CHEMICAL ENGINEERING
CONTROLLING SUSPENSION RHEOLOGY • METHANE REFORMING
VOL. 122 NO. 1 JANUARY 2015

CHEMICAL ENGINEERING

January 2015

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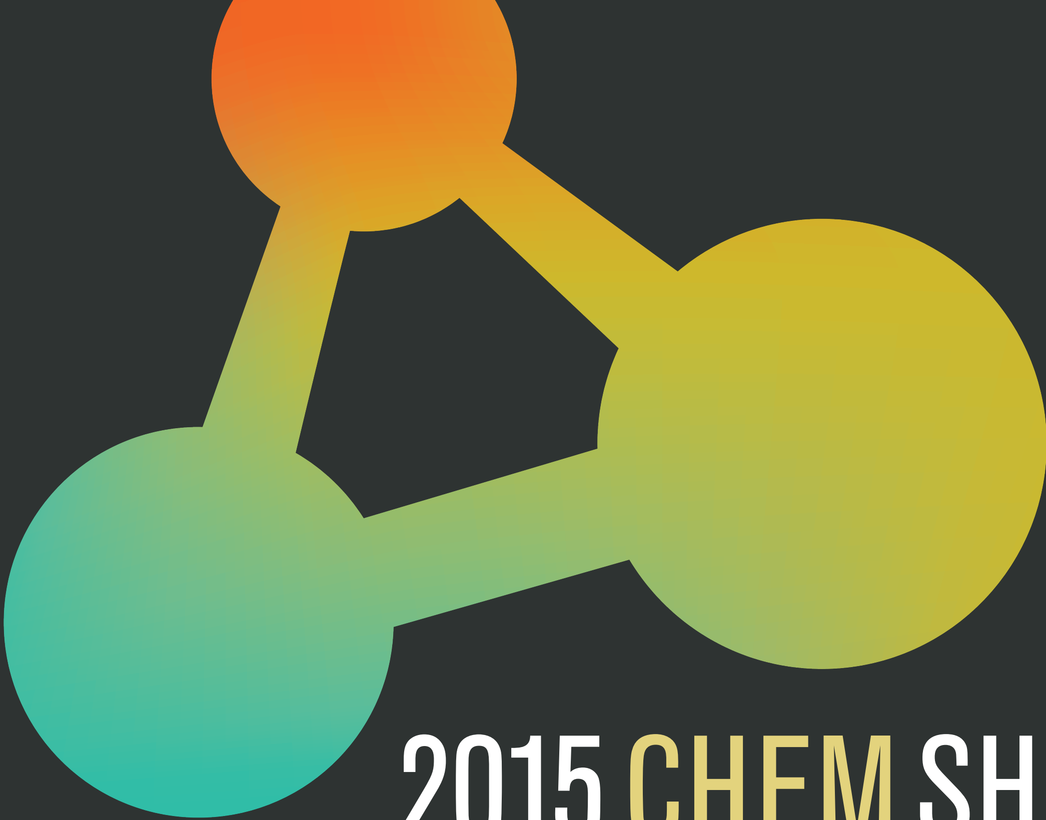

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PUBLISHER

MICHAEL GROSSMAN
Vice President and Group Publisher
mgrossman@accessintel.com

EDITORS

DOROTHY LOZOWSKI
Editor in Chief
dlozowski@chemengonline.com

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

SCOTT JENKINS
Senior Editor
sjenkins@chemengonline.com

MARY PAGE BAILEY
Assistant Editor
mbailey@chemengonline.com

AUDIENCE DEVELOPMENT

SARAH GARWOOD
Audience Marketing Director
sgarwood@accessintel.com

JESSICA GRIER
Marketing Manager

GEORGE SEVERINE
Fulfillment Manager
gseverine@accessintel.com

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

ART & DESIGN

ROB HUDGINS
Graphic Designer
rhudgins@accessintel.com

PRODUCTION

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

INFORMATION SERVICES

CHARLES SANDS
Director of Digital Development
csands@accessintel.com

CONTRIBUTING EDITORS

SUZANNE A. SHELLEY
sshelley@chemengonline.com

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

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

TETSUO SATOH (Japan)
tsatoh@chemengonline.com

JOY LEPREE (New Jersey)
jlepree@chemengonline.com

GERALD PARKINSON
(California)
gparkinson@chemengonline.com

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EUROPEAN EDITORIAL OFFICES

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

CIRCULATION REQUESTS:

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Editor's Page

The Kirkpatrick Award: Call for nominations

As this new year opens, we at *Chemical Engineering* are looking forward to the wide variety of articles, activities and offerings that we have lined up for our readers. A highlight of 2015 is to honor the most-noteworthy chemical engineering technology commercialized anywhere in the world during 2013 or 2014 with this magazine's 2015 Kirkpatrick Chemical Engineering Achievement Award.

Chemical Engineering has awarded this biennial prize continuously since 1933. The 2015 winner will join a distinguished group that includes milestones such as Genomatica's process for bio-based 1,4-butanediol (BDO; 2013); Chevron Phillips Chemical for significant advances in alpha-olefins technology (2005), Cargill Dow LLC for its production of thermoplastic resin from corn (2003); and Carbide & Carbon Chemical's petrochemical syntheses (1933). The full list of winners can be found at www.chemengonline.com/kirkpatrick/.

