation in nearly every structural component of an agitated reactor. With regard to fatigue, the interface between the agitator and reactor (the agitator mounting flange), or the connections between the vessel shell and the support of all internal components are critical.

In these critical areas, such as the agitator flange, tank lid or internal components like baffles or heat exchangers, the stress intensity is, again, determined by using FEA. These computed results define the parameters for a fatigue-proof-component design, taking into account the highly dynamic character of mixing processes. The design must then be verified as compliant with international codes, such as ASME.

Practical examples

***Hydrogenation reactor*.** Figure 10 shows a reactor type that is typically used for the reduction of nitro-groups to make toluene diamine, aniline and other compounds. The vessel is a continuously operated, 50-m^3 hydrogenation reactor with a combined gassing agitator. The gas feed is efficiently dispersed by the bottom impeller, which is a concave turbine. The hydrogen, which is not instantaneously dissolved and converted, rises to the head of the reactor and accumulates. Hence it must be permanently re-circulated, which is achieved by a self inducing turbine via holes in the flange coupling and a hollow shaft. The liquid feed also enters directly into the suction slots of this turbine, thus leading to an instantaneous micromixing of dissolving hydrogen and the liquid reactants. Such reactions are highly exothermic, therefore a sufficient heat exchanging area is provided by six to eight tube bundles. The intense flow off the impellers into these bundles leads to nearly isother-

TABLE 2. DECREASE OF THE 1ST NATURAL FREQUENCY DUE TO SPECIFIC OPERATING CONDITIONS (TYPICAL VALUES)

Component	Operating Condition	1st Natural Frequency (Relative Values)
Vessel	Empty	1
	Filled	0.6
Baffle	Empty vessel	1
	Filled vessel	0.4
Feed pipe	Without scale on surface	1
	With 5-mm scale on surface	0.7
Heat exchanger	Vessel and pipes empty	1
	Vessel and pipes filled	0.3

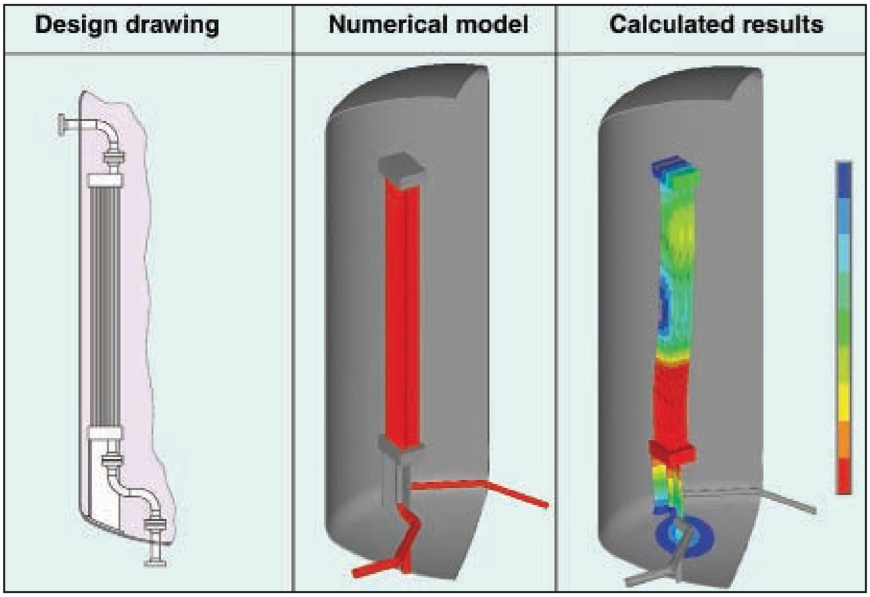

FIGURE 11. Dynamic loads on the heat exchanger bundle are examined from the initial design (left) to the numerical computer model (middle) and the final results (right). The colors indicate the local deflection

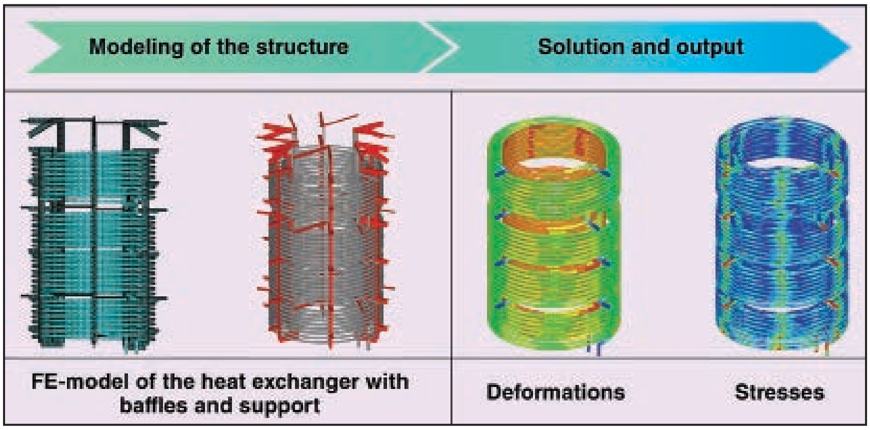

FIGURE 12. A finite element (FE) model, and calculated deformations and stresses of a double-coil heat exchanger, including baffles and supports are shown

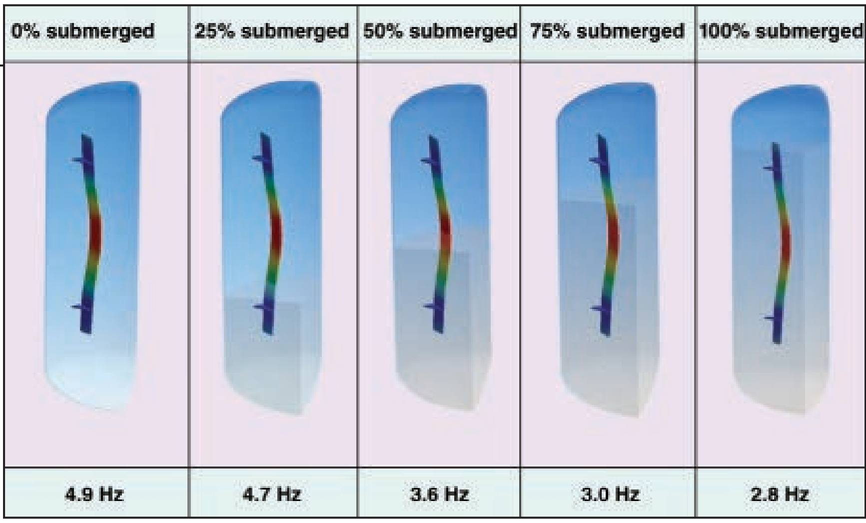

FIGURE 13. The filling level influences natural frequencies of a submerged baffle. Shown here as computed by finite element fluid-structure-interaction (FSI) analysis, a dramatic decrease of up to 43% can be expected for a baffle that is totally surrounded by fluid (right) as compared to a baffle in air (left)

mal conditions throughout the overall reactor. A specific power input between 5 and 10 kW/m^3 is required to achieve a conversion of over 99% in such a single-stage continuous reactor. For a 50-m^3 reactor volume, this equates to 250 to 500 kW shaft power.

This high power level creates respectively high loads, acting as forces on the impellers and shaft, that must be accommodated by the agitator flange and vessel head. The shafts in this typical reactor are of a overhung design and not supported by steady bearings, which are prone to abrasion by solids — typically catalysts, such as Raney nickel. In addition to the high power level, an intense fluid flow is generated, which in turn imposes dynamic loads on the heat exchanger bundle and its individual tubes.

The general approach to characterizing these loads for the mechanical dimensioning of the heat exchanger bundle can be seen in Figure 11. The first stage (left side) shows a conceptual design of the heat exchanger. A layout is usually rebuilt in virtual reality by removing all irrelevant and unnecessary details. These simplifications enhance the stability of the analysis and the quality of the results, thereby reducing computation time considerably. This pre-processing transfers the initial design into an adequate numerical computer model (Figure 11, middle). Taking into account all relevant boundary conditions (constraints, loads, and so on) the model is capable of calculating natural frequencies, stresses and deformations. The results of a modal analysis are shown on the right side of Figure 11.

TABLE 3. OPTIMIZATION OF THE MANUFACTURING COSTS OF A 50-M^3 REACTOR WITHOUT AFFECTING THE OVERALL STIFFNESS OF THE STRUCTURE (all designs offer the same stiffness of the vessel head)

				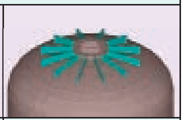
Number of stiffeners	0	4	8	12
Head thickness, mm	30	20	13	10
Costs	high	moderate	very low	low
Rating	– –	–	++	+

FIGURE 14. Titanium and titanium alloys are welded in a clean room to avoid contamination by ferrous particles

NOMENCLATURE

A	m^2	projected area
c_w	-	drag coefficient
C	-	force coefficient (general)
C_{ax}	-	axial force coefficient
C_r	-	radial force coefficient
C_t	-	tangential force coefficient
d	m	main dimension of internal component
D	m	impeller diameter
d_S	m	shaft diameter
Δf	%	difference of natural frequency to excitation frequency
Δp	N/m^2	pressure difference
f_k	1/s	vortex frequency
F	N	hydraulic force (general)
F_{ax}	N	axial force
$F_{ax,i}$	N	axial force per blade
F_r	N	radial force
$F_{t,i}$	N	tangential force per blade
γ_{ad}	deg	angular deflection of the agitator flange
H	m	liquid level
l	m	lever of radial force
L	m	length of agitator shaft
m	kg	impeller mass
M_b	Nm	bending moment
M_t	Nm	shaft torque
N	1/s	shaft speed
N_c	1/s	critical shaft speed
p	bar	vessel pressure
P_{mot}	kW	motor power
r	m	lever of tangential force
ρ	kg/m^3	density of product
S	-	Strouhal number
T	m	reactor diameter
v	m/s	local flow velocity

Double-coil heat exchanger. Another example is given in Figure 12, which illustrates the model and the results of an analysis of a double-coil heat exchanger with baffles. In this study, the deformation behavior and the stress distribution of the coils is simulated. These results provide valuable information for this complex construction, determining the number of needed heat-exchanger supports and their dimensions.

Vessel filling and emptying. This example illustrates why giving consideration to a purely structural design is not sufficient, because the vibration behavior is influenced considerably during filling and emptying of the vessel. Figure 13 shows the influence of the filling level, at a certain density and temperature, on the baffle's natural frequencies. This highlights the risk of neglecting these aspects. An optimum mechanical design requires a detailed knowledge of the process parameters.

The effect of the vessel fill-height on the natural frequencies has an even greater impact on heat exchangers. The surrounding liquid and the fluid inside the heat exchanger itself increase the exchanger's mass while lowering its natural frequency. These influences are accurately managed by the FEA and FSI methods.

However, in some cases an advanced procedure combining both CFD and FEA tools is necessary. This is achieved by using compatible software that requires adequate computing power [*6*]. Such simulations transfer the results of a CFD calculation to a subsequent FEA and vice versa.

The agitator flange

The agitator flange, together with its supporting structure (usually the vessel top head), represents the most critical interface between agitator and vessel and hence requires special attention during the design phase. If the vessel head's thickness is undersized, this may result in costly plant shutdowns for reinforcement work or, in the worst case, a failure of the whole vessel-agitator system.

Different criteria are applied to provide an optimal interaction between the vessel and the agitator. A well proven empirical rule is the value of the "maximum allowable angular deflection" of the agitator flange, which incorporates the maximum dynamic loads generated by the agitator. An experienced designer knows practical values for the maximum allowable deflection (γ_{ad}) to ensure a sufficient stiffness of the agitator flange and the vessel.

The manufacturing costs of a vessel can be significantly reduced by a tailored optimization of the vessel head using stiffeners. This is illustrated in Table 3, where four different designs of a vessel head are compared with regard to stiffness and relative manufacturing costs. In this example, the third design (eight stiffeners) offers the best compromise between cost and structural strength — a reduced wall-head thickness — which results in the reduction of material costs.

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Materials of construction

A careful choice of materials for the construction of the reactor is of great importance, and the material choice should take into consideration a wide range of chemicals with their different properties, the process conditions, hydraulic loads, temperatures, wear and corrosion. Ferrous materials, such as carbon or stainless steels, are not suited to all operating conditions and in these situations, non-ferrous materials, such as nickel-based alloys or titanium, may have to be specified.

The handling and manufacturing methods of non-ferrous materials require a special quality-assurance routine, and also specialist expertise. The welding of titanium, for example, requires approved welders and a clean room to avoid contamination from ferrous particles, as well as strict separation from all ferrous materials (Figure 14).

The optimal selection of the material of construction and customized dimensioning prevents unnecessary investment and also decreases manufacturing costs effectively. This is especially valid for applications that require high grade materials, such as titanium, tantalum and zirconium, where a cost saving potential would become even more evident. ■

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Full-Length Sleeving for Process Heat Exchanger Tubes

Stanley Yokell
MGT Inc.

How to calculate the effects of temperature when the sleeves have a higher coefficient of thermal expansion than the installed tubes

As heat exchangers age, their tube thickness decreases because of erosion, corrosion or a combination of both. Installing thin sleeves in tubes in which the tube walls have become so thin that failure is imminent is a maintenance technique useful for extending heat exchanger life.

One should consider sleeving when: (1) it would be very costly to replace aged exchangers because of the installation position or the shutdown time required to remove the existing one and install a replacement exchanger or tube bundle; (2) replacement tubing delivery is so long that unscheduled shutdowns for plugging failed tubes become so frequent as to cause serious loss of production; and (3) some decrease in the effective heat transfer surface is acceptable.

Background information

The power generation industry has long used sleeving of tubular heat exchangers to extend the life of steam surface condensers and closed feedwater heaters. The thermal- and pressure-loss effects of sleeving closed feedwater heaters has been discussed in Ref. 1, which provides equations for calculating the effects of sleeving with short sleeves, sleeving with full-length sleeves and in either case sleeving only some tubes (partial sleeving). Spreadsheets for performing such calculations are also available for download [*1*]. These calculation methods may be adapted for process heat exchangers with some modifications.

A detailed discussion about sleeving tubes to extend process heat exchanger life can be found in Ref. 2, and briefly in Ref. 3. (See also the box on p. 49 for a note on ferrules and sleeves.) This article discusses some of the factors to examine when considering full length sleeving for process- and power-plant heat exchangers.

Sleeving process

In sleeving, the thin sleeve is inserted into the tube with as close a fit as is practical. The sleeve is then expanded, usually hydraulically, but sometimes by other means, using special tools (Figure 1). The expanding pressure used is just sufficient to create enough residual interfacial pressure between the tube inside diameter (I.D.) and the sleeve outside diameter (O.D.) to maintain intimate contact between the sleeve O.D. and tube I.D. This is different from expanding tubes into tubesheets where the process has to create sufficient interfacial pressure between the tube and surrounding ligament to provide pullout and pushout strength under all conditions of operation.

Thermal effects of sleeving

Sleeving introduces an additional resistance to heat flow called contact resistance. There is always an oxide layer present on tube and sleeve surfaces. These oxide layers resist the transmission of heat. The contact resistance is the sum of the resistance to heat transfer of the oxide layers on the outside surface of the sleeve and the inside surface of the tubes. As a rule of thumb, the effect of the barrier to heat transfer is a reduction of the effective heat transfer area by approximately 30%. However, if the original thermal design calculations are available, you can make a much closer estimate using the spreadsheets referred to above and the authors' list of estimated barrier resistances provided in Ref. 1.

The smaller flow channel of the sleeve causes the tube-side flow velocity to increase, which results in an increase in pressure drop through the tubes and a slight increase in the tube-side film coefficient of heat transfer.

For the circumstance in which all the tubes are sleeved for their full straight length, if the original thermal design calculations are available, add the interfacial barrier resistance to the resistances of the original calculation to obtain the sum of all resistances as shown in Equation (1). Invert the sum to obtain the reduced overall coefficient of heat transfer as shown in Equation (2). Using the calculated log-mean temperature difference, calculate the new overall coefficient of heat transfer as shown in Equation (3). Calculate the duty of which the exchanger is capable after sleeving as shown in Equation (4).