How to nominate

Nominations may be submitted by any person or company, worldwide. The procedure consists simply of sending, by March 15, an unillustrated nominating brief of up to 500 words to: awards@chemengonline.com

In order to be considered, each nomination should include the following: 1) a summary of the achievement and novelty of the technology; 2) a description of the difficult chemical-engineering problems solved; and 3) a description of how, where and when the development first became commercial in 2013 or 2014.

If you know of an achievement but do not have information to write a brief, contact the company involved, either to get the information or to propose that the firm itself submit a nomination. Companies are also welcome to nominate achievements of their own.

The path to the winner

After the deadline for nominations, March 15, we will review the nominations for validity. The nominations will then be sent to senior professors at accredited university chemical-engineering departments, who accordingly, constitute the Committee of Award. Each professor will vote, independently of each other, for a maximum of five best achievements.

The entries that collectively receive the most votes become the finalists in the competition. Each finalist company will then be asked to submit more-detailed information, such as a description of the technology, performance data and examples of the teamwork that generated the achievement.

Copies of these more-detailed packages will then be sent to a Board of Judges, which will have been chosen from within the Committee of Award. The Board will judge the entries to select the most noteworthy. The company that developed that achievement will be named the winner of the 2015 Kirkpatrick Chemical Engineering Achievement Award and the other finalist companies will be designated to receive Honor Awards. The awards will be bestowed in November at the Chem Show in New York. ■

Dorothy Lozowski, Editor in Chief

Letters

AIChE names new officers for 2015

The American Institute of Chemical Engineers (AIChE) has announced that Cheryl Teich, reaction engineering expertise area leader at The Dow Chemical Company (Dow; Midland, Mich.), becomes president of the organization in 2015. President-elect Gregory Stephanopoulos, the W.H. Dow Professor of Chemical Engineering at the Massachusetts Institute of Technology (Cambridge, Mass.), joins Teich on AIChE's Board of Directors.

Newly elected directors of the AIChE Board are: Alan Nelson, research and development director for Performance Monomers at Dow; John O'Connell, professor emeritus of chemical engineering at the University of Virginia (Charlottesville); Anne Skaja Robinson, chair of the Chemical and Biomolecular Engineering Dept. at Tulane University (New Orleans, La.); and Sharon Robinson, senior staff member at the Oak Ridge National Laboratory (Oak Ridge, Tenn.). AIChE directors serve three-year terms.

American Institute of Chemical Engineers
www.aiche.org

ISA call for LDAR presenters

The Program Committee of the International Society of Automation's (ISA) 15th Annual Leak Detection and Repair (LDAR) Fugitive Emissions Symposium has issued a Call for Presenters, inviting professionals in the air-compliance field to submit abstracts for presentation consideration at the conference. The symposium will be held May 19–21 at the Astor Crowne Plaza hotel in New Orleans, La.

Presenters are sought who can deliver addresses (or write technical papers) pertaining to the following subject areas: long-term sealability; lowering and preventing leaks; environmental/LDAR compliance; LDAR design and validation; consent decree updates; low leak technologies; implementing LDAR programs at plants and refineries; LDAR compliance; batch programs; reducing air emissions; emission performance; and LDAR regulations.

New program topics are also available. Abstracts should be submitted to techconf@isa.org by January 15. Abstracts should be 300 words or less and describe what the presentation (non-commercial) will cover.

For more details and information on the conference, visit the website at www.isa.org/events-conferences/isa-15th-ldar-2015/.

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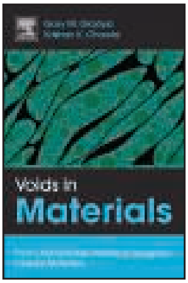

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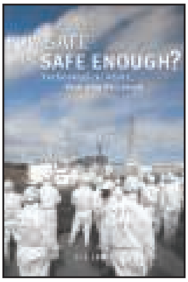

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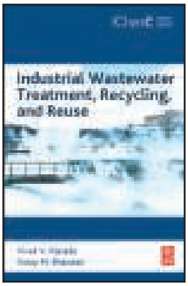

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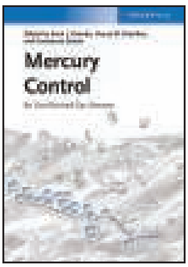

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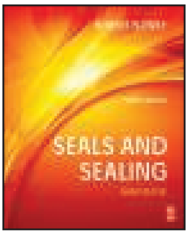

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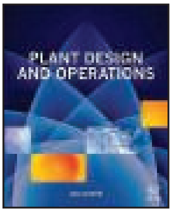

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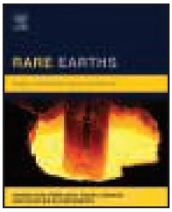

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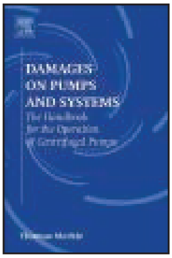

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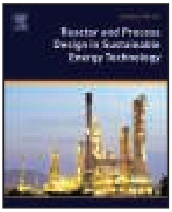

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Scott Jenkins

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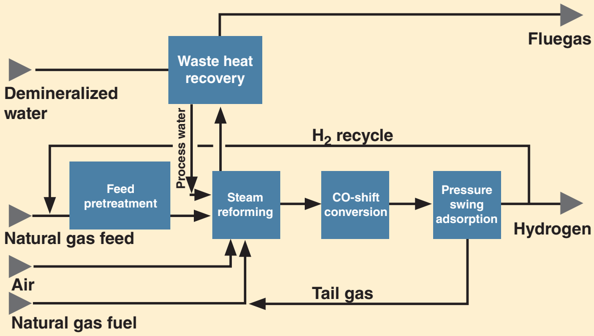
Modular hydrogen-production technology uses modified SMR process



A modular, skid-mounted hydrogen-production plant developed by Linde AG (Munich, Germany; www.linde.com) uses a modified version of conventional steam-methane reforming (SMR) to generate hydrogen from inexpensive natural gas, rather than relying on more costly methods of hydrogen production, such as from ammonia, methanol or water (by electrolysis), or by truck delivery.

At scales larger than 1 million ft^3/d, SMR is the dominant means of hydrogen production, but at scales smaller than that, cost and reliability become issues, according to Linde. Linde's heat-integrated, modified SMR process lowers hydrogen costs by 20–30% compared to truck delivery.

The technology, known as Hydroprime, features an elaborate heat-recovery system that allows water to be used as a feed, rather than steam, as would be the case in conventional SMR. Hydroprime combines desulfurized natural gas with preheated demineralized water inside tubes filled with a nickel catalyst to produce diatomic hydrogen gas in a reforming reaction. A subsequent CO-shift conversion produces additional hydrogen over an iron oxide catalyst. The hydrogen is purified to 99.999% H_2 with a pressure-swing adsorption (PSA) operation. The compact, modular unit can use tailgas from the PSA unit as part of the fuel for process heat.

The product hydrogen is generated at flowrates between 0.15 and 0.3 million ft^3/d. The open skid design offers simple site installation, a small footprint and excellent accessibility for maintenance, Linde says. Several Hydroprime installations have been deployed to date in Europe and Asia, and have demonstrated excellent results, the company says.

Solar-electric hybrid furnace could enable improved magnesium processing

A new high-temperature reactor that can draw power from conventional electricity as well as from a solar-thermal heating system could enable a cleaner, lower-energy route to lightweight magnesium alloys. The custom-made reactor was built by thermal processing equipment company Harper International (Buffalo, N.Y.; www.harperintl.com) in support of a research grant from the Dept. of Energy's Advanced Research Projects Agency–Energy (ARPA-E; Washington, D.C.; arpa-e.energy.gov). The reactor will be used in the laboratory of Alan Weimer at the University of Colorado at Boulder (www.colorado.edu) for projects related to the high-temperature processing of magnesium oxide to obtain Mg metal.

Current methods to produce magnesium metal from MgO are batch processes that are not energy efficient, explains Harper sales engineer Brian Fuller. The hope is that the hybrid reactor can enable a continuous process that requires less energy and labor in the production of magnesium metal.

Harper's system will be employed in the reaction of MgO with carbon at high temperatures to generate Mg vapor and carbon monoxide. "The reaction is known to be possible, but it's very hard to carry out reliably and effectively," Fuller says. The Mg vapor is converted to solid metal, while the CO is processed in downstream systems.

The research-scale reactor utilizes unique materials of construction and is designed to allow for tight control over pressure and temperature, Fuller points out. Harper engineers equipped the reactor with a mechanism to switch back and forth between electrical heating and concentrated solar-energy power, to mimic day-and-night cycles.

'High-entropy' alloy

Researchers from North Carolina State University (Raleigh; www.ncsu.edu) and Qatar University (Doha; www.qu.edu.qa) have developed a new metal alloy that is claimed to have a higher strength-to-weight ratio than any other existing metal material. The low-density, nanocrystalline alloy — $Al_{20}Li_{20}Mg_{10}Sc_{20}Ti_{30}$ — belongs to a new class of materials known as high-entropy alloys, which consist of five or more metals in approximately equal amounts. This particular alloy has a density comparable to aluminum, but is stronger than titanium alloys, says Carl Koch, Kobe Steel Distinguished Professor of Materials Science and Engineering at N.C. State. It has a strength-to-weight ratio comparable to some ceramics, but we think it is tougher (less brittle) than ceramics, he says.