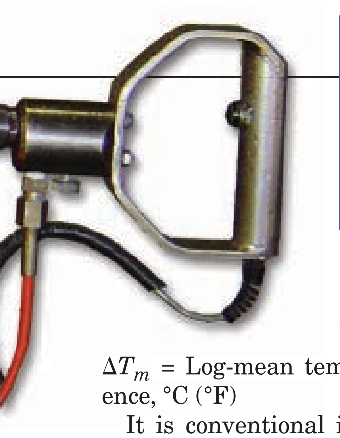
$$\Sigma_r = r_{fo} + r_o + r_b + r_{mt} + r_{ms} + r_s + r_{fs} \quad (1)$$

Where Σ_r = the sum of various resistances, r, (see below), m^2-°C/W (h-ft^{-}-°F/Btu)

$$U = 1/\Sigma_r, \text{ W/m}^2\text{-°C (Btu/h-ft}^2\text{-°F)} \quad (2)$$

$$Q = UA\Delta T_m \quad (3)$$

These variables are defined as follows:
r_{fo} = Fouling resistance on the outside of the tube
r_o = Film resistance of thin film of fluid on tube exterior
r_b = Resistance of the contact oxides on the tube I.D. and sleeve O.D.
r_{ms} = Resistance of the sleeve metal
r_{mt} = Resistance of the tube metal
r_s = Film resistance of the thin film of fluid on the sleeve interior
r_{fs} = Fouling resistance on the inside of the sleeve
U = Overall heat-transfer coefficient
A = Heat transfer surface area, m^2 (ft^2)
Q = Heat duty, W/h (Btu/h)



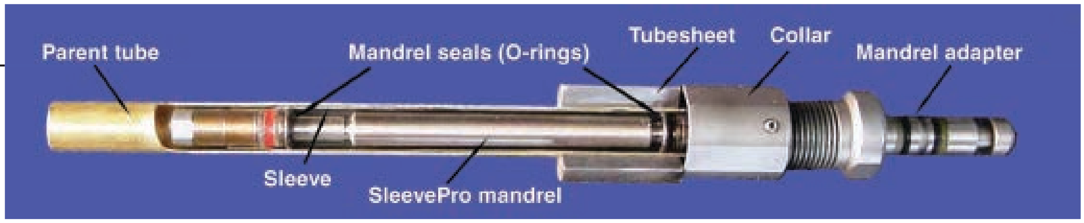


FIGURE 1. Sleeving consists of expanding thin tubes (sleeves) into the tubes of heat exchangers. One method for sleeving involves the use of special tools, such as those shown here, which apply hydraulic pressure to force the sleeves into a tight fit. For more on sleeving methods, see Ref. 2 (Photos courtesy of HydroPro, Inc.)

ΔT_m = Log-mean temperature difference, °C (°F)

It is conventional in heat transfer calculations to adjust the resistances by referring them to the tube O.D. to adjust for the difference between the surface inside and outside the tube, that is, by multiplying the resistances by the ratio of inside surface area to outside surface area.

Pressure loss due to sleeving

You can calculate the new pressure loss in the conventional way based upon the flow regime, which is usually turbulent, but may be viscous or in the transition zone. For a quick conservative guess you can calculate the velocity of the fluid flowing through the tubes before and after sleeving. Then you can multiply the known (usually measured) pressure drop before sleeving by the ratio of the after-sleeving velocity to the before-sleeving velocity squared as shown in Equation (4).

$$\Delta p_s = \Delta p_n \left(\frac{\upsilon_s}{\upsilon_n}\right)^2 \quad (4)$$

Where, in consistent units,
Δp_s = Pressure drop after sleeving
Δp_n = Pressure drop before sleeving
υ_s = Velocity through the sleeved tubes after sleeving
υ_n = Velocity through the tubes before sleeving

Mechanical effects of sleeving

Some mechanical effects of sleeving are obvious; others are not. The following discusses the mechanical effects.

Effect of pressure. During the design of a new heat exchanger according to the rules of the ASME Boiler and Pressure Vessel Code, the designer must investigate not only the capability of the tubes to withstand the design internal pressure at the design temperature, but also whether the tubes can resist the shell-side pressure at design conditions. For the latter purpose, the rules of the code's Section VIII Division 1 Paragraph UG-28 apply.

Although the ASME Code's jurisdiction ends when the manufacturer ships the exchanger, the rules of UG-28 are useful in determining whether the thinned tubes are capable of withstanding the shell-side (external) pressure and whether sleeving enhances this capability sufficiently to permit continued operation without downgrading the shell-side pressure.

If the system is designed so the tube-side pressure will always be higher than that of the shell side and to not allow application of the shell-side pressure when the tube side is not under pressure, you need to consider only the capability of the sleeved tubes to bear the internal pressure. But if the system is not so designed, investigate the sleeve-tube capability for withstanding the maximum external pressure to be applied.

This calculation involves calculating the ratios L/D_o and D_o/t where in consistent units, L is the length of the tube, D_o is the tube O.D. and t is the tube thickness. Using these ratios, determine Factor A from Figure G in Subpart 3 of Section II Part D of the Code, and determine Factor B that the tube can withstand. Usually, Factor B cannot be read directly from the printed curves. In such cases calculate the permissible external pressure using Equation (5).

$$P_a = \frac{2AE_t}{3(D_o/t)} \quad (5)$$

Where
P_a = Allowable external pressure, kg/cm^2 (psi)
E_t = Tube modulus of elasticity at the design temperature, kg/cm^2 (psi)

Effect of differential thermal expansion between tube and sleeve. In the process of expanding the sleeve,

A NOTE ON FERRULES AND SLEEVES

There seems to be considerable confusion about what ferrules and sleeves are and how they are used in heat exchangers. This short note aims to clarify the differences between ferruling and sleeving.

Ferrules are used: to protect tube ends from the effects of turbulence; to bring a hot tubeside fluid past the inner face of the tubesheet; and to carry tubeside fluid through a ceramic or heat resistant tubesheet coating.

In just about every application, the end of the ferrule that is exposed is flared or flanged over to a small amount less than half the ligament width. Sometimes the flared-over end is welded to the ligament. And in some rarer applications, the inner end of the ferrule is welded to the tube I.D. In almost all applications, the ferrule is expanded to intimate contact with the tube — preferably hydraulically but often by roller expanding.

Short sleeves, on the other hand, were developed in the power generation industry to cover discrete tube wall penetrations inside surface condenser tubes. The penetrations may be a considerable distance in from the inlet tube end. So the short sleeve was slid into the condenser tube so as to cover the perforation and expanded to intimate contact, sometimes with the sleeve ends welded to the tube to make sure there was no leakage between sleeve and tube.

Consequently, the definition of a ferrule is a short sleeve, flared or flanged at the tubesheet end and always installed in the tube inlet.

Full length sleeving was developed to accomplish the following:

- Restore plugged tubes to approximately 70% usefulness by effectively restoring the tubes' integrity. The effective loss of surface results from the increased wall thickness and resistance to heat flow across the interface boundary of sleeve and tube
- Restore so-called insurance plugged tubes to service. In the power generation industry, where it is common to monitor the wall thickness of feedwater heater tubes and other tubular equipment tube walls, it is common practice to "insurance plug" tubes with walls thinner than can safely operate without the risk of failure, or if a tube has failed, to plug the surrounding tubes to make sure that jets of high-pressure water escaping through a tube wall penetration has not damaged an adjacent tube. Here again, restoration is only about 70% because of increased wall thickness and the interfacial barrier to heat flow.

For more information on sleeving, see Ref. [*2*] ❑

EXAMPLE CALCULATION

Data	U.S.	Metric
Service Temperatures	°F	°C
*Tubes (estimated average between in and out)	779	415
Shellside	487.4	253
*Estimated average tube metal temperature, rounded	760	404.4
T_a = Ambient temperature	70	21.1
Existing Tubing Material of Construction SA-213 T12		
1 Cr-1/2 Mo Alloy K11562		
Yield at 68°F (20°C); psi, kg/cm^2	32,000	2,250
Yield at 668°F (334°C); psi, kg/cm^2	23,994	1,687
Tensile at 68°F (20°C); psi, kg/cm^2	60,000	4,218
Tensile at 663°F (334°C); psi, kg/cm^2	57,700	4,057
Tube O.D., in. (cm)	1.669	4.24
Tube thickness, in. (cm)	0.173	0.44
Tube length, in. (cm)	310.6	788.9
Tube cross-sectional area, in.^{2} (cm^2)	0.813	5.24
α_t, Tube/sleeve thermal coefficient of expansion from 68°F (20 °C); in./in./°F (cm/cm/°C)	6.53E-06	3.63E-06
E_t, Tube modulus of elasticity 68°F (20°C); psi (kg/cm^2)	3.06E+07	2.15E+06
E_t, Tube modulus of elasticity 668 °F (334°C); psi (kg/cm2)	2.70E+07	1.90E+06
Sleeving with SA-213 T12		
Sleeve O.D. = Tube O.D. – (2x tube thickness), in., (mm)	1.323	3.362
Sleeve thickness, in. (cm)	0.02	0.0508
Sleeve cross-sectional area, in.^{2} (cm^2)	0.082	0.529
Residual interfacial pressure at assembly was not estimated		
Equation (7), $(A_tE_tA_sE_s)(T_o — T_a)(\alpha_t - \alpha_s)/(A_tE_t + A_sE_s)$		
= 0, consequently no change from production interfacial pressure. Tube & sleeve are not in creep range		
Sleeving with Hastelloy C-276 SB 622/622B UNS10276		
Yield at 68°F (20°C); psi (kg/cm^2)	40,000	2,812
Yield at 663°F (334°C); psi, (kg/cm^2)	26,222	1,844
Tensile at 68°F (20°C); psi, (kg/cm^2)	100,000	7,031
Tensile at 668°F (334°C); psi (kg/cm^2)	88,460	6,219
α_s, Sleeve thermal coefficient of expansion from 68°F (20°C), in./in./°F (cm/cm/°C)	7.13E-06	3.96E-06
E_{s20}, Modulus of elasticity at 68°F (20°C); psi (kg/cm^2)	2.98E+07	2.10E+06
E_{s334}, Modulus of elasticity at 668 °F (334 °C); psi (kg/cm)	2.71E+07	1.91E+06

Sleeve O.D., in. (mm)	1.323	3.362
Sleeve thickness, in. (mm)	0.02	0.0508
Sleeve cross-sectional area, in.^{2} (mm^2)	0.082	0.529
*These estimates have been made without having the original exchanger data sheets or thermal design calculations, which were not available as of the date of calculations.		
Interfacial pressure change calculation		
Residual interfacial pressure after sleeving at ambient was not estimated.		
Calculation of ΔP, change in interfacial press resulting from temperature change calculation of unit load on sleeve exterior, F		
For Equation (7):		
A_tE_t =	8.39E+09	1.50E+09
A_sE_s =	2.22E+06	1.01E+06
$A_tE_tA_sE_s$ =	1.86E+16	1.50E+15
$A_tE_t + A_sE_s$ =	8.39E+09	1.50E+09
$A_tE_tA_sE_s/(A_tE_t + A_sE_s)$ =	2.22E+06	1.01E+06
α_t =	6.53E-06	3.63E-06
α_s =	7.13E-06	3.96E-06
$\lvert\alpha_t - \alpha_s\rvert$ =	6.04E-07	3.36E-07
$T_o - T_a$ =	690	383.3
$(A_tE_tA_sE_s)(T_o - T_a)(\lvert\alpha_t - \alpha_s\rvert)/(A_tE_t - A_sE_s)$, lb (kg)	925.4	129.5
Calculation of pressure on unit length of sleeve, Equation (8)		
Increase in interfacial pressure at optimum temperature, $\Delta P = F/\pi D_o$, psi (kg/cm^2)	222.6	15.65
Total external pressure at temperature	222.6	15.65
(Calculated using American Standard units and converted to metric)		
Calculation of allowable interfacial pressure on the Hastelloy 276 sleeves		
In accordance with Section VIII Div. 1 Par. UG-28 ASME Code		
Sleeve length L, in. (cm) =	310.6	788.92
Sleeve O.D., D_o, in. (cm) =	1.323	0.343
L/D_o =	234.7	
D_o/t =	66.2	6.8
A = Factor from Fig. G in Subpart 3 Section II Part D =	0.00017	
P_a = Allowable external pressure [Equation (5)] = $2AE_{t334}/3(D_o/t)$=	46.4	3.25
Conclusion. The effect of the difference between the thermal expansion of the Hastelloy C-276 sleeves inside the SA213TP12 tubes is to create more external pressure than the sleeves can sustain and would lead to the sleeves collapsing when the tube/sleeve metal temperature approached the working temperature. This might not apply to short sleeves		

the sleeve is strain hardened. When the expanding pressure is released, the sleeve relaxes but not to its original diameter. This produces a residual interfacial pressure between the sleeve and parent tube. The residual contact pressure is just sufficient to maintain contact between the sleeve and tube.

For most applications, sleeve material and tube material have the same specification. Therefore, the increase from the ambient temperature at which the sleeves are installed does not cause substantially different radial-expansion rates in the sleeve and parent tube. Only the creep properties of the sleeve and tube limit the temperature at which the sleeved exchanger can function with the sleeve-tube interface intact.

However, it may be desirable to use a sleeve material that is more resistant to corrosion and erosion than the parent sleeve material. When this is the case, you must investigate the feasibility of using a different metal to estimate the increase in interfacial pressure between the sleeve and tube that occurs at operating conditions to make sure that the sleeve can withstand the external pressure generated.

You can calculate the increase in external pressure that results from heating the sleeve-tube combination using simple strength of materials calculations for shrink fitting a tube on a tube. Here you calculate the radial force created by the differential thermal expansion and divide it by a unit of tube surface area.

The following parameter will be used in the next equations presented:

A_t = Tube cross-sectional area, m^2 (ft^2)
A_s = Sleeve cross-sectional area, m^2 (ft^2)
A_o = Surface area per unit of tube length, cm^2 ($in.^2$)
E_t = Tube elastic modulus, kg/cm^2 (psi)
E_s = Sleeve elastic modulus kg/cm^2 (psi)
F = Force per unit of tube length created by the difference in thermal coefficient of expansion between the tubes and sleeve when heated to the operating metal temperature, kg (lb)
L = Tube length, cm (in.)
T_o = Calculated metal operating temperature of the sleeve-tube structure determined from the heat transfer resistances, shell side average fluid temperature and tube side average fluid temperature, °C (°F)
T_a = Ambient temperature during assembly, °C (°F) assumed to be 20 °C (70 °F)
α_t = Tube thermal coefficient of expansion at the calculated metal temperature, cm/cm/°C, in./in./°C
α_s = Sleeve thermal coefficient of expansion at the calculated metal temperature, cm/cm/°C, in./in./°C
δ_t = Radial deflection of tube resulting from temperature increase from

assembly temperature to tube metal temperature at operating conditions, cm (in.)

δ_s = Radial deflection of sleeve resulting from temperature increase from assembly temperature to tube metal temperature at operating conditions, cm (in)

Equation (6) describes the equilibrium condition at the metal operating temperature.

$$\frac{FD_0}{A_t E_t} - \delta_t = \frac{FD_0}{A_s E_s} + \delta_s$$
$$= \frac{FD_0}{A_t E_t} - \alpha_i D_o \left(T_o - T_s\right) \quad (6)$$
$$= \frac{FD_0}{A_s E_s} - \alpha_s D_o \left(T_o - T_a\right)$$

This leads to Equation (7)

$$F = \frac{A_t E_t A_s E_s}{\left(A_t E_t + A_s E_s\right)} \left(T_o - T_a\right)\left(\alpha_i - \alpha_s\right) \quad (7)$$

And the pressure of the tube on the sleeve per unit length is then as shown in Equation (8).

$$P_o = \frac{F}{\pi D_o} \quad (8)$$

An example makes it clear

The box on p. 50 presents an example of a calculation using the equations discussed above. The calculations make use of English units because of the unavailability of some metric units and to avoid conversion errors. However, metric dimensions and temperatures have been converted to English units. ■

Edited by Gerald Ondrey

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A Safety-Centered Approach To Industrial Lighting

The proper design and operation of lighting is essential to ensure plant safety and support good maintenance practices

Boris Viner
Humatrack SafeLight

The use of appropriate hazardous-area lighting in the chemical process industries (CPI) is a key factor when it comes to improving overall plant safety and worker productivity, and supporting the best maintenance practices. The potentially hazardous conditions associated with many industrial settings place high demands on the lighting fixtures, and it is essential that pathways, walkways and stairways in multi-level platforms or facilities be properly illuminated.

This article discusses the importance of using the most effective lighting practices in hazardous environments, and presents a conceptually new lighting approach — dubbed safety-centered lighting — that seeks to help facility operators choose and install the best hazardous-area lighting throughout the facility by combining knowledge of human physiology with the latest advances in lighting technologies, area-illumination techniques and installation practices.

Today's lighting fixtures based on light-emitting-diode (LED) technology offer significant improvements over conventional options for hazardous-area lighting such as incandescent, fluorescent or high-pressure sodium (HPS) lamps. As discussed below, LED fixtures can provide direct improvements in overall safety, while reducing maintenance and energy requirements, as well.

A better approach

An appropriately designed industrial lighting program requires a keen understanding of both the human factors that dictate how a person processes visual cues and lighting, and the nature of the lighting scenario itself. Today, sufficient data are available to substantiate that proper lighting is a key contributing factor to overall plant safety, and that well-lighted facilities tend to have better safety and productivity records compared to poorly lit ones.

Unfortunately, while chemical plants, petroleum refineries and other types of CPI facilities often expend significant time and effort to incorporate improved operating practices that are intended to keep their workers safe, opportunities to improve the type and nature of the lighting throughout the facility are often overlooked.

One of the reasons for this dilemma is that conventional lighting fixtures have limitations in terms of how the light fixures function and how the resulting light is perceived by the end user. For instance, incandescent or fluorescent lamps are commonly used to identify the locations of emergency safety systems, such as industrial showers and eyewash stations. However, these fixtures provide practically no useful signaling during the day because the lighting blends into sunlight.