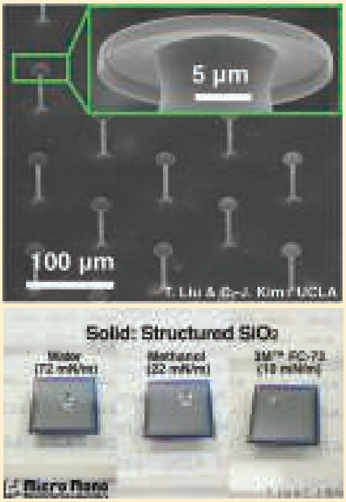
Onsite CN^- generation

Gold mines using traditional cyanide-leaching extraction processes will benefit with the launch of a new technology allowing onsite production of sodium cyanide. The technology, developed by Synergen Met Pty Ltd (Brisbane, Australia; www.synergenmet.com), will eliminate a range of hazardous activities associated with the use of the highly toxic cyanide, such as transportation, onsite handling, and maintaining large cyanide inventories. "For

(*Continues on p. 12*)

Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

This 'superomniphobic' texture repels all liquids . . .



Researchers from the University of California at Los Angeles (UCLA; www.ucla.edu) Henry Samueli School of Engineering and Applied Science have created what is claimed to be the first surface texture that can repel all liquids, no matter what material the surface is made of. Up to now, superhydrophobic surfaces have been created that repel water, analogous to the so-called lotus effect — the phenomenon that causes water to bead-up and roll off of lotus plants' leaves. Up to now, nanostructures mimicking those of the lotus leaves (which are responsible for this effect) have not worked with oils due to the low surface tension of oils.

The UCLA engineers formed a surface covered with thousands of microscale flathead "nails,"— each about 20 µm in head diameter — and spaced about 100 µm apart (photo, top). Unlike the microstructured "hairs" found in natural and manmade superhydrophobic surfaces, the "nail heads" on the UCLA surface have a nanoscale detail, which resembles a letter T in cross section. On this engineered surface, even completely wetting liquids roll around like a ball and slide right off when the surface is tilted (photo, bottom).

The team made the same microscale pattern on surfaces of glass, a metal and a polymer. In each case, the engineered surface super-repelled all liquids in a series of tests. The surface super-repelled all available liquids, including water, oils and many solvents — including perfluorohexane, the liquid with the lowest known surface tension, says UCLA.

The texture could have industrial or biomedical applications. For example, the surface could slow corrosion and extend the life of parts in chemical and power plants, solar cells or cookware. The research is described in a recent issue of *Science*.

. . . and this new material repels oil and water, too

KIT/Rapp

Meanwhile, a new class of highly fluorinated polymers is being developed at the Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology (KIT; Karlsruhe, Germany; www.kit.edu) that repels both water and oil. Last month, IMT was awarded €2.85 million funding from the Federal Ministry of Education and Research (BMBF; Bonn, Germany) to further develop the material, which has been dubbed "fluoropore."

"When combining the chemical properties of fluoropolymers with the roughness of the lotus plant, surfaces are obtained, from which both water and oil droplets will roll off," says IMT mechanical engineer Bastian Rapp. In the laboratory, he has already produced surfaces with the so-called "lotus 2.0 effect" — which is super-repellent to both oil (photo, right) and water (photo, left). In practical use, however, they turned out to have an insufficient stability, and are especially prone to abrasion. So more work needs to be done to further develop the fluoropore. For this work, Rapp won the NanoMatFutur competition for young scientists, launched by the BMBF.

One of the many potential applications for the new material is fine-pore screens, whose chemistry and structure allow for the separation of oil/water mixtures used as cooling lubricants in chemical process industries.

the first time, mining companies can produce cyanide on demand and feed directly into existing mills," says managing director Christopher Dunks.

At the heart of the new process is a high-temperature plasma torch, which instead of ammonia (used in existing technologies), uses N_2 or simple hydrocarbons, which are more accessible feedstocks that can be produced on-site using off-the-shelf technology. The advantages of using a plasma torch include its high thermal efficiency (up to 90%), its suitability for modulation, and ease of operation, says the company.

The company is finalizing testing at its pilot plant in Australia and plans to develop a commercial prototype in 2015, which will be the size of a standard 40-ft shipping container that is readily transportable.

New enzyme

Last month, Novozymes (Copenhagen, Denmark; www.novozymes.com) launched a new enzyme, dubbed Eversa, which is said to be the first commercially available enzymatic solution to make biodiesel fuels from waste oils. The enzymatic process converts used cooking oil or other lower-grade oils into biodiesel.

Most of the vegetable oils currently used in the food industry are sourced from soybeans, palm or rapeseed, and typically contain less than 0.5% free fatty acids (FFA). Existing biodiesel process designs have difficulty handling oils containing more than 0.5% FFA, meaning that waste oils with high FFAs have not been a viable feedstock option until now, says the company.

"The idea of enzymatic biodiesel is not new, but the costs involved have been too high for commercial viability," says Frederik Mejlby, marketing director for Novozymes' Grain Processing division. "Eversa changes this and enables biodiesel producers to finally work with waste oils and enjoy feedstock flexibility to avoid the pinch of volatile pricing."

(*Continues on p. 14*)

Polymer produced from CO_2 waste gas makes commercial debut

For the first time, polypropylene carbonate (PPC) polyol, a versatile polymer made from CO_2, is available at a commercial scale. Produced by Novomer Inc.'s (Waltham, Mass.; www.novomer.com) polymerization process, PPC polyol has been adopted into a formulation for polyurethane hot-melt adhesives by Jowat AG (Detmold, Germany; www.jowat.com). In addition to PPC's status as a "green" alternative (via CO_2 waste utilization) to traditional petroleum-based polymers, adhesives applications can take advantage of a key benefit of PPC — its hydrolytic stability and chemical resistance, which set it apart from typical polyester polyols.

PPC is manufactured via a batch reaction between CO_2 and propylene oxide using a proprietary cobalt-based catalyst (for more on this PPC production process, see *Chem. Eng.*, July 2013, pp. 16–19). PPC capacity has been scaled up considerably in the past year at a production facility in Houston. In 2013, production capabilities were less than 100 tons, but recent commercial interest necessitated an increased volume, so the process has been scaled up to produce PPC in the multi-thousand-ton range. The reaction occurs at a moderate temperature (around 35°C) so the process is easily scaleable from a heat-transfer standpoint. Waste-exhaust gases from nearby industrial facilities, including ethanol-fermentation and power-generation plants, provide the CO_2 for the reaction. Improvements in catalyst efficiency and removal techniques were also incorporated with scaleup. Going forward, the company hopes to increase its PPC production capacity and eventually transition to continuous production with options for producing various grades of PPC for a wider range of end uses.

CO_2-capture project is largest to use calcium-looping technology

A cement plant in Taiwan has been retrofitted with the largest CO_2-capture plant to use calcium-looping technology to date. The project, run by Taiwan's Industrial Technology Research Institute (ITRI; Hsinchu, Taiwan; www.itri.org), demonstrates ITRI's high-efficiency calcium-looping technology (Heclot) at a scale of 1 ton CO_2 captured per hour, and at a capture efficiency of more than 90%.

Calcium-looping technology can reduce the cost of carbon capture by up to half, compared to traditional amine-based CO_2 capture, ITRI scientists say, and the Heclot project is unique in its ability to meet a target international

(*Continues on p. 14*)

CALCIUM-LOOPING TECHNOLOGY (*Continued from p. 13*)

threshold-capture-cost of $30/ton of CO_2 for a fossil fuel power plant.

In this Heclot project, CO_2-laden exhaust gas from the cement plant is introduced into a fluidized-bed carbonator reactor, where the CO_2 reacts with calcium oxide (CaO) to form calcium carbonate between 600 and 650°C. The $CaCO_3$ then enters a calciner, where it undergoes oxy-fuel combustion to release the CO_2 in high concentrations and re-form CaO. The concentrated CO_2 is cooled and compressed for use in growing microalgae and for enhanced gas recovery (EGR), where it is sequestered underground, while the CaO is returned to the carbonator.

Carbon capture by calcium looping uses less energy than amine-based CO_2 capture and the CaO is a cheaper raw material, explains Heng-Wen Hsu, leader of the ITRI project. "The CaO fines that are no longer useful in the carbonator can be used in cement manufacture," he notes, "so there is virtually no waste in the process."

ITRI is seeking partners to build an even larger demonstration facility using the Heclot system. The ITRI work parallels a similar project at the Technical University of Darmstadt (Germany; www.tu-darmstadt.de) that was discussed in a previous issue (*Chem. Eng.*, January 2013, p. 11), although both the carbonator and calciner units differ in the two projects.

(*Continued from p. 12*)

(For more on industrial enzymes, see Newsfront, pp. 19–22.)

Phase-change slurry

Researchers from the Fraunhofer Institute for Environmental, Safety and Energy Technology (Umsicht; Sulzbach-Rosenberg; www.umsicht.fraunhofer,de) and RWTH Aachen University (both Germany; www.rwth-aachen.de) have developed a new phase-change material (PCM) trade-named CryoSol^{Plus}. The PCM is a dispersion of solid paraffin beads and water, and can be circulated as a heat-transfer fluid, as a storage medium for thermal systems, and for cooling. When the dispersion absorbs heat, the paraffin melts, thereby storing the energy without a change in temperature. The researchers have developed mats with capillary tubes that can be used in ceilings, for example, to maintain room temperatures as it gets hot outside, thereby reducing the demand for air conditioning in buildings.

LED sight-glass light

Illumination is required for visual inspection of a process through a sight glass in a vessel or tank. A newly demonstrated light source, developed by L.J. Star Inc. (Twinsburg, Ohio; www.ljstar.com) and marketed as the LumiStar3000, is said to be world's brightest sight-glass light. The company says the product delivers 3,000 lumens of light, four times the brightness of a 100-W halogen lamp. And because it uses a specially designed light-emitting diode (LED) as the light source, the LumiStar3000 consumes only one tenth of the energy of a halogen bulb. ❏

Biodegradable drilling lubricant garners positive field results

An encapsulated, biodegradable drilling-fluid additive designed to reduce friction on drill bits and piping inside oil wells has been demonstrated successfully in more than 30 wells across North America following its launch in mid-2014.