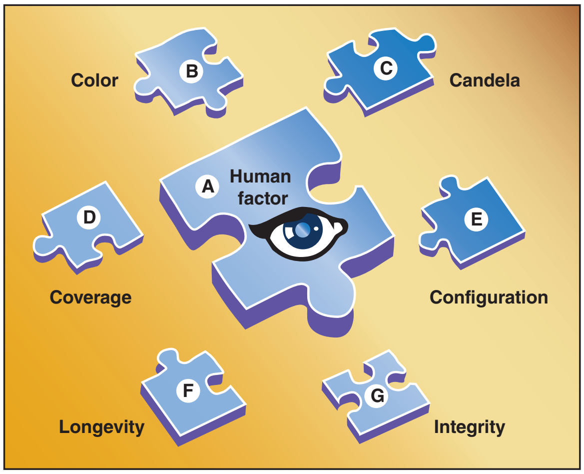
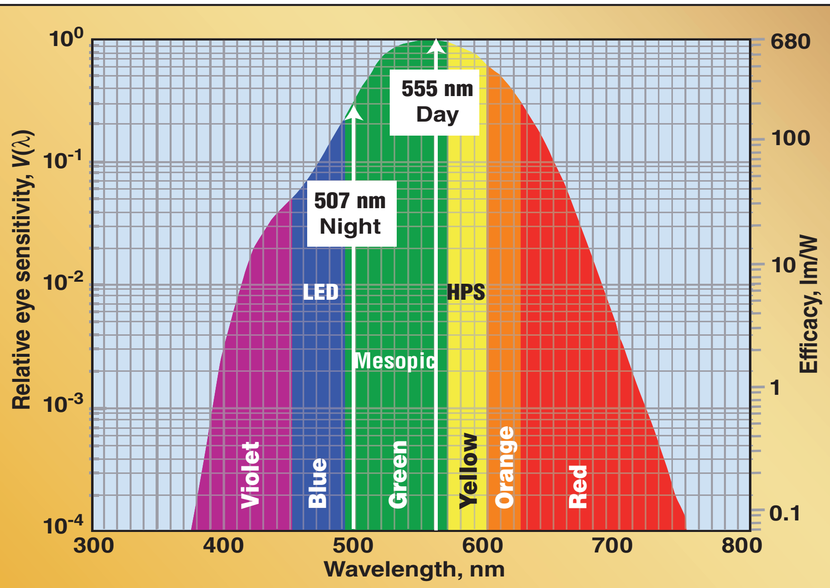


FIGURE 1. When devising the best lighting scenarios for CPI facilities, all of these factors — which influence the true impact that the selected lighting options will have in the workplace — must be considered

This has potentially serious implications in industries where employees may be exposed to hazardous chemicals or fire, because workers who may be inadvertently exposed to chemical compounds in the workplace must be able to get to the emergency eyewash or safety shower as quickly as possible to wash the affected areas.

Because the first few seconds after exposure to a hazardous substance are critical to avoid more severe injury or permanent scarring, eyewashes and safety showers must not only be located within reach of employees, but they must be easily identified and properly illuminated and accessible during both daytime or nighttime conditions, so that affected workers can reach them without hesitation.

As discussed below, LED-based lighting can deliver an immediate and valuable benefit over prevailing incandescent or fluorescent fixtures during the precious seconds needed to locate safety showers and eyewashes, because LED-based fixtures are better able to focus the light at an optimal, targeted color range, making the safety shower or eyewash loca-



Lm/W = Luminous efficacy, which is the light output of a light source divided by the total electrical power input to that source, expressed in lumens per watt
nm = nanometers; All wavelengths in the color spectrum, as perceived by human sight, are expressed in nm
The V (λ) function represents the relative eye sensitivity, in terms of the wavelength of the color produced by the light

FIGURE 2. This chart shows relative eye sensitivity as a function of light wavelength, and can be used when evaluating competing industrial area-illumination options. The goal is to maximize effective lumens (those that can be appropriately utilized by the human eye). Note that the optimum wavelength selection for safety showers would be green location lights, since the wavelength falls in the mesopic region between peak sensitivity for both day and night vision

FIGURE 3. LED-based location lighting is useful for signaling the location of safety showers and eyewashes, since they remain visible in daylight conditions

tion light visible at any time of the day or night.

Meanwhile, with regard to area-illumination lighting, it has been widely accepted that where artificial light is used, lighting level calculations could ignore the color of the light source. As a result, HPS light sources (whose light falls on the yellow portion of the spectrum) are popular in industrial facilities, even though they emit rather poor quality of light at night.

By contrast, the newer, LED-based lighting technologies are better able to provide appropriate lighting that takes advantage of the capabilities and limitations of the human visual system. The remainder of this article presents a new seven-point lighting profile that provides a unique perspective on the complex interactions between the human visual system and key aspects of artificial industrial-illumination and signal-lighting options.

A new lighting profile

As shown in Figure 1, the seven-point lighting profile presented here consists of the following measurable attributes: a) human factor, b) color, c) candela, d) coverage, e) configuration, f) longevity, and g) integrity. Each is discussed below.

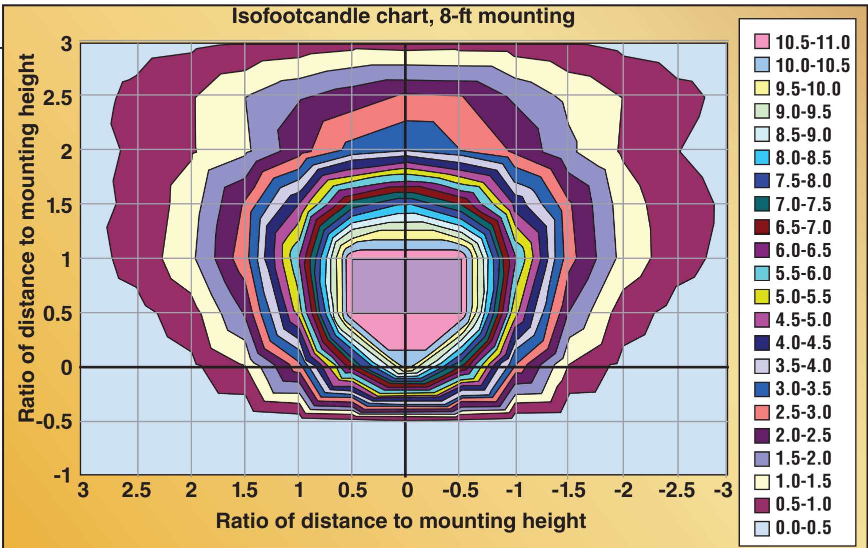
Human factor. As the biggest part of the "puzzle," the human factor is discussed first and at the greatest length, because ultimately, many of the drivers for developing the most "physiologically" appropriate lighting relate to the human eye. In essence, the best lighting technologies — those that contribute greatly to overall facility safety — are those that are optimized for the human eye.

It is important to realize that all forms of artificial light are not the same, and different types of light are interpreted in different ways as a function of the complex physiology of the individual viewer. For instance, the retina acts like a light-sensitive screen at the back of the eye, and it has many light receptors that convert light into electrified signals sent to the vision centers of the brain. Because of their shapes, the two major categories of light receptors are called cones and rods. Cones are responsible for day vision, rods play an important role in nighttime vision, and therefore the sensitivity of the individual human eye varies at different light levels.

The very central part of the retina, the fovea, contains only cones while the rest of the retina contains both rods and cones. Cones are active at high light levels and are most densely situated in the central part of the field of view, so when we look directly at an object, we are using our cone receptors. Cone-activated vision is defined as photopic (day vision).

The rods are responsible for human vision at low light levels, and are prevalent in the peripheral field of view, away from our direct line of sight. Rod-activated vision is defined as scotopic (night vision).

Both in theory and in practice, the



The isofootcandle chart is derived from the candlepower data, and shows exact plots of equal footcandle levels on the work plane when the fixture is at a designated mounting height. The color legend represents the intensity (candelas) of a cross-sectional photometric distribution curve.Isofootcandle chart, 8-ft mounting

FIGURE 4. The photometric data shown here for an LED-based fixture installed at an 8-ft (2.4-m) mounting height demonstrate how such fixtures can effectively focus artificial, industrial white lighting on straight lines and avoid spillage, thereby contributing to optimum illumination, especially in multi-level platforms

determination of lamp lumens involves knowing both the spectral power distribution (SPD) of the lamp and the visual response of the eye. Interestingly, it is not simply defined as a form of energy in the same way as other forms of radiation; rather, it is defined as energy as evaluated by the human eye (a reflection of the visual effect — which differs by individual — that is created by that light energy source).

Color. When it comes to how the eye responds to color, vision scientists have known for most of the twentieth century that lighting conditions play a big part. While it's been widely accepted that the cones in the eye handle day vision and the rods are designed for night vision, up until now lighting manufacturers have continued to rely on light meters to measure a lamp's lumen output that is calibrated by examining the eye's sensitivity to only cone-activated (photopic) vision — completely ignoring the effect of rod-activated (scotopic) vision. Unfortunately this approach represents a gross oversimplification of how human vision works, and signals a missed opportunity in terms of optimizing industrial lighting options.

This is perhaps one of the most fascinating and important subjects to be addressed for efforts to improve industrial lighting in recent years. In the past, it has been widely accepted that under virtually all circumstances where artificial light is used, lighting level calculations could ignore light source color, relying only on a certain lamp lumen rating (usually as provided by the manufacturer). In these instances, calculated values of candelas, lumens, or lux (lumens per square meter) are not dependent upon whether the light source is white, bluish white, yellow or pink in nature.

However, published research indicates the importance of lamp SPD. It is only recently that the lighting industry has begun to acknowledge the magnitude of the color effects involved, and to show serious interest in considering the true properties of the light. With this in mind, some lighting experts have started to use the term "effective lumens" to define the modified lumen output of a lamp, taking into account the shifting color sensitivity of the eye at low light levels.

For example, until recently the lumen has been defined as the amount of light as perceived by the eye under photopic (day) conditions. Based on this definition, HPS lamps tend to have high lumen ratings.

However, due to the yellow color of the source light produced by HPS lamps, at least half of the light can't be effectively utilized by human eyes at night. So, it is not as important that the sodium lamp produces a high output of energy, but rather that its energy peak is near the maximum photopic sensitivity wavelength of the eye (see Figure 2, yellow region).

As a result, one should really determine the "effective lumens" of the HPS light source at scotopic (night) levels. To do this, the lamp power at each wavelength would need to be multiplied by the scotopic eye sensitivity at each wavelength, and the values summed. The effective lumens value, therefore, will be different from the conventional lumens value (which, as noted, is considered only under photopic or daytime conditions).

Because a relatively small portion of the overall energy output of the HPS lamp occurs at wavelengths shorter than the peak, the effective lumens available for scotopic (night) conditions is greatly reduced. This shows that sodium lamps (being a source of yellow light) produce relatively little useful light ("effective lumens") for nighttime conditions, and therefore their effectiveness under low light levels — when it is essential to have adequate industrial lighting — is drastically reduced.

By contrast, for a white light source, such as that produced by an LED-based fixture, the energy output lies in the high-sensitivity region of the eye for low light levels (Figure 2).

As a result, the effective lumens increase as the light level is reduced at night and the eye shifts to a greater blue/green peak sensitivity.

As shown in Figure 2, the peak sensitivity of the human eye for night vision is a wavelength of 507 nanometers (nm), and the peak sensitivity of the human eye for daytime vision is a wavelength of 555 nm. The region between these two peaks is referred to as mesopic viewing conditions. Even under mesopic viewing conditions, yellow light sources have reduced effectiveness, while LED sources have superior overall effectiveness.

To provide a mechanism to determine the true quality of light, the author proposes the concept of a ratio — called the Quality of Light Factor (QLF) — to determine a rating for the illumination provided by a fixture that reflects actual lumens utilized by the human eye. The author proposes that the value of QLF can be simply defined as a "mininum" ratio value for comparative purposes. For instance, if an HPS lamp is rated with a QLF equal to one, then the QLF of the LED lamp would need to be rated as a minimum of 2, as the strength of the scotopic eye sensitivity of LED light would be a number of times greater than the scotopic eye sensitivity of HPS source.

It is beyond the scope of this article to recommend actual QLF values that should be used for different sources under different conditions. Nonetheless, as a general rule of thumb, the strength of the scotopic eye sensitivity of an LED is a number of times higher than that of an HPS source. Thus, when purchasing industrial lighting systems, the QLF of an LED-based system should be rated much higher than the QLF of a conventional system, such as one based on HPS lamps.

When it comes to safety shower and eyewash locations, lights must be visible under both daytime and nighttime conditions. The color chart provided in Figure 2 shows that the best type of lights for signaling safety showers and eyewashes are those that provide a wavelength in the mesopic range (as described above). As shown in Figure 3, an LED-based light fixture is perfectly visible during daytime conditions.

Candela. Candela is a measure of the intensity of a light source. It relates to the "light focusing" capabilities of a given light fixture and is thus a function of the light fixture's optical design.

Coverage. Coverage is a measure of the amount of effective light that is spread out for the intended area-illumination application. Adequate coverage is achieved through optical design of the LED fixture, to ensure optimum "light distribution" for industrial white lighting (Figure 4).

Configuration. The configuration of a balanced lighting layout refers to the exact positioning of the fixtures (Figure 6). Proper configuration within the industrial space is essential, and it is achieved by proper spacing between the stanchion mounts of industrial lights. The goal is to ensure optimum area illumination that usually contributes to safety.

Longevity. Longevity is a measure of how long-lasting a light source is, and it is a direct contributing factor to overall facility safety, since it reduces the need for maintenance personnel to climb structures to maintain or repair light fixtures or replace bulbs. With this in mind, the use of state-of-the-art light fixtures, such as those based on LED technology, which tends to have longer service life compared to other types of conventional lamp sources (incandescent, fluorescent and HPS), typically translates into improved safety and reduced maintenance and lifecycle costs. LED-based lights also tend to have reduced energy requirements compared to conventional lamp types, and this helps to provide a rapid return-on-investment.

Integrity. The integrity of the chosen lighting solution relates to a fixture's optimized mechanical and electrical design. For instance, LED fixtures provide greater integrity thanks to several modernizing advances that are now widely available, such as universal input voltage capabilities and much cooler temperature ratings. Both of these aspects contribute to greater integrity, multi-application capabilities and improved safety.

LED fixtures are also particularly useful as a robust light source because they have no filaments, which makes them particularly well-suited for areas that may be exposed to high vibration.

Additionally, in an LED system, lumen maintenance is directly proportional to thermal management. LED systems are typically designed with cooling fins to compensate for heat buildup during use (Figure 5).

Dialight

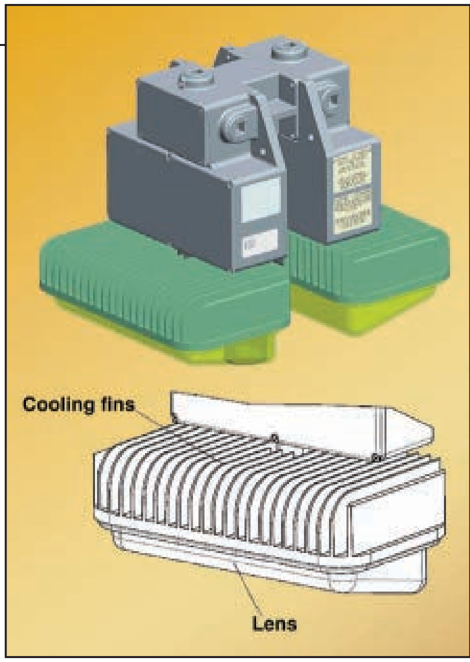


FIGURE 5. Today's LED-based industrial lighting fixtures typically include cooling fins to help disseminate heat buildup during operation

Recommended practices

Given the discussion presented above, the author offers the following recommendations for optimizing light source efficiency using LED-based fixtures for hazardous-area illumination. Although the example discussed below focuses on a flare-gas-recovery plant, the following recommendations can be considered by most chemical plants, petrochemical units and other CPI plants.

- LED technology provides better — directional control of light than is possible using conventional incandescent, fluorescent or HPS lighting options. This is important in applications such as gas-recovery units where numerous railings straight walkways and multi-level structures need to be properly illuminated. Unlike conventional lights, some of today's patented LED fixtures contain several reflectors to further optimize light distribution. The ability to effectively focus the light on straight lines where it is needed helps to reduce spillage of light beyond the target focus area to just a few feet. LED fixtures also require lower wattage than conventional lighting compared to incandescent, fluorescent or HPS lighting options
- The functional advantages described above also enable LED lights to be spaced at a greater distance than what would be required using conventional light fixtures. As a result, the use of LED fixtures can help users to reduce the number of lighting fixtures required to illuminate the same area by as much as 50% compared to the use of conventional lighting options. The ability to use fewer lights reduces capital costs, installation time and costs, maintenance costs and overall energy requirements
- Unlike conventional lights, today's LED fixtures can easily be installed using multiple mounting options (that is, they can be wall-mounted or stanchion-mounted and can be used as side-by-side modules (Figure 6).