The lubricant product, known as Encapso, was developed by Solazyme Inc. (South San Francisco, Calif.; www.solazyme.com), an industrial biotechnology company that makes renewable oils and products. Solazyme recently announced a partnership with Versalis, the chemical arm of oil-and-gas company Eni S.p.A (Milan, Italy; www.eni.com) whereby Versalis would market Encapso to the oil-and-gas industry.

Encapso consists of specifically tailored triglycerides that serve as lubricants inside polysaccharide cells, which serve as an on-demand delivery mechanism. Solazyme uses its proprietary biotechnology platform to convert sugars to triglycerides and encapsulate the triglyceride in a polysaccharide shell. The product is dried to produce a light powder, which is added to oil-drilling fluid at the well site.

The encapsulated cells, with their payload of lubricating oils, circulate in the drilling fluid until they encounter areas of high shear stress and friction. At those points, the cells rupture, freeing the lubricant and reducing friction for sliding pipe and lessening torque requirements for spinning drill bits.

"Using the encapsulated cells as a delivery system for lubricant allows the lubricant to be deployed in a targeted way," says Rob Evans, Solazyme vice president for sales and business development. "so the Encapso product is used up less quickly and less lubricant is lost."

Solazyme's ability to engineer encapsulations with specific characteristics, and to carefully control its biotechnology process allows the company to tailor the triglyceride profile of the lubricant inside the cells, adds Jad Finck, director of sales at Solazyme. Because of Encapso's inherent biodegradability and unique, on-demand delivery method, Solazyme is looking at additional industrial applications for the technology.

A one-step, phosgene-free route to urethane

Researchers at the National Institute of Advanced Industrial Science and Technology's (AIST) Interdisciplinary Research Center for Catalytic Chemistry (Tsukuba, Japan; www.aist.go.jp) have developed a new reaction process to synthesize aromatic urethane — a promising starting material for the production of polyurethanes. Unlike traditional urethane routes, no phosgene is required.

The process is a one-step reaction in which an amine is reacted with a tin-alkoxide compound and pressurized CO_2. Yields as large as 82% have been achieved by reacting aniline and dibutyltin dimethoxide (mole ratio of 1:5) for 20 min at 150°C, using a CO_2 pressure of 5 MPa. A 49% yield was found using 2,4-diaminotoluene — the precursor for polyurethanes. After the reaction, the tin compound could be recovered and reused after treatment with an alcohol.

The group plans to enhance the efficiency, and scale up the process to realize industrial applications.

Generating power from kerosene and ammonia

The National Institute of Advanced Industrial Science and Technology (AIST; Tsukuba City, Japan; www.aist.go.jp), in collaboration with Tohoku University (www.tohoku.ac.jp), succeeded in demonstrating what is said to be the world's first ammonia-fired power. The achievement was carried out in a micro-gas turbine with a fuel composed of 70 vol.% kerosene and 30 vol.% NH_3. The goal of the project is to utilize ammonia as a hydrogen carrier for the production of electrical power.

The researchers replaced the standard combustor of a kerosene-fired, 50-kW gas turbine with a prototype combustor that enables co-firing with liquid kerosene and ammonia vapor. The micro-gas turbine employs diffusion combustion to stabilize the flame. The functionality of each component of the micro-gas turbine was demonstrated at the AIST's Fukushima Renewable Energy Institute.

Initially, the gas turbine was fired with kerosene. When the power output reached 25 kW, NH_3 gas was introduced at increasing flowrate, until stable operation ensued. More than 25 kW of power was generated when 10% of the heat was supplied by NH_3 combustion, and 21 kW at 30% NH_3. It was demonstrated that emissions of oxides of nitrogen (NOx) could be reduced to below 10 parts per million (ppm) by adjusting the NH_3 supply to the existing NOx-removal unit.

Currently, the researchers are working to increase the ammonia-to-kerosene ratio, as well as to generate power with only NH_3 firing, and the co-firing with methane and NH_3. AIST and Tohoku University are also developing a low-NOx combustor.

Direct fermentation to produce propylene

Global Bioenergies (Evry, France; www.global-bioenergies.com) says that last month it developed a proprietary strain of microorganism that directly produces propylene by the fermentation of glucose. The company claims this is the first time propylene has been produced entirely by a biological process — without any chemical step.

The announcement follows Global Bioenergies' previous breakthroughs in the production of bio-based isobutene, which is now being piloted (*Chem. Eng.*, March 2014, p. 12), and butadiene (*CE*, September 2014, pp. 19–24).