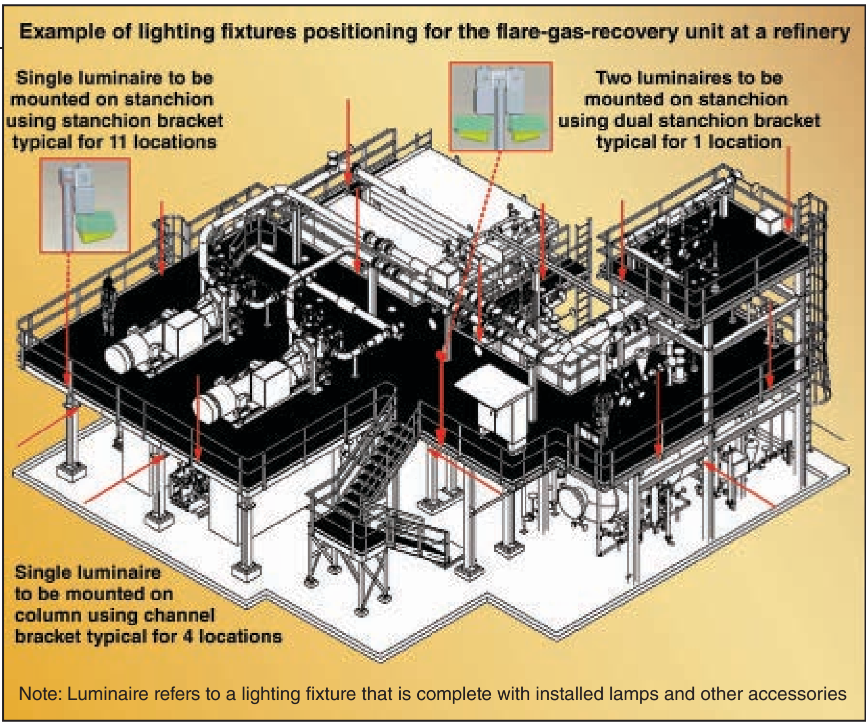


FIGURE 6. **Shown here is the appropriate positioning of LED-based light fixtures throughout a typical flare-gas-recovery unit at a petrochemical facility**

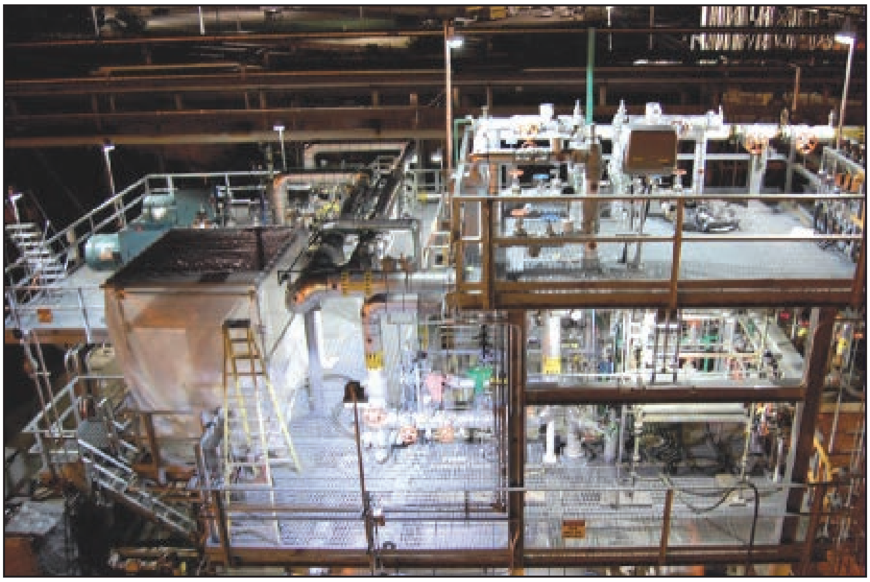


FIGURE 7. **As seen in this photo, taken in the field at a gas-recovery unit, the use of new LED-based lighting technologies can lead to tremendous visual acuity improvements at petrochemical facilities by providing adequate light where it is needed the most (throughout the multi-level platform). Notice that the penetration of the light from the higher elevation of the structure down to the lower floor, and the distribution of light throughout the entire structure provides optimum overall illumination**

Large facilities often stock a few dozen types of lighting fixtures to be used at different locations, so the ability to standardize on such multi-purpose LED fixtures can drastically reduce the amount of inventory the facility must manage while still providing the desired lighting at different locations throughout the facility

Appropriate lighting plays a critical role in supporting overall industrial safety (Figure 7). Understanding the complex properties of the human visual system provides us with the answers we need to develop better and safer lighting fixtures that will have significant impact on overall facility safety throughout the CPI.

The lighting profile discussed here — which considers the complex interactions between competing lighting options and the human eye — provides a new methodology for evaluating and selecting competing lighting options that are most appropriate for industrial applications under both daytime and nighttime applications. With the introduction of new LED lighting technologies in recent years, it is now possible to provide an ideal light source — one that is designed to take advantage of maximum retinal efficiency in the human eye.

The recommendations provided here aim to help CPI facilities to employ optimum color and light sources that would be most compatible with the physiology and functionality of the human eye under daytime and nighttime conditions. As discussed, choosing the most appropriate color during the selection of visual signal lights can ensure that workers will have clear and easy access to safety showers and other critical safety systems at any time of the day or night.

LED lighting technology lends itself well to industrial applications that are considered classified hazardous areas. A well-designed LED fixture takes advantage of the directional characterization of the LED and will deliver more effective lumens to the targeted application, therefore increasing the overall system efficacy for area illumination at CPI plants.

The practical examples presented demonstrate how the new LED lighting technologies in conjunction with the QLF can contribute to improvement in safety and maintenance and save energy. ■

Edited by Suzanne Shelley

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Particle Sizing Across the CPI

This survey of modern measurement technologies demonstrates how selection criteria vary by application

Remi Trottier, Shrikant Dhodapkar and **Stewart Wood**
The Dow Chemical Co.

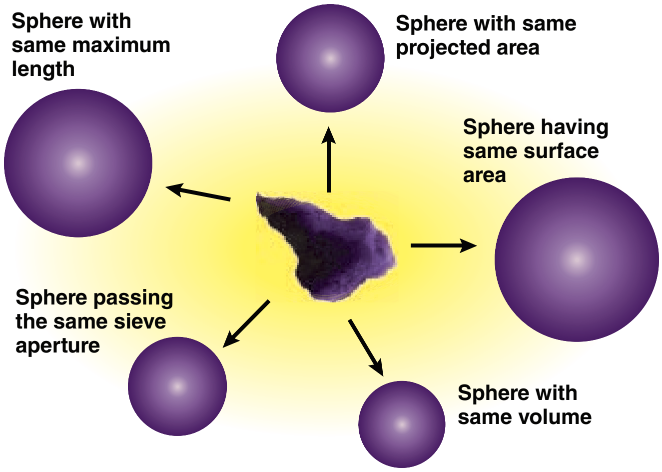


FIGURE 1. Non-spherical particles can be assigned a number of different diameters depending on which parameter is used in the measurement process

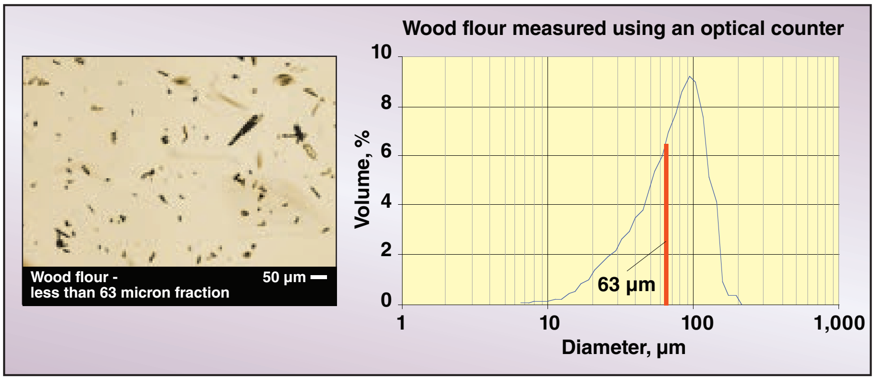


FIGURE 2. Different techniques measure different aspects of non-spherical particles. For example, elongated wood flour particles that can pass through a sieve along their length (left), will be reported (right) as larger particles using a technique measuring the equivalent projected area of the particles

Particulate systems are everywhere; they are responsible for bright red sunsets, the texture of chocolate and the rate of drug delivery in the human body. Particulate processing and size control originated back in prehistoric times where mixtures of pigments were finely pulverized and used in the painting of cavern walls. From those primitive beginnings, the use and processing of particulate matter has grown to be of paramount importance in virtually all modern industries. For example, the flow of granular materials, the sintering behavior of metallurgical powders, the combustion efficiency of powdered coal, and the hiding power and gloss of aluminum pigments [*1*] are all particulate systems that are heavily influenced by particle size and shape. Meanwhile, the past decade has seen rapid evolution and growth of applications in nanosized particulate materials, signaling that the increasing importance of particle characterization is set to continue [*2–5*].

A particle can be defined as single unit of material having discrete physical boundaries that define its size, usually in micrometers, µm (1 µm = 1×10^{-4} cm = 1×10^{-6} m). Particle science is typically limited to particulate systems within a size range from 10^{-3} to 10^{4} µm, thereby encompassing seven orders of magnitudes.

In an attempt to meet the challenge of these remarkably wide particle characterization requirements, from nanosize to millimeters, a considerable number of technologies have been developed over the years to measure the size of particles.

Because of the remarkably wide diversity of technologies for particle sizing applications, each of which explores the size distribution from a different perspective, the size distributions as generated by different methods generally do not agree. A careful evaluation of the particulate system to be evaluated must first be carried out before a particular family of technology and specific instrument can effectively be selected. It is important to clearly define which parameter (such as median, concentration of fine particles, distribution standard deviation, aspect ratio, and so on) is of importance in the measurement, along with the required precision and accuracy needed for each identified parameter. Items that will affect the choice of instrumentation and need to be considered are the working size range, accuracy, detection limits, and resolution of any particular technology (Table 1). Other important items are initial instrument cost, operational cost, throughput, reliability, and quality of the maintenance program from the manufacturer. Measurement validation is a must prior to committing to any particular technology.

Effects of particle shape

When it comes to particle characterization, we do not live in a spherical universe, and therefore, particle shape issues are a leading cause of disagreements between instruments. The problem with a simple linear dimensional descriptor, such as diameter, is that it is difficult to adequately and uniquely specify a size for irregular shaped particles. For example, what is the size of the particle at the center of Figure 1? The answer depends on how you measure it. It is common practice to describe a non-spherical particle to be equivalent in diameter to a sphere having the same mass, volume, surface area, settling velocity (uniquely defined parameters) or other defined parameters as the particle in question. For example, laser diffraction instruments report the size of irregular shaped particles as the diameter of spherical particles having a similar diffraction pattern as the particles being analyzed. Given the wide choice of modern particle-sizing technologies that are available, therefore, the reported particle-size distribution often becomes dependent on the particular brand of instrumentation used for measurements.

As an example, Figure 2 illustrates the size distribution of wood flour that passed through a 63-µm sieve. The vertical line on the graph represents the 63-µm dia., which corresponds to the sieve aperture. How can particles up to 200 µm pass through a 63-µm aperture? The answer is that different techniques measure different size parameters of the particles. While the <63-µm sieve dia. measurement is relatively straightforward, the remarkably larger particle size corresponds to a projected surface-area diameter as measured using an optical particle counter. Therefore, when reporting particle size data, it is necessary to specify the method by which the data were generated.

Overview of technologies

A wide variety of particle measurement technologies has evolved to meet the almost endless variability of industrial needs, including both laboratory and online applications. Although there has been a big push in recent years to develop online technologies, the vast majority of characterization is performed in the laboratory. Taking the laboratory to the process is proving to be a particularly challenging problem. As we will see, some laboratory technologies lend themselves better than others for online applications.

All of the modern particle-sizing technologies can be classified into three broad classes:

Fractionation techniques: Technologies that fractionate particles according to size prior to detection and measurement

Stream counting techniques: Technologies that rapidly count and measure particles individually

Ensemble techniques: Technologies that have the ability to measure a large number of particles simultaneously

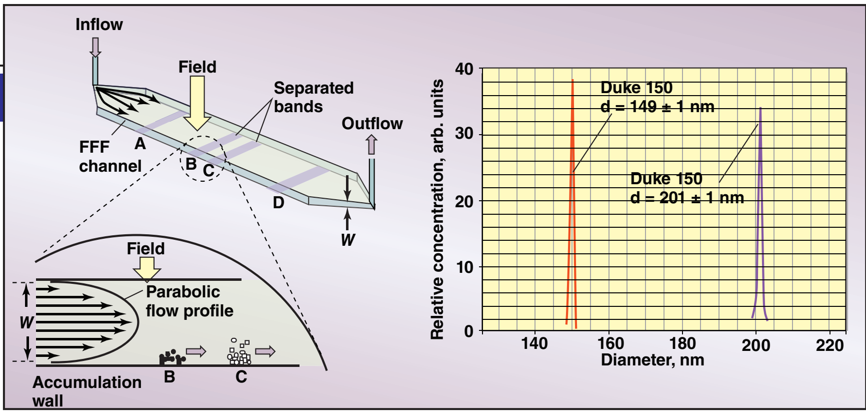


FIGURE 3. Field-flow fractionation is carried out in ribbon-shaped channels from 50 to 500 µm thick, where particles are separated in size bands traveling at different velocities. The graph here shows the separation of a latex particle sample consisting of a mixture of 150 and 200 nm populations

Depending on the type of information that needs to be extracted from the size analysis, one type of technology may be advantageous over another. For example, particle or stream counters offer the ultimate resolution, but may suffer from poor counting statistics for wide distributions. Ensemble techniques offer high precision, but can suffer from lack of accuracy for multi-modal, or more complex distributions. Fractionation techniques offer fairly high resolution and high accuracy, but generally lower throughput especially for wide distributions.

Every method, with the exception of imaging technologies, provides the measurement of an equivalent spherical diameter in one form or another. The spherical diameter information can be deduced indirectly from the behavior of the particles passing through restricted volumes or channels under the influence of gravity or centrifugal force fields, and from interaction with many forms of radiation, or ultrasonic waves. In addition to size information, image analysis is the sole technology that can also provide reliable shape information.

Fractionation techniques

This family of techniques includes several distinct technologies in which particles are separated by size before being measured. Among the most common of these techniques are sieving, sedimentation, hydrodynamic chromatography and field flow fractionation. Some fractionation techniques make use of models that are based on first principles of physics and therefore do not need calibration, while others do require calibration. Both the dynamic range and the resolution of these techniques are governed by the efficiency of the separation process they utilize. The resolution is typically better than ensemble techniques, but below that of counting methods. The dynamic range depends on the particular technique being utilized; wet and dry sieving can be used for measuring particles in the size range from five to several thousand microns; centrifugal, and gravimetric sedimentation is useful for particles from about 0.05 to 100 µm; and hydrodynamic chromatography and field flow fractionation are typically used for particles smaller than a few microns. The fractionation family of methods does not lend itself to online or in situ applications, and therefore has not been developed for in-process measurement.

Sieving. Sieve analysis is the workhorse of the mineral processing industry to assess ore crushing for mineral release; in heavy construction work to evaluate soils, sand, and gravel for foundation stability; in powder metallurgical operations for porosity control; and in agriculture for grading seed quality and uniformity. One major advantage of sieving is that it is straightforward and low cost. However, analysis must include attention to details, or erroneous results can ensue. The finer mesh sieves can be easily damaged by careless handling and tend to become clogged with irregular shaped particles. Regular inspection and maintenance is a must when using sieves. Many practitioners tend to forget that a sieve is a precision instrument and should always be treated as such. Sieves are available with openings from approximately 5 µm upward in several series of sizes in geometric progression (square root of 2 or 4th root of 2). Wire woven sieves have approximately square openings; and electroformed sieves have round, square, or rectangular openings. Wire

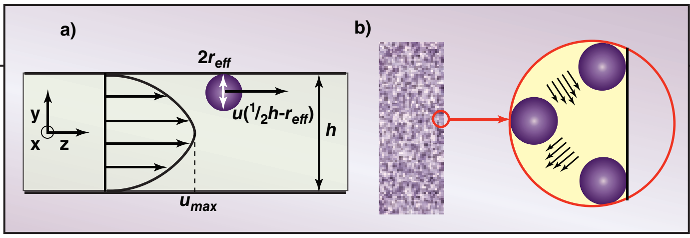


FIGURE 4. In CHDF (a) and HDC (b), the larger particles are excluded from the boundary layers, thereby experiencing a larger velocity (*u*) than the smaller particles

woven sieves tend to be sturdier and less expensive than electroformed sieves, and have a greater proportion of open area. They are much more frequently employed than their electroformed counterparts except in the very-fine particle range where only electroformed sieves are available.