Propylene is a key building block of the petrochemical industry, and is used for the production of plastics, such as polypropylene. The company says over 80 million metric tons of propylene are produced per year, corresponding to a market exceeding $100 billion. ■

MOVING TO MODULAR

Larger and more complex processes are now being offered in this unique building approach

Source: Koch Modular Process Systems

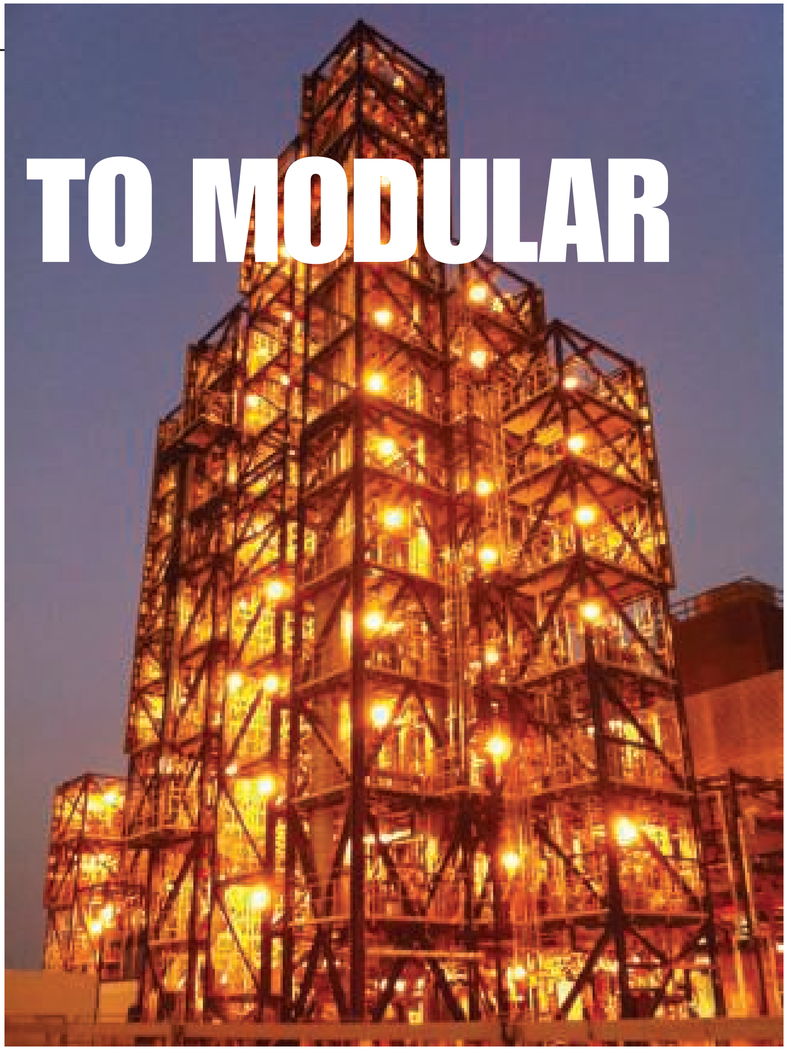


FIGURE 1. This modular system comprising three reactions steps and nine distillation steps — a complete chemical production process — was designed and constructed off-site in a controlled environment as modules

If the word "modular" brings to mind a trailer office parked on site, it's time to revisit modular systems. Today's modular system go well beyond office space and tool sheds, and can contain almost anything from a skid-mounted filtration system to a cleanroom laboratory to a petroleum refinery, which is built elsewhere and delivered as a complete unit to a site, where it is then erected.

And, large modular process systems, especially, are impressive feats of engineering. For example, according to Brian Loftus, contracts manager at Koch Modular Process Systems (Paramus, N.J.; www.modularprocess.com), which designs, plans and builds large-scale modular mass-transfer systems, a typical modular process system of this type includes all of the process equipment, such as columns, reactors, heat exchangers and pumps, mounted within a structural steel frame. After the process equipment is installed within its frame in the shop, the piping components, field instrumentation and electrical wiring are completed. Items like tracing, thermal insulation, lighting, control systems, safety showers and fire protection systems may also be installed at the shop. Finally, all these components are tested and then the module is shipped and erected on site (Figure 1).

While this type of modular process unit may contain different equipment and serve a different purpose from modular refineries, water systems or smaller-scale process systems, all modular process systems have one thing in common: They are pre-fabricated to the maximum extent possible in a fabrication shop that is remote from the user's plant site. Because modular systems are typically built indoors in a controlled, assembly-line fashion, many advantages can be realized, says Loftus.

Modular benefits

"Because modular process systems are built using industrial manufacturing techniques under stringent quality controls and in a controlled environment by skilled technicians, there are plenty of advantages for the customer," says Brad Spindler, industrial water business unit manager with Wunderlich-Malec (Minnetonka, Minn.; www.wmeng.com), which constructs electrical enclosures for power distribution and control systems used in power and process plants, and modular industrial-water-process skids and systems (Figure 2) that supply makeup and process water, or clean and recycle a facility's wastewater. "The modular approach to building at our site versus the customer's site eliminates the inefficiencies of onsite construction, including site restraints, labor stacking and weather delays."

Also, because construction takes place in the fabricator's shop, building can begin before site permits are obtained, which leads to a drastically reduced construction timeline. All of these factors come together to reduce the schedule for delivery of the completed project, which arrives at the user's site ready to be erected on a pre-laid foundation.

"Because we have a well established system of suppliers, and the process of parallel tasking and detailing allows for a very high level of efficiency during design and construction, the modular project is quite short," explains Loftus.

He says a typical schedule, depending upon materials, level of complexity, customer specifications and number of modules being made, ranges from 9 to 12 months when starting at the process-design stage.