Dry sieving is typically performed by shaking the stack manually, or using a mechanical vibrator, or with air pulses of sonic frequency. In another device, agitation on the sieve is provided by a rotating air jet [*6*]. In wet sieving, water or another liquid that does not dissolve the material, is continually applied to facilitate particle passage. A detergent is frequently added to promote particle dispersion during wet sieving, and antistatic additives have been used to help fractionate systems of larger particles that have a high level of static cohesive forces. The sieve diameter of a particle is therefore defined as the size of the sieve aperture through which the particle in question just passes through. Mass fractions of the particles are then presented in tabular or graphical form.

Sedimentation. Sedimentation analysis is suitable for a wide variety of materials and is used for both quality control and research work, such as agglomeration studies, and gives well-defined, relatively high resolution results. The technique has been employed in the evaluation of soils, sediments, pigments, fillers, carbon black, phosphors, clays, minerals, photographic halides, as well as organic particles. Measurement of the settling rate for particles under gravitational or centrifugal acceleration in a liquid provides the basis of a variety of techniques for determining particle sizes. Gas-phase sedimentation has been investigated [*7*], but difficulties achieving adequate particle dispersion and the effect of electrostatic charging have restricted this application. In liquid-phase sedimentation, the particles initially may be distributed uniformly throughout a liquid (homogeneous start) or concentrated in a narrow band or layer at the liquid's surface (line start). The particle movement is monitored using light or x-ray beams. The particle size determined by sedimentation techniques is an equivalent spherical diameter, also known as the equivalent settling diameter, which is defined as the diameter of a sphere of the same density as the particle that exhibits an identical free-fall velocity. The terminal velocity of the particle is determined from Stokes' law, given by Equation (1):

$$v = \frac{gd^2(\rho_p - \rho)}{18\eta} \qquad (1)$$

Where: v is the terminal velocity of the particle, g is the gravitational constant, d is the particle diameter, ρ_p is the particle density, ρ is the liquid density and η is the liquid viscosity.

One of the key implications of Stokes' law is that the larger particles settle at a faster rate, which is proportional to the square of the diameter ($v \propto d^2$). Therefore, the settling rate of a 10 µm particle will be 100 times that that of a 1 µm particle. This square relationship implies good separation efficiency on the basis of particle size, which in turn gives sedimentation methods their relatively high resolution.

Field-flow fractionation. Field-flow fractionation (FFF) has been widely used in characterizing the size of biological materials and in the paint and pigment industry. It is a separation technique where a field is applied perpendicular to a particle suspension flowing through a micro channel (Figure 3). The applied field pushes the particles toward the bottom of the channel while diffusion works to oppose the applied field to form a balance where particles of different sizes are confined to specific regions of the channel. Since a parabolic flow exists within the channel, the particles that are confined to a region close to the center of the channel will travel faster than those that are confined to a region near the bottom of the channel thereby separating the particles. A number of fields have been successfully applied, namely gravitational, centrifugal, magnetic, thermal and cross flow.

Hydrodynamic chromatography. Capillary hydrodynamic fractionation (CHDF) and hydrodynamic chromatography (HDC) are two other separation techniques that make use of microchannels. In these techniques, particles carried in an elution fluid are separated in a microchannel (Figure 4a) or a column packed with spherical material (Figure 4b). Since the larger particles are excluded from the boundary layers as the result of their size, they travel in the central regions of the eluent flow where the velocities are higher. Smaller particles gravitate to the slower flows near the wall of the micro channels and as a result experience lower eluent velocities. This size-dependant flow sampling creates a fractionation where large particles elute from the microchannels first and smaller particles last. The composition of the eluent is carefully chosen to control the attraction of the particulate to the microchannel surface. The various size species eluting from the microchannels are detected using an optical detector. Instruments are calibrated with a series of standards of known sizes. This technology has been used for measuring the size distribution of colloidal systems such as latex, organic pigments, carbon black, emulsions and liposomes.

Stream counters

In stream counters, also referred to as particle counters, the particles to be analyzed are moved through a sensing zone where they are detected and analyzed one at a time, thus producing a number-based size distribution. Several of those methods do not operate on first principles of physics, and therefore need to be calibrated. They offer the ultimate in resolution, but can suffer from poor counting statistics when the data are converted from a number distribution to a mass or volume distribution where the size range is greater than a factor of 50 (the ratio between the smallest and largest possible values). In an effort to increase the dynamic range of these techniques, most of the modern instruments come equipped with multiple sensors, or magnifying optics. Some of these techniques have been successfully used in online or at-line applications.

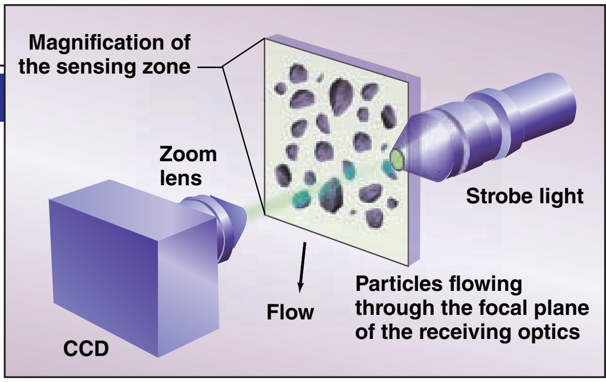


FIGURE 5. This dynamic image-analysis configuration uses strobe illumination to freeze fast moving particles within the focal plane of the receiving charge-coupled device (CCD) camera. The sheath flow can take the form of a dry aerosol dispersion or a wet dispersion flowing through a flow cell

Dynamic image analysis. Particle characterization by image analysis consists of examining and measuring the size or shape of particles that have been optically magnified. The pioneering studies of particle characterization by imaging technologies were carried out in the late 1960s and early 1970s. The projected area of the profiles were estimated by direct comparison with sets of reference circles, known as a reticule, engraved on the eyepiece of the microscope. The ever-increasing power of data processing capability, coupled with the high performance and falling costs of television cameras and scanners has led to the development of highly sophisticated and powerful image processing and analysis systems, which emerged in the 1980s and early 1990s. Further advances in microelectronics, such as faster image capture and processing, have led to the transformation of the highly sophisticated modern image analyzer into a much faster particle-size and shape analyzer. This new breed of instruments (Figure 5) has gained considerable popularity within the past decade. The particles to be analyzed are dynamically presented to the instrument as dry particles carried in a gas stream, or falling from a vibration feeder, or as liquid dispersions moving through thin flow cells. This type of dynamic image analysis system is normally used for particles greater than 5-µm dia. The transformation in technology has made it possible to move from image analysis systems that gave a lot of information about few particles, to systems that quickly give a lot of information on a lot of particles.

Imaging technology has also been used for online applications in the chemical, pharmaceutical and oil-and-gas industries.

Optical particle counters. Another stream counter uses the principle of light blockage to count and measure the size of individual particles. These instruments are widely used for monitoring contamination levels in oil, hydraulic fluids, water treatment facilities, and any other low level particulates in liquids. As a particle passes through the sensing zone (Figure 6), it projects a shadow onto the detector

TABLE 1. APPLICABILITY OF VARIOUS MEASUREMENT TECHNOLOGIES

	Method	Dynamic Range, µm	Pros	Cons	Medium	Distribution Type	Resolution*	Precision**	Accuracy***
Fractionation techniques	Sieving Wet / Dry	5 – 5,000	Low cost. No composition information required.	Not automated. Low throughput. Shape dependent	Wet / Dry	Mass	Poor	Good	Good
Fractionation techniques	Sedimentation / gravitational / centrifugal	0.05 – 100	Can analyze complex distributions, Large representative sample (10^9 particles). PSD calculations simple — Stokes' Law	Limited dynamic range. Single density samples. Longer analytical time for wide distributions	Wet	Mass	Excellent	Good	Good
Fractionation techniques	Field flow fractionation	0.01 – 10	Can analyze complex distributions. Large representative sample (10^9 particles). No composition information required	Calibration needed. Correction for detector response required.	Wet	Mass	Excellent	Good	Good
Fractionation techniques	Hydrodynamic chromatography / Capillary hydrodynamic chromatography	0.01 – 2	Works well for complex distributions. Large representative sample (10^9 particles)	Calibration needed. Particle deposition in packed columns. Detector response correction needed. Band broadening correction needed. Fractionation can be composition dependent	Wet	Mass	Good	Good	Good
Stream counting techniques	Dynamic image analysis	2 – 5,000	Visual representation. Shape characterization possible. Rapid analysis. Can analyze complex distributions	Limited dynamic range for each magnification — a factor of one hundred	Wet / Dry	Number	Excellent	Good	Excellent
Stream counting techniques	Optical counters	0.5 – 5,000	Rapid analysis. Can analyze complex distributions. Quantitative particle concentration. Can measure extremely low concentration. No knowledge of composition required	Requires extensive dilution of concentrated dispersions. Requires refractive index difference between particle and suspending medium. Requires calibration	Wet / Dry	Number	Excellent	Good	Good
Stream counting techniques	Electrozone counters	0.4 – 600	Rapid analysis. Can analyze complex distributions. Quantitative particle concentration. Can measure extremely low concentration. No knowledge of composition required	Requires extensive dilution of concentrated dispersions. Limited dynamic range per aperture. Aperture plugging. Calibration required. Conductive solution required	Wet	Number	Excellent	Good	Excellent
Ensemble techniques	Laser diffraction	0.04 – 2,000	Simple operation. High throughput. Capable of dry and wet analysis. No calibration	Complex deconvolution algorithms. Less accuracy for complex distributions. Refractive indices necessary for accuracy	Wet / Dry	Volume	Good < 500 µm; > Poor	Excellent	Good; Complex distributions poor
Ensemble techniques	Dynamic light scattering	0.01 – 1	Simple operation. High throughput. No calibration required	Complex deconvolution algorithms. Less accuracy for complex distributions	Wet	Volume	Poor	Good	Good
Ensemble techniques	Acoustic spectroscopy	0.1 – 1,000	High concentration. Well suited for online applications	Complex deconvolution algorithms. Diminished accuracy for complex distributions. Much sample information required	Wet	Volume	Good	Good	Good

*Resolution: Poor = Differentiates between dp (particle size) of X and 2X; Good = Differentiates between dp of X and 1.5X; Excellent = Differentiates between dp of X and 1.1X
**Precision: Poor = Coefficient of variation (of reported size parameter) >0.1; Good = Coefficient of variation from 0.1 to 0.02; Excellent = Coefficient of variation <0.02
***Accuracy: Poor = Measured value differs (from true value) by >20%; Good = Measured value differs by 2–20%; Excellent = Measured value differs by <2%

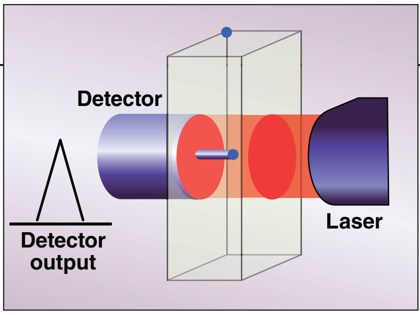


FIGURE 6. An optical particle counter can measure both the size and concentration of particle dispersions. Laser diodes and incandescent light bulbs have been used as the source of illumination

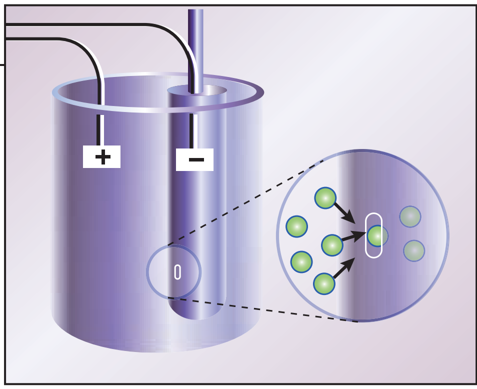


FIGURE 7. In a resistazone counter, a pressure differential drives a suspension of particles through a small orifice where an electrical current flows from one side to the other. The volume of electrolyte displaced within the orifice, which corresponds to the volume of the particle, is measured electronically from the change in resistance through the orifice

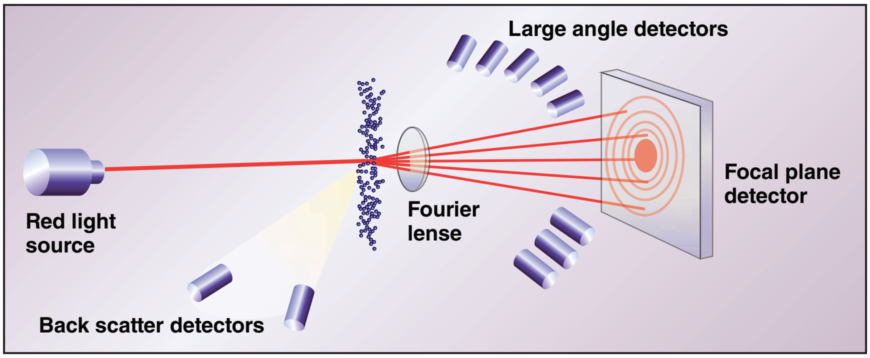


FIGURE 8. In a laser-diffraction-based size analyzer, the size distribution of a particle population is calculated from the group diffraction pattern projected onto the detector array. The large angle detectors are used to extend the lower limit of the size measurement. Laser diffraction is the most popular method of particle size analysis today

which in turn produces a pulse that is proportional to the amount of light blockage. The pulse height is compared to a calibration curve generated from uniform particles of known size, typically latex standards. A highly diluted particulate dispersion is a must to avoid coincidence counting (multiple particles in the sensing zone). Coincidence will affect the accuracy of the measurement in two ways: the particle count or concentration will be underestimated, and the particle size distribution (PSD) will be overestimated. It is therefore important to remain within the concentration limits of the instrument, as recommended by its manufacturer.

Optical counters have been used online for monitoring particulate levels of clean liquids and gasses, well below the parts-per-million (ppm) level. For higher concentration slurries, a precise sample volume is extracted from the process, injected into an autodilution system, and analyzed for size and concentration analysis.

Electrozone counters. Another instrument that was introduced in 1954 by Wallace H. Coulter uses the principal that when particles dispersed in an electrolyte move through a small orifice, the electrical resistance of a current flowing through the orifice changes. Furthermore, the change in electrical resistance is proportional to the volume of electrolyte displaced by the particle. The basic principle behind this instrument is illustrated in Figure 7. This technology can be found in virtually all hospital laboratories for analysis of complete blood count (CBC), and has also be used extensively in the paint, ceramics and glass industries.

Nano tracking analysis. A technique has recently been developed where the positions of individual nanosize particles undergoing Brownian diffusion are tracked in realtime using a charge-coupled device (CCD) camera mounted on a microscope. A tracking image-analysis software package measures the displacement of the particles in a two-dimensional plane using a series of successive images and calculates the diffusion coefficient from which the hydrodynamic diameter of the particle can be evaluated. Since the particles being tracked are too small for direct observation, a highly focused laser beam is used to illuminate the particles, which in turn scatter light towards the microscope objective. The lower limit of this technique is dependent on the optical properties of the particles, and range from 10 to 35 nm. The upper limit is around 1 µm.

Ensemble techniques

Although ensemble methods are the least accurate and suffer from the lowest resolution as compared to the other classes of techniques — especially in cases of non-spherical particles and wide distributions — they are the most widely used within virtually all industries. Despite the inherent disadvantages, ensemble measurement techniques are popular because they are typically simple to use, offer high throughput, have the ability to generate high-precision data and generally do not require calibration. Very often, in quality control, precision is the most important attribute of a measurement to insure consistency in the product. Ensemble techniques have been the most popular choice for online applications, with and without dilution.

Laser diffraction. Particle sizing by laser diffraction is the most popular method of particle size analysis today and models are available from many vendors. In laser diffraction, size distribution of a population of particles in suspension is measured from the angular variation in the intensity of light scattered by the particles. Modern instruments are equipped with modules for liquid dispersion as well as aerosol dispersion for wet or dry analysis. A particle with a diameter much larger than the wavelength of light scatters predominantly in the forward direction (Fraunhoffer diffraction), while a particle with a diameter that is of the same order as the wavelength will scatter more efficiently at wider angles. Figure 8 illustrates the basic principle behind laser diffraction instruments for the determination of particle size distribution. As an electromagnetic wave encounters a particle, a number of processes can occur, depending on the size and optical properties of the particle. Light and particle interaction can take place through external reflection, internal reflection, absorp-

KEY QUESTIONS TO ASK FOR SELECTION OF PARTICLE SIZE ANALYZERS

1. What is the expected size range of particles in the sample? The applicability of various analyzers for different size ranges is shown in Table 1. It is better to chose an instrument such that the measured size distribution is in the mid-range of instrument capability. Avoid measuring near the upper or lower size limits of instruments where the resolution and accuracy are usually lower.

2. What particle size parameter appropriately describes the process characteristics or the product quality? Measured particle size should be relevant to the system characteristics of interest. For example, projected area diameter is relevant in coating applications, whereas surface-volume diameter is relevant for fluidization applications. While numerical conversions between number, surface and volume distributions can be performed, the conversions are not accurate when the distribution is wide or when the shape deviates from spherical. Measure what you really want, especially when the particle shape is not spherical or the particle size range spans more than a factor of ten.

3. Is the shape information desired as the output? If shape is desired, imaging technology must be used.

4. Parameter of distribution of interest to be measured: a) distribution tails — coarse or fines; b) width of distribution; c) multimodal distribution. If size distribution spans less than a factor of ten, most instruments are suitable. For multimodal distributions or skewed distributions, avoid using laser diffraction techniques (unless validated). Use particle counters or fractionation techniques instead. For wide distributions (spanning greater than a factor of 1,000 of particle size range), nothing works well. In that case, sample must be fractionated into various cuts and then the distributions on each cut can be measured.

5. Is the absolute value of PSD important or is the change in PSD (QC objective) important? For quality control (QC) applications, laser diffraction is usually a good choice. It should be validated that the instrument is capable of adequate response to control the process — proper detection of important features in a distribution (detection limit or resolution). When measurement accuracy is desired, especially for extreme shapes (fibers, platelets, highly irregular particles), use image analysis. For bulky materials, laser diffraction or dynamic light scattering may be a good choice for simple distributions; other fractionation methods may be more appropriate for multi-modal or skewed distributions.

6. Does the application require online measurement? For online measurement, a technology that can measure at process concentration must be chosen or one that can auto-dilute the sample. For measurement at high concentrations, use ultrasonic spectroscopy, for moderate concentrations use laser diffraction, and dynamic image analysis, and use optical counters for low concentration.

7. What are your data quality objectives (accuracy, precision and resolution)? See Table 1.

8. What is the size of available sample? If sample size is limited, instruments requiring only the smallest sample are advantageous, but if large samples are readily available, instruments using larger samples reduce sampling errors. Optical counters require the smallest sample size and can detect and count every particle in the sample.

9. Is the native sample in dry state or in liquid dispersion? If dry, can it be dispersed in some liquid without dissolution, agglomeration, swelling, settling and attrition? If the sample is in a dry and free-flowing state, preferably use a dry measurement. If sample is in a wet dispersion, use a wet method. Use proper dispersing forces to measure individual particles without breaking them. Sample dispersibility, dilution and dispersion stability are critical factors. Sample delivery system must bring a representative sample to the measuring zone — no settling or segregation of larger particles. All fractionation techniques, ultrasonic spectroscopy and dynamic light scattering are suitable for wet analysis. Dynamic image analysis and laser diffraction can be performed in both wet and dry modes.

10. Is the sample composed of a single component or multiple components with different physical properties (differing in optical properties or densities)? Any optical detectors will be affected by multicomponent systems having different indices of refraction. Multicomponents with different densities will cause errors in sedimentation techniques. If particles are transparent and are a close match to the refractive index of the suspending medium, particles will be difficult or impossible to detect.

11. Is the suspending medium transparent? All optical devices need a transparent medium. For opaque medium, consider ultrasonics and x-ray detection or wet sieving. Sample dilution is another possibility.

12. How reliable is the technology? Consider a) frequency of calibration requirements and cost, and ease of calibration; b) extent of automation; c) operator dependence; d) mean time between failures. Calibration is usually not a big issue — modern instruments do not need frequent calibrations. All instruments need frequent verification using commercial or in-house standards. Most modern instruments are automated. Ensemble instruments (such as laser diffraction) tend to be simpler to use and have higher throughput. Most modern instruments are reliable and can operate a long time between failures.

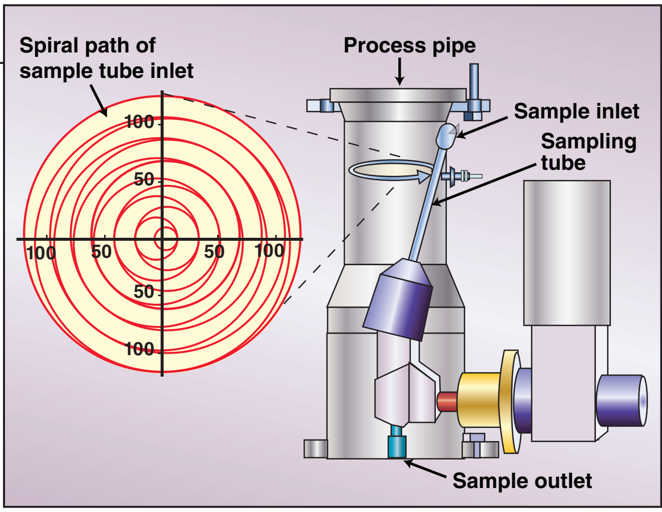
13. What is the cycle time (which includes sample preparation, analysis and cleaning)? Most ensemble techniques perform automatic rinsing and cleaning. Single particle counters are more difficult to rinse because a higher degree of cleanliness is necessary. Fractionation technology tends to have a longer analytical time for wide distributions. Fractionation is slower than an ensemble approach but offers higher resolution.

14. Is the technique capable of handling hazardous samples and limiting potential operator exposure to hazards during preparation, analysis and cleaning? Ask for special provision to handle hazardous materials. Most particle size analyzers are not designed for handling highly hazardous materials. Specified modifications must be made, such as, a closed sample loop, isolation in an enclosed space or hood, or special ventilation. ❏

tion and diffraction. If the particle diameter is large compared to the wavelength, (particle diameter > 20 µm) diffraction is the only significant phenomenon that needs to be considered. If the particle diameter is of the same order as the wavelength, a more complex scattering theory (Mie scattering) is applied where all light-particle interactions need to be considered. As a result, the reliability of laser diffraction instruments will be highly dependant on the optical system implemented and the robustness of the scattering models used when analyzing particles in the size range below a few microns in diameter.

Over the past decade, there have been developments that extend the application of laser diffraction technology into in-process monitoring for both dry and wet applications. For dry applications, a side stream from the process line is drawn and diluted with clean air if necessary and delivered to the sensing zone of the instrument. To insure representative sampling, automated samplers (Figure 9) have been designed to draw a small sample throughout the cross section of a process pipe. This technology has been successfully utilized for online monitoring of grinding and air classifying of powders, and has been used extensively in the cement industry.

For wet analysis, the key is to extract a representative sample from the process, dilute the sample and deliver it to the analyzer. Heavy dilution on



Source: Sympatec GmbH

FIGURE 9. This automated sampler is capable of extracting representative samples for dry material being transported through pipes. The sampled material is transported from the sample outlet and delivered to the instrument for analysis

the order of 1,000:1 is sometimes performed using multistage samplers.

Dynamic light scattering. Another ensemble technology for measuring colloidal systems that has become popular over the past decade uses the Brownian diffusion of the particles to deduce the size distribution. This technology is known as dynamic light scattering, photon correlation spectroscopy or quasi-elastic light scattering. As a beam of laser light shines through a colloidal dispersion, a large number of small particles encountered by the beam will scatter light in all directions. Careful monitoring of the intensity of this scattered light reveals fluctuations in its intensity over time. Those fluctuations, in which the size information of the particles is buried, are caused by the random Brownian motion of the particles. The higher diffusivity of the smaller particles generates higher frequency fluctuations, while the larger particles generate lower frequency fluctuations. A signal processing technique known as autocorrelation is typically used to extract the particle size information. This technique is suitable for any colloidal dispersion ranging in size from about 0.005 to 1 µm, is very reliable for unimodal distributions, and has been used extensively for the study of microemulsions, liposomes and latex. For suspensions having broad distributions, or for multimodal distributions, the extraction of the particle size distribution from the autocorrelation function becomes extremely difficult, and is therefore unreliable.

Acoustic spectroscopy. Recently, a technique has been developed to probe particles suspended in a liquid medium using ultrasound, thereby exploiting the inherent advantage that sound can propagate through opaque, high-concentration dispersions. Furthermore, sound waves interact with particle sizes ranging from 0.01 to 1,000 µm, thereby covering a remarkably broad range. A sonic wave is sent through the dispersion, which is mechanically agitated to maintain a homogeneous suspension, and its attenuation is measured. The distance traveled by the sonic wave is accurately known. The attenuation measurement resulting from the various extinction mechanisms (viscous, thermal, scattering and diffraction) is repeated for a series of frequencies ranging from 1 to 150 MHz.

Two distinct approaches are being used to extract particle size data from the attenuation spectrum: an empirical approach based on the Bouguer-Lambert-Beer law and a more fundamental or first-principles approach [*8*]. The first-principle approach implies that no calibration is required, but certain physical constants of both phases — such as speed of sound, density, thermal coefficient of expansion, heat capacity, thermal conductivity, attenuation of sound, viscosity for fluid phase and shear rigidity for solid phase — are required for accurate measurements. Ultrasonic spectroscopy technology, developed in the early 1990s, is proving useful in the lubricant and food industries for measurement of oil-in-water emulsions at process concentrations. As this technology further develops and matures, it is anticipated that it will find a wider range of industrial applications, especially for online applications. ■

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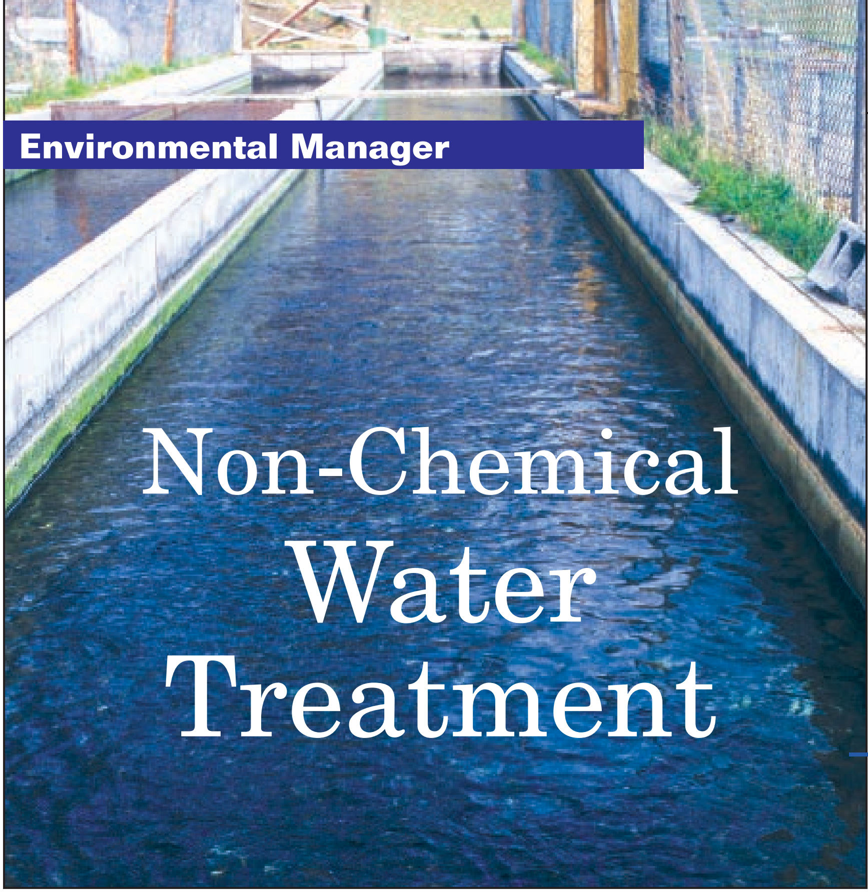

Environmental Manager

Non-Chemical Water Treatment

Mechanical processes can offer an environmentally friendly and safer option to chemical water treatment

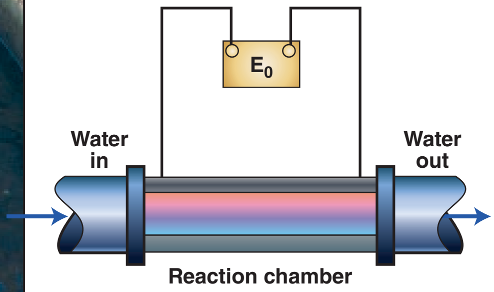

FIGURE 1. The efficacy of magnetic fields for reducing scaling, such as those produced by passing current through coils wrapped around a pipe, has been controversial for many years

William F. Harfst
Harfst and Associates, Inc.

Non-chemical methods for conditioning water for use in cooling towers and boilers have been investigated, marketed and installed for over 100 years. In light of the recent incentives to "go green," these methods offer engineers, operators and owners the option of replacing corrosive, toxic chemicals with physical or mechanical processes that claim to produce the same or superior results to those obtained by traditional chemical treatment methods — often without many of the attendant environmental, health and safety concerns.

Because of the growing interest in conserving water, reducing discharge of chemicals into the environment, limiting exposure of workers to hazardous chemicals, and the ever-present need to save energy, engineers are once again reviewing the benefits of non-chemical water treatment methods. A review of the literature along with many years of experience indicates that some of these methods produce results as promised by the manufacturer, whereas others fall short of this goal.

The array of non-chemical water treatment equipment is impressive. And the assertions for the benefits derived from using these devices are equally impressive. A simple, but not all-inclusive, list of equipment types is as follows:

- Magnetic
- Electrostatic
- Ultrasonic
- Galvanic or cathodic
- Electro-chemical
- Electro-deposition
- Electro-deionization (EDI)
- Membrane separation
- Ozone
- Ultraviolet

The claims made for these devices include the prevention of scale in boilers and heat exchangers and the control of corrosion on steel, copper, galvanized steel and other alloys. In the case of cooling tower operation, certain non-chemical methods are claimed to reduce bacterial growth that produces biofilms on system components.

This article offers an unbiased presentation and discussion of the claims made for the various non-chemical water treatment methods, a scientific explanation for how they work (or don't work), and recommendations for the selection and use of non-chemical water-treatment equipment in utility and process applications.

Magnetic field devices

Magnetic fields created by permanent and electromagnets are incorporated into many water conditioning devices. As early as 1873, A.T. Hay was issued a patent for the use of an electromagnetic field to prevent scale in steam locomotives. Since then, permanent magnets have been mounted inside pipe sections and reaction chambers or clamped to the outside of pipe runs to cause the water to be conditioned as it flows through the magnetic field.

More recently, induction coils (solenoids) producing anywhere from 0.060 to 100-kHz electromagnetic fields have been used to condition water. The coil is wrapped around a length of PVC or stainless-steel pipe to form a reaction chamber as shown in Figure 1. The strength of the magnetic field is proportional to the current flowing through the coil and the number of turns of the wire.

The manufacturers of this equipment claim that it controls scale in heat exchangers by modifying the surface charge on particulate matter in the water. This allows scale-forming ions, such as calcium and carbonate, to react on the surface of the particulate or colloidal matter resulting in the formation of calcium carbonate powder that preferentially settles out in the tower basin or is removed by a sidestream separator instead of forming hard, calcite scale in the heat exchanger.

The magnetic field is also said to control bacteria populations by "electroporation." By this method, bacteria cell walls are ruptured by exposure to electromagnetic fields that vary in strength over time.

A major disagreement and debate exists in the literature and amongst consultants on the efficacy of magnetic water-conditioning equipment. Most of the research on this subject has been conducted in the former Soviet Union with very favorable results. These devices are reported to be used with great success and economic advantage.

The results of independent investigations performed in the U.S., however, are almost universally negative. In a well-publicized paper presented in 1958 at the AWWA Annual Conference by Eliassen, Skrinde and Davis of the Massachusetts Institute of Technology [*1*], the conclusions reached by these researchers indicated that magnetic water conditioners produced no measurable or permanent change in the physical or chemical properties of water in terms of the ability of the magnetic field to alter scale formation or inhibit corrosion. The effect, if any, of the magnetic field would be limited to the residence time inside the reaction chamber. The magnetic field does not impart any permanent alteration of the chemical properties of the water.

This is not to say that electromagnetic devices do not have their ardent supporters. Very favorable results have been reported by investigators, but these are generally based on empirical evidence, visual inspections and testimonials from satisfied users. Typically, the research is conducted using protocols established by the manufacturers of the equipment who have a financial interest in the outcome of the evaluation. Clearly, further research by an independent, unbiased organization is required to verify and substantiate the claims made by the marketers of magnetic water conditioners.

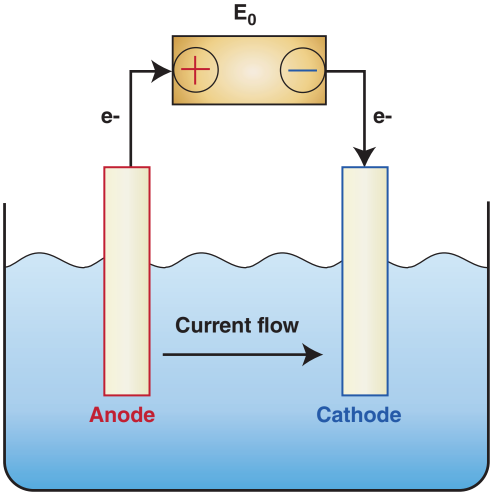

FIGURE 2. Electrochemical cells can be used to generate small quantities of chlorine or bromine for water treatment

Electrostatic devices

Another class of non-chemical water conditioning devices focuses on passing the water through an electrostatic charge. These are designed with a positively charged insulated, central electrode that is inserted into the center of a grounded cylindrical casing, which serves as the negative electrode. The application of high voltage on the central electrode produces an electrostatic charge across the annular space between the electrodes. The water is conditioned as it flows rapidly through the electrostatic field.

These units operate at 110–120 V (60 Hz), but typically draw a very low current of about 0.1 A. This suggests that very little work is done since the power requirement is only 1 to 2 W.

These devices are said to work by virtue of the water molecules being rearranged into an orderly array between the electrodes. This causes the scale-forming ions, such as calcium and magnesium, to be surrounded by a "cloud of water molecules," thus preventing scale formation. The device is also claimed to remove old scale deposits by promoting increased solubility through reduced surface tension of the water.

In addition to scale prevention, the manufacturers of electrostatic water-conditioning equipment claim that bacteria are controlled by disruption of the charged surfaces of the cell wall. This interferes with the organisms' ability to absorb nutrition and reproduce.

Like with the magnetic water conditioners, little independent evidence exists in the U.S. to support the claims made by the electrostatic equipment manufacturers beyond testimonials and subjective visual inspections of plant equipment. Several of these devices were actively marketed in the 1970s by reputable industrial-equipment manufacturers, but have since been discontinued.

Ultrasonic water treatment

Ultrasonic water treatment is primarily targeted at preventing or controlling bacterial growth in water-using systems. Sound waves outside the range of human hearing are produced by a low power, high-frequency generator inside a reaction chamber. The microorganisms are destroyed by the ultrasonic wave energy that causes fatal changes inside the bacteria cells.

The medical literature indicates that high-energy ultrasonic generators have been shown to be effective in killing bacterial and viral organisms. However, this requires high power and a prolonged contact time. Sizing a unit for a typical industrial cooling tower that is capable of providing sufficient power (kilowatts) at the design flowrate is a challenge.

Notwithstanding the size of the unit, the antibacterial properties of the ultrasonic device are limited to killing organisms that are free-floating in the water (planktonic). The ultrasonic waves produce no residual effect and are, therefore, incapable of controlling or limiting the growth of biofilms (sessile organisms) and algae.

Electrochemical methods

Several classes of water treatment equipment are designed around the fundamental scientific principles of electrochemistry. These rely on an anode (+), a cathode (-), a current path, and an electrolyte (in this case water). A simple illustration of an anode/cathode cell is depicted in Figure 2.

Sacrificial anodes and cathodic protection: Corrosion is considered to be an electrochemical process whereby current flows from the anode to the cathode. A chemical reaction (oxidation) occurs at the anode causing metal to be dissolved into

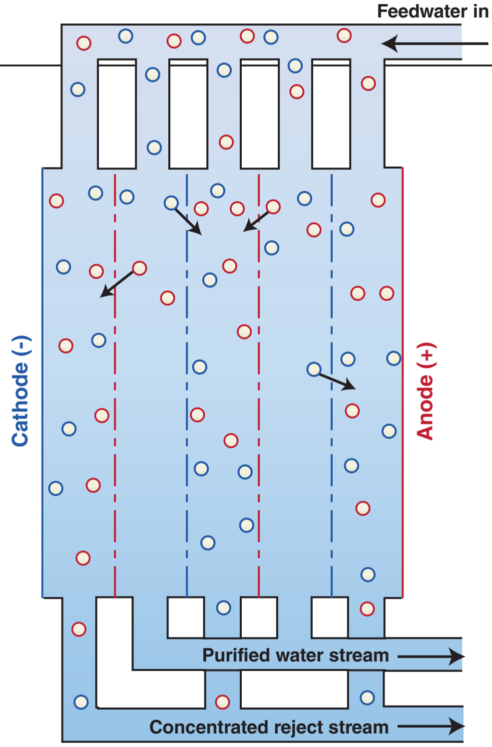

FIGURE 3. Electro-deionization is similar to reverse osmosis in that it utilizes ion exchange membranes and resins to separate the feedwater into a purified water stream and a concentrated brine stream

the water; that is, corrosion occurs at the anode. A complementary chemical reaction (reduction) occurs at the cathode. No corrosion occurs at the cathode as it is "protected" by the current that flows onto the metal surface from the anode.

If two dissimilar metals are coupled together in an anode/cathode cell, the less noble or less stable metal will become the anode. The anode is sacrificed thereby protecting the more noble metal, which functions as the cathode. Thus, if zinc is coupled with steel, for example, the zinc anode will be consumed as current flows from the zinc onto the steel. The higher the corrosion current, the faster the anode will be consumed. Galvanized steel is thus protected by virtue of the 3–4 mil zinc coating being slowly sacrificed to protect the underlying steel.

It is possible to enhance the corrosion protection by impressing a d.c. current from either a battery or rectifier. In this case, the impressed current flows from the anode through the water and onto the cathode. Sufficient overvoltage must be applied to establish a current density on the metal surface that is sufficient to maintain passivation of the metal to be protected. The negative terminal of the rectifier must be connected to the structure to be protected, otherwise it will be established as the anode (+) and corrode. This corrosion control method is used to protect buried and underwater structures, gas pipe lines, ship hulls and water towers throughout the world.

Electrolysis: Direct current (d.c.) electricity is used to produce oxidation/reduction chemical reactions in a variety of chemical processes. Chlorine, caustic soda, aluminum, magnesium and copper are made or refined industrially in large electrochemical cells.

On a smaller scale, electrolysis can be used to generate chlorine and bromine on site from an electrolytic cell that uses sodium chloride salt or a mixture of sodium chloride and sodium bromide salts as the feedstock. In this case, a prepared 3–4% brine solution is used to produce chlorine at the anode with hydrogen and hydroxide produced at the cathode. The chlorine is mixed with water to produce a 0.4–0.8% sodium hypochlorite solution that is either stored in a holding tank for future use or dosed directly from the generator into the tower. The hydrogen is vented to the atmosphere.

Onsite electrochemical chlorine generators eliminate the need to store gaseous chlorine, which is a regulated substance, and 12% liquid chlorine, which is corrosive and tends to slowly decompose during storage.

Electro-deposition: One of the fundamental goals in cooling tower operation is to prevent scale deposition on heat transfer surfaces due to the precipitation of sparingly soluble salts of calcium carbonate, magnesium hydroxide and silica. This is traditionally accomplished by the judicious control of tower bleed to limit the cycles of concentration. Chemical scale inhibitors are also routinely used to enhance the solubility of these scale-forming salts.

More recently, a new method of scale control has been introduced that removes these scale forming impurities by the electrochemical deposition of calcium and magnesium (and other) salts at the cathode of an electrochemical cell. Direct current is applied to the cell at a rate sufficient to drive the precipitation reactions at the cathode. These devices are electro-synthesis cells that produce a buildup of calcium hydroxide, magnesium hydroxide and other salts at the cathode. These insoluble salts are then removed to allow the continued flow of current from anode to cathode.

The driving force for the electrochemical cell reaction is determined by the voltage applied between the electrodes. The total voltage is determined by the theoretical voltage, which is the sum of the anode and cathode half-cell voltages; the overvoltage required to achieve the desired production level; and the electrolyte resistivity (water resistivity). This determines the total cell voltage required to drive the reaction.

The current requirement can be estimated from a formula worked out by Faraday that expresses the quantity of electric charge required to produce the desired yield of precipitated salt. This is the product of the electric current and the length of time it flows through the cell. The estimated power requirement is determined by multiplying the voltage times the current flow to yield the kilowatt-hour per kilogram of salt produced. Because of the high electrical resistance of water, the power cost for this process can be significant over traditional chemical treatment methods.

Other factors that should be reviewed with this process include the cost for equipment maintenance, solids disposal and electrode replacement. As with all electrochemical processes, the selection and durability of the anode is important.

Microbiological control

Ozone: Ozone is second only to fluorine as an oxidizing agent. As such, ozone functions as a very strong oxidizing biocide in cooling towers and drinking water systems. It has been marketed as an alternative to other oxidizing biocides, such as chlorine and bromine, for bacteria and algae control in cooling towers since 1970.

Ozone is produced in a corona discharge generator by passing a stream of dry air through an electric arc to yield O_3. The generators come in various output capacities depending on the rated capacity of the cooling tower and microbiological demand. Typically, 0.5 to 1.0 lb of ozone per 100 tons of air conditioning is employed. The power consumption is about 15 kWh per pound of ozone produced.

Most experts agree that ozone is very effective in controlling microbiological growths in cooling towers. However, additional claims by ozone proponents that it conserves water, prevents scale deposition and mitigates corrosion are in dispute. Some ozone programs have been applied with no tower bleed resulting in the deposition of a white sludge in the tower basin and low flow areas of the system. Because it is such a strong oxidizing agent, ozone tends to attack materials of construction if overly applied or poorly controlled.

Ultraviolet light: Ultraviolet (UV) lamps produce light with a wavelength of 254 nm. When bacteria are exposed to UV radiation, the organisms are rendered unable to reproduce and thus considered dead. This process is most effective in water that is relatively clean and pure to minimize the absorption of light by suspended solids and other debris.

The UV dosage required to destroy microorganisms is measured in microwatt-seconds per centimeter squared ($\mu Ws/cm^2$). Depending on the organism (bacteria, yeast, mold, viruses, algae), this can vary from 2,500 to over 26,000 $\mu Ws/cm^2$.

Ultraviolet light is only lethal during the time that the organism is exposed directly to the light. It produces no residual effect in the water and therefore, does not kill biofilms that form on surfaces not exposed to the UV radiation.

Membrane separation

Another class of non-chemical water treatment methods that have come into their own in the last 30 years is reverse osmosis (RO) and electro-deionization (EDI). These processes remove over 99% of the dissolved solids present in the raw feedwater to produce a purified water stream.

Reverse osmosis (RO): RO utilizes a pressure differential across a semi-permeable membrane to reject dissolved salts at the membrane surface while allowing the purified water to permeate through the pores of the membrane. These membrane separators have been fabricated in a variety of configurations including spiral wound and hollow fiber modules. (For more information, see: Strategies for Water Reuse, *CE*, September 2009, pp. 34–39.)

The RO process produces a concentrated brine stream that is typically 25% of the feedwater flow. As such, reverse osmosis has a lower recovery rate of 75% as compared to ion exchange. Unless a use for the RO reject is found, reverse osmosis will consume more fresh water than ion exchange.

On the positive side, RO is a continuous process that doesn't require the use of regeneration chemicals like concentrated acid and caustic soda that are used in the batch regeneration of ion exchange demineralizers.

Electro-deionization (EDI): This process is similar to RO in that it utilizes ion exchange membranes and resins to separate the feedwater into a purified water stream and a concentrated brine stream. Instead of pressure differential, however, this is done in conjunction with an electric field produced by the potential difference between an anode (+) and cathode (–). The potential difference between the electrodes creates the driving force across the membrane. Positively charged ions selectively pass through the membrane and are attracted to the cathode. Negatively charged ions are separated by the membrane and move toward the anode. The result is a final product stream of de-ionized water as illustrated in Figure 3.

Reverse osmosis and electro-deionization are used in many applications to replace more traditional ion-exchange processes. When used in place of ion exchange demineralizers, for example, the acid and caustic regeneration chemicals can be eliminated. This limits worker exposure to these chemicals, reduces the amount of acid and caustic discharged to waste, and eliminates the need to purchase, ship, store and handle corrosive chemicals.

Concluding remarks

The non-chemical water treatment methods discussed in this article share one thing in common. They utilize electric current in one fashion or another to condition water. Instead of buying, shipping, storing and feeding chemicals to prevent scale, mitigate corrosion, and control microbiological growths, these devices simply plug into the wall. This feature offers many benefits at a time when plants are seeking ways to decrease worker exposure to hazardous chemicals and reduce waste disposal costs.

However, as indicated, some of these devices make claims that are difficult to substantiate based on independent, unbiased, scientific evaluation. As expected, the manufacturers of this equipment offer testimonials and case studies to support their claims. Notwithstanding claims to the contrary, many cases have been reported where the equipment failed to perform as advertised, resulting in equipment damage and unscheduled downtime. For this reason, it is best to seek the advice of an unbiased, knowledgeable expert when considering the application of non-chemical water treatment methods.

The good news is that when properly applied, many of the non-chemical technologies discussed in this article help plants conserve water, reduce chemical consumption, minimize waste, and save energy. This is not only good for the environment, but good for business, too. ■

Edited by Gerald Ondrey

Reference

1. Eliassen, R., Skrinde, R. T., Davis, W. B., Experimental Performance of 'Miracle' Water Conditioners, *J.Am. Water Works Assoc.*, Vol. 50, No. 10, October 1958.

Author

William Harfst is president of Harfst and Associates, Inc., an independent water management consulting firm (P.O. Box 276, Crystal Lake, Ill. 60039; Phone: (815) 477-4559; Email: wfh@mc.net; Website: www.harfstassociates.com). He has over 36 years of water treatment experience helping industrial, institutional, commercial and government clients select, apply and control water treatment programs for boiler, cooling and wastewater applications. He graduated from the University of Illinois with a B.S. in Chemistry cum laude in 1972 and went on to hold various technical and management positions with three major water treatment companies before starting his consulting practice in 1991. His current focus is on helping clients conserve water, reduce chemical consumption, minimize waste and save energy.

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Flow Measurement

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Flowrate totalizer simplifies the sums

Specifically designed for computing and displaying flowrates and totals from flowmeters with pulse, sine-wave or frequency outputs, the RT20 Rate Totalizer (photo) can be battery or externally powered and features a large six-digit LCD total, eight-digit cumulative totalizer and five-digit rate display. The instrument displays resettable (batch) total, cumulative total and instantaneous flowrate in engineering units as programmed by the user. A robust IP66/67-NEMA 4X aluminum field and panel mountable housing makes the unit suitable for the most rugged applications. It also features a backlit panel enabling distance viewing at night when de-powered. The RT20 is designed for simple PIN protected flowchart programming with English language prompts guiding users through the programming routine thereby reducing the need to refer to the instruction manual. — *Trimec (Europe) Ltd, Haywards Heath, West Sussex, U.K.*
www.trimec-europe.com

Vortex flowmeters fight corrosion with a stainless steel shield

The Rosemount 8800D Series of vortex flowmeters (photo) has recently been expanded to include stainless-steel transmitter housings, which are often required for applications in corrosive environments. The new housing increases the reliability and longevity of the transmitter in these environments, greatly reducing the overall cost of ownership. Typical applications for the non-clogging, minimal leak-point design include food, beverage and life science applications, where the numerous chemical processes and clean-in-place solutions can result in corrosion and premature failure, plus offshore oil and gas applications and high pressure gas or water injection for enhanced oil recovery. — *Emerson Process Management, Baar, Switzerland*
www.emersonprocess.eu

New product line is certified for greenhouse gases measurement

This new line of GHG mass flowmeters (photos, top right) is certified by the manufacturer for compliance with the U.S. EPA's recent greenhouse gas (GHG) reporting rule (40 CFR Part 98; for more see *CE*, March, p. 17). Certified mass flowmeters provide an economical way to totalize methane or natural gas burned, enabling the calculation of CO_2 equivalent emissions, says the manufacturer. Meanwhile, models are available for producing highly accurate and repeatable results for CH_4 as well as N_2O, SF_6, HFCs, PFCs and CO_2, as called out in the EPA mandate. To make it easier for customers facing this measurement challenge, a team of flow application and service engineers has been trained in the EPA's GHG reporting rule and is available to answer customer questions. — *Sierra Instruments, Monterey, Calif.*
www.sierrainstruments.com

Monitor non-condensing and saturated steam within 1%

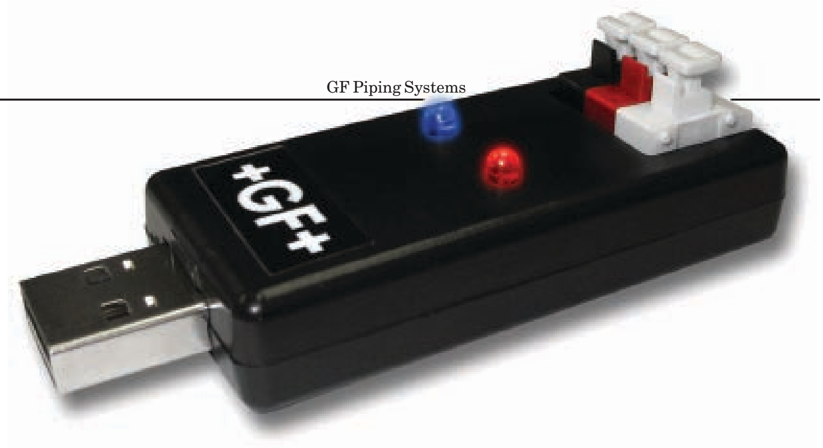
Designed for boiler monitoring and other energy-related uses, RNS Series (insertion) and RWS Series (wafer) vortex steam flowmeters are suitable for measuring non-condensing steam and saturated process steam at pressures up to 150 psi. The meters have no moving parts and are virtually maintenance-free, working in operating temperatures of –20 to 366°F. The units can compensate for changes in temperature and pressure, achieving accuracies of ±1% of reading and repeatability of 0.5%. — *Racine Federated, Racine, Wisc.*
www.racinefed.com/vortex.cfm

Dust-proof, water-proof and suitable for hazardous environments

Designed according IP65 requirements for dust- and water-proof operation, the new In-Flow CTA mass flowmeters (photo) work on the basis of direct through-flow measurement (no bypass), following the constant-temperature-anemometer principle. The modular, rugged construction contains no moving parts and has no obstructions to the flow path, which makes the instruments

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

Bronkhorst Cori-Tech



GF Piping Systems

ideal for low pressure-drop applications and virtually insensitive to moisture or particulates. ATEX approval covers use in Category 3, Zone 2 hazardous areas. The flowmeters can be combined with integrated or close-coupled control valves to form compact, digital mass-flow controllers, covering the range of 10–200 mL/min up to 50–5,000 L/min. — *Bronkhorst High-Tech B.V., Ruurlo, The Netherlands*
www.bronkhorst.com

Convert local flow signals for long distance transmission

Signet 8550 Meters (photo) convert the signal from a Signet flow sensor into a 4–20-mA signal for long distance transmission. Features include single or dual input/output, two optional relays for process control, and scalability for virtually any flow range or engineering unit. Suitable applications include flow control, monitoring and leak detection of water and wastewater and other chemical process applications. The 8550 is available in three packaging options for maximum configuration flexibility: integral-pipe, universal field mount or panel installation. Performance characteristics include an operating temperature of –10 to 70°C (14 to 158°F), state-of-the-art electronic design for longterm reliability, signal stability and simple user setup and operation. — *GF Piping Systems, Tustin, Calif.*
www.gfpiping.com

(Continues on p. 72)

Siemens AG

Manage flow data remotely and see production improvements

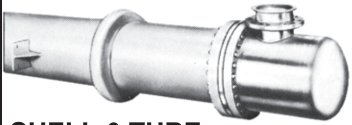
The new remote data manager Sitrans RD500 (photo) integrates Web access, alarm event handling and data capture for remotely installed flowmeters and other process instruments, and offers a solution to many applications where regular data access to instrumentation and the data they provide are limited. For instance, remote monitoring of raw material inventory at multiple production sites supports just-in-time production, and results in lower logistic and clean up costs for the manufacturer and supplier. In applications where remote leak detection is desired, Sitrans FUS ultrasonic clamp-on flowmeters can be fitted on both ends of a pipeline to ensure there are no leaks, and no material is being lost during transport between tanks. The meters are remotely monitored using a Sitrans RD500, and the information is made available at a central location where possible leaks can be identified and trigger an alarm. The compact Sitrans RD500 requires only simple configuration: no engineering or programming is required. It accepts analog, voltage, digital, temperature and Modbus inputs, and provides flexible communications options via Ethernet, cellular and landline modems. Standard data transfer options are offered for regular reporting and alarms to remote servers, email-clients — including cell phone, PDA and desktop computers — and SMS messaging. — *Siemens AG, Industry Automation Div., Nuremberg, Germany*
www.siemens.com/sitransrd

Install this multivariable unit without process shutdown

The MassTracker insertion style turbine flowmeter, combines measurement of mass or volumetric flow, density, temperature and pressure in one instrument. With a wide 25:1 turndown, typical applications include flow monitoring of steam and natural gas for fiscal or load control, combustion air, fluegas for environmental compliance, heat content calculations for chilled water and measurement of a variety of other liquids in line sizes from 3 to 80 in. (75 mm to 2,000 mm). Hot-tappability makes installation and service possible without process shutdown. A negligible pressure drop limits energy and operating costs. — *Spirax Sarco, Inc., Blythewood, S.C.*
www.spiraxsarco.com ■

Rebekkah Marshall

HEAT EXCHANGERS



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Extraordinariat (W 2) für Industrielle Biokatalyse

erstmals zu besetzen. Bei der Professur handelt es sich um eine Stiftung der Süd-Chemie AG (München). Die Stiftungsprofessur ist zunä chst auf 5 Jahre befristet.

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Die Bewerberin/der Bewerber soll sich an der Lehre im Bereich Biotechnologie, Biochemie und Chemie beteiligen. Eine wichtige Aufgabe ist die Mitwirkung am Aufbau eines neuen, fakultä tsübergreifenden Master-Studiengangs *Industrial Biotechnology* zum WS 2010/11.

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Die Technische Universitä t München hat sich in der Exzellenzinitiative des Bundes und der Lä nder das strategische Ziel gesetzt, den Anteil von Frauen in Forschung und Lehre deutlich zu erhöhen. Wissenschaftlerinnen werden deshalb nachdrücklich um ihre Bewerbung gebeten.

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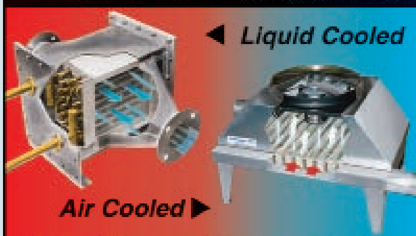

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BUSINESS NEWS

PLANT WATCH

Outotec to deliver a copper smelter for plant in China

March 16, 2010 — Outotec Oyj (Espoo, Finland; www.outotec.com) has been awarded a contract by Tongling Non-Ferrous Metals Group for the design and delivery of a new copper smelter to be built in Jinchang in Anhui province, China. The new plant will have a capacity of 200,000 metric tons per year (m.t./yr) of copper. The capacity will be expanded to 400,000 m.t./yr in a second phase with minor adjustments. The new smelter is scheduled to start up in mid-2012.

Air Liquide to build ASU in China for steel producer

March 16, 2010 — Air Liquide (Paris; www.airliquide.com) has signed a longterm contract, by which it will invest about €40 million in Yichun, Heilongjiang Province (northeastern China), to supply Xilin Steel Group with oxygen, nitrogen and argon. A 1,200 m.t./d air separation unit (ASU) will be designed and built by Air Liquide Hangzhou, the engineering teams of Air Liquide in China, and will be commissioned in 1st Q 2012.

Lanxess to expand capacity of high-performance rubber

March 9, 2010 — Lanxess AG (Leverkusen, Germany; www.lanxess.com) has plans to expand the global capacity of Neodymium Polybutadiene (Nd-PBR). Lanxess will invest about €20 million to increase production by an additional 50,000 m.t./yr at its sites in Dormagen, Germany; Orange, Tex.; and Cabo, Brazil. The extra capacities will go onstream between the 1st Q of 2011 and 1st Q of 2012.

Outotec also to supply sinter plant to South Africa

March 8, 2010 — Outotec Oyj has an agreement with South African Kalagadi Manganese Pty. Ltd. for the design and delivery of a manganese sinter plant to be built in Hotazel in the country's Northern Cape Province. The new plant will ultimately produce 2.4-million m.t./yr of sinter. The plant commissioning is scheduled for March 2012.

Linde strengthens specialty gases capabilities in Africa

March 8, 2010 — Linde Gases, a division of The Linde Group (Munich, Germany; hiq.linde-gas.com), has announced that it is making a €1.2-million investment in expanding and upgrading its specialty gases plant in Johannesburg, South Africa. The new plant will enable Linde to produce a greater range of specialty gases mixtures onsite. While most of the outlay will be capital expenditure for new equipment, a significant amount has been invested in making the plant more environmentally friendly. This includes silencers for noise-pollution mitigation as well as scrubbers to reduce greenhouse gas emissions.

Total announces plans to repurpose its Dunkirk refinery site

March 8, 2010 — Total (Courbevoie, France; www.total.com) has presented a plan to permanently shut down refining operations at its Dunkirk site. Under the plan, the Flandres refinery, which reported a loss of more than €130 million in 2009, will shut down, resulting in a gradual dismantling of units that could continue to 2013. The refinery will be repurposed as an industrial and technical facility engaged in three new activities: a refining operations support center; a refining training center; and a logistics depot.

Uhde's Prenflo process to be part of joint R&D project BioTfueL in France

March 8, 2010 — BioTfueL is a new joint project launched by five French partners and Uhde GmbH (Dortmund, Germany; www.uhde.eu). BioTfueL integrates the various technology stages of the so-called biomass-to-liquid (BTL) chain. The overall budget for the BioTfueL project is €112.7 million, which includes the construction and operation of two pilot plants in France to produce biodiesel and biokerosene based on biomass gasification using Uhde's Prenflo-PDQ process. The plants are scheduled to go into operation in 2012.

MERGERS AND ACQUISITIONS

Eastman Chemical to acquire Genovique Specialties

March 17, 2010 – Eastman Chemical Co. (Kingsport, Tenn.; www.eastman.com) has entered into an agreement to acquire Genovique Specialties Corp., a global producer of specialty plasticizers, benzoic acid, and sodium benzoate. Following the completion of the transaction, Genovique Specialties will become part of Eastman's Performance Chemicals and Intermediates segment. The acquisition is expected to be completed after receipt of required regulatory approvals and satisfaction of other customary closing conditions. Terms of the transaction were not disclosed.

Bayer MaterialScience acquires Artificial Muscle

March 9, 2010 — Bayer MaterialScience LLC (BMS; www.bayermaterialscience.com), a subsidiary of Bayer AG (Leverkusen, Germany; www.bayer.com), has acquired Artificial Muscle, Inc. (AMI; Sunnyvale, Calif.). AMI is a pioneer in the field of electroactive polymers for the consumer electronics industry. The purchase price is being kept confidential.

Toyo, Modec and Petrobras cooperate to verify small- and medium-scale GTL plant

March 8, 2010 — Toyo Engineering Corp. (Toyo; www.toyo-eng.co.jp) and Modec, Inc. (both Tokyo, Japan; www.modec.com), which have been working together on the development of gas-to-liquids (GTL) technology, concluded a cooperation agreement with Petroleo Brasileiro S.A. (Petrobras; www2.petrobras.com.br) to construct a verification facility. This facility will be constructed within the Petrobras refinery, located in Fortaleza, Ceara, Brazil (for more, see p. 16). Construction is due to finish at the beginning of 2011 when the verification operation will take place, and data will be collected for designing commercial plants. The new GTL process will enter the commercialization phase by the end of 2011.

Merck KGaA plans to acquire Millipore

March 1, 2010 — Merck KGaA (Darmstadt, Germany; www.merck.de) and Millipore Corp.; Billerica, Mass.; www.millipore.com) have entered into a definitive agreement under which Merck KGaA will acquire all outstanding shares of common stock of Millipore, for a total transaction value, including net debt, of approximately €5.3 billion ($7.2 billion). The transaction was approved by the boards of directors of both companies. Merck plans to maintain Millipore's headquarters in Billerica and combine it with Merck's U.S. chemicals headquarters. Completion of the acquisition requires the approval of Millipore shareholders. Merck anticipates that the transaction will be completed in the 2nd half of 2010.

Evonik acquires catalyst business from H.C. Starck

March 1, 2010 — Evonik Industries AG (Essen, Germany; www.evonik.com) has acquired the catalyst business of H.C. Starck GmbH (Goslar, Germany). Following a transition phase, Evonik will produce the Amperkat catalysts in Hanau, Germany. ■

Dorothy Lozowski

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April 2010; VOL. 117; NO. 4

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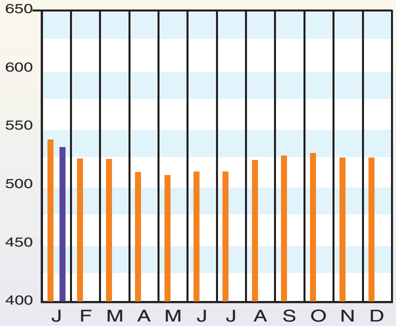
Process machinery	601.9	597.9	620.0
Pipe, valves & fittings	794.5	776.3	781.8
Process instruments	419.7	417.5	389.6
Pumps & compressors	903.0	895.2	902.1
Electrical equipment	469.2	467.2	457.9
Structural supports & misc	640.2	620.0	671.5
Construction labor	330.8	331.2	324.5
Buildings	494.7	494.6	500.0
Engineering & supervision	342.4	343.2	350.3

Annual Index:
2002 = 395.6
2003 = 402.0
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9



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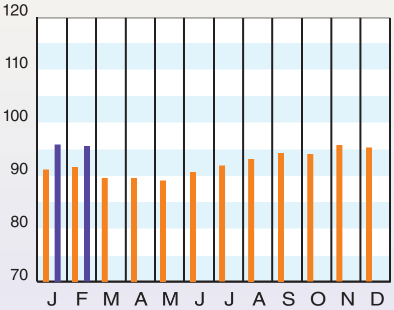
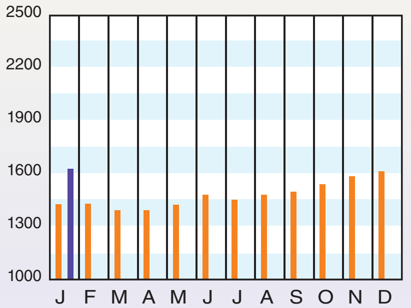
CURRENT BUSINESS INDICATORS

	LATEST			PREVIOUS						YEAR AGO		
CPI output index (2000 = 100)	Feb.'10	=	95.6	Jan.'10	=	95.9	Dec.'09	=	95.3	Feb.'09	=	91.7
CPI value of output, $ billions	Jan.'10	=	1,629.0	Dec.'09	=	1,616.8	Nov.'09	=	1,587.0	Jan.'09	=	1,427.8
CPI operating rate, %	Feb.'10	=	71.1	Jan.'10	=	71.1	Dec.'09	=	70.6	Feb.'09	=	66.8
Producer prices, industrial chemicals (1982 = 100)	Feb.'10	=	265.7	Jan.'10	=	260.1	Dec.'09	=	254.9	Feb.'09	=	224.1
Industrial Production in Manufacturing (2002=100)*	Feb.'10	=	99.1	Jan.'10	=	99.3	Dec.'09	=	98.4	Feb.'09	=	97.7
Hourly earnings index, chemical & allied products (1992 = 100)	Feb.'10	=	151.2	Jan.'10	=	150.8	Dec.'09	=	150.9	Feb.'09	=	145.8
Productivity index, chemicals & allied products (1992 = 100)	Feb.'10	=	137.6	Jan.'10	=	134.3	Dec.'09	=	134.1	Feb.'09	=	129.1

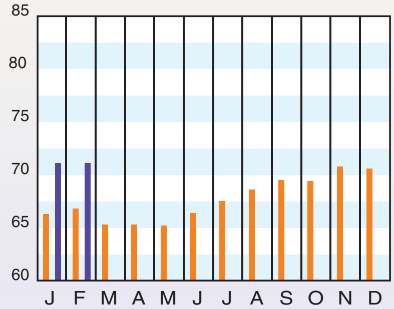
CPI OUTPUT INDEX (2000 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)

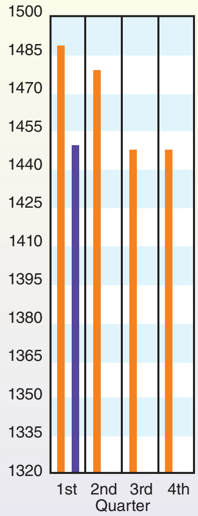


MARSHALL & SWIFT EQUIPMENT COST INDEX

(1926 = 100)	1st Q 2010	4th Q 2009	3rd Q 2009	2nd Q 2009	1st Q 2009
M & S INDEX	1,448.3	1,446.5	1,446.4	1,477.7	1,487.2
Process industries, average	1,510.3	1,511.9	1,515.1	1,553.2	1,561.2
Cement	1,508.1	1,508.2	1,509.7	1,551.1	1,553.4
Chemicals	1,481.8	1,483.1	1,485.8	1,523.8	1,533.7
Clay products	1,496.0	1,494.3	1,495.8	1,526.4	1,524.4
Glass	1,403.0	1,400.1	1,400.4	1,439.8	1,448.1
Paint	1,515.1	1,514.1	1,515.1	1,554.1	1,564.2
Paper	1,416.4	1,415.8	1,416.3	1,453.3	1,462.9
Petroleum products	1,615.6	1,617.6	1,625.2	1,663.6	1,668.9
Rubber	1,551.0	1,560.5	1,560.7	1,600.3	1,604.6
Related industries					
Electrical power	1,389.6	1,377.3	1,370.8	1,425.0	1,454.2
Mining, milling	1,552.1	1,548.1	1,547.6	1,573.0	1,567.5
Refrigeration	1,772.2	1,769.5	1,767.3	1,807.3	1,818.1
Steam power	1,475.0	1,470.8	1,471.4	1,509.3	1,521.9

Annual Index:

2002 = 1,104.2	2004 = 1,178.5	2006 = 1,302.3	2008 = 1,449.3
2003 = 1,123.6	2005 = 1,244.5	2007 = 1,373.3	2009 = 1,468.6



CURRENT TRENDS

Current Business Indicators continue to improve, and according to the American Chemistry Council's 1st Quarter Outlook, global chemical output is expected to rise 6.5% in 2010, and expand further in 2011 and 2012. The report concludes that the U.S. recession, which officially began in December 2007, ended in the summer of 2009 and has since followed a V-shaped growth trajectory.

Meanwhile, the 2009 overall average for capital equipment prices (as reflected in the *CE* Plant Cost Index) hit its lowest level in more than two years. ■

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