The time to erect modular facilities is usually reduced as well. "After the modules arrive in the field, a single module might be erected within a month, with the average multi-module system taking two to three months. Once the modules are erected, the customer would be ready to commission a water startup, followed by chemical introduction," says Loftus.

Ken Reynaud, senior vice president with Plant Process Equipment, a subsidiary of Plant Process Group (League City, Tex.; www.plantprocess.com/refining), agrees. "Our modular refineries arrive at the site like an erector set. The foundation is already poured, the trucks roll up, a crane lifts the modules off the truck, and everything is efficiently set up and ready to go. The time it takes to erect a modular refinery is dramatically less than to stick-build the same size facility."

In addition to shortened schedules, fabricators say the quality of modular systems is often higher than conventionally built systems. "Because we are building in a controlled environment we have workers at designated stations, and those workers are highly skilled welders, fitters [and so on]," says Reynaud. "If you work onsite, you don't know the skill level of the workers. If the welders aren't capable, the welds fail, and so on. But building under controlled circumstances affords the ability to control the quality of the workers and, therefore, the quality of the work."

Spindler adds that factory fabrication also allows the use of stringent quality systems and factory testing to ensure that finished systems conform to technical requirements. "Eighty percent of the commissioning and startup is already complete on a system before it's even shipped to the site," he says.

Finally, there are also cost efficiencies. "Because our design is very precise and we are working within the known space of a well-defined structural frame, and because we detail every isometric, we have a fully detailed bill of materials, upon which our assembly shop can rely," explains Loftus. "So, when they place the order for materials, our shop doesn't order excess, which assists with cost efficiency. In traditional stick-build, extra materials are always ordered for contingency planning, which drives up costs."

"Our clients make money by making a product, not by having us building a plant in the middle of their floor," says Bruce Blanchard, national sales manager with GEA Filtration (Columbia, Md.; www.geafiltration.com), which provides modular filtration skids. "Not only is modular faster because of the controlled environment, but it's less expensive because we aren't disrupting production or creating downtime, which results in lost production dollars," he emphasizes.

Source: GEA Filtration

FIGURE 3. Crossflow filtration, microfiltration, nanofiltration, ultrafiltration and reverse osmosis plants can all be placed on modular skids

Source: Wunderlich-Malec

FIGURE 2. These complete, modular integrated water solutions are pre-assembled and factory tested to meet the client's functional requirements

More and more modular

Because of the associated benefits, more operations and processes are being offered in modular form to meet a myriad of process needs. Here's a summary of some of the modular systems currently available to processors.

Process systems. A diverse variety of process systems can be provided in modules from filtration skids to water purification to mass-transfer systems.

Membrane filtration. Crossflow filtration, microfiltration, nanofiltration, ultrafiltration and reverse-osmosis plants can all be placed on modular skids by GEA Filtration. And, there has been an increased need for these molecular-level separation plants due to a lot of activity in the nutritionals market, says Blanchard. "The basic technology allows for converting a mixed nutritional stream into a very specific nutritional stream," he says. "For example, if you take a nutritional product that has fats, proteins and carbohydrates, it can be segmented so it has more proteins and less carbohydrates, which falls into creating healthier nutritional products by manipulating food chemistry."

What is the reason for doing this modularly? "The standardized approach to a modular format of these filtration plants results in a more compact plant that takes up less floor

WHEN TO SAY 'NO' TO MODULAR

While modular process systems offer many advantages, there are times when they may not be feasible. Dennis Euers, strategic business manager with Wunderlich-Malec, outlines some constraints that reduce the feasibility of going modular:

- Size matters. If a system is to be delivered by road, there are often restrictions on size and weight. However, it is possible to design and package equipment as multiple units that can be shipped and assembled on site. Barge shipping is also possible if there is water access
- Processes that require large tanks or vessels for storage and reaction time may not be suitable applications for a modular build
- Ideal modular process skids include some level of complexity, incorporating piping, pumps, equipment, electrical and instrumentation. Simple processes can be effectively delivered onsite without the engineering effort modular systems require
- Some site constraints, such as in installations within existing systems or system modifications at a facility, may not lend themselves to the logistics and ability to get a modular system installed. In these cases, onsite field activities are often a better choice ❑

space in a facility, which is worth about $200 to 300 per square foot," explains Blanchard. "Our standardized, modular design allows them the operations they need in a space- and money-saving package that doesn't disrupt existing production" (Figure 3).

Industrial water solutions. Due to increasingly stringent regulations regarding water, there is an increasing demand for process skids and systems that supply makeup and process water, and for units that clean and recycle wastewater streams, according to Spindler. Wunderlich-Malec's systems go through a very detailed engineering process to incorporate all the equipment, pumps, vessels and instrumentation in an optimal layout so that the equipment and components can serve as a fully functional system on a stand-alone skid.

"What that means is that if our clients have a phased facility expansion, it is very easy to add additional units when they need them, so they are able to expand the operation as their business expands or as regulations further tighten," says Spindler. "Also, if the system serves a temporary need, a modular system can be placed, started and operated and, if needed, re-located to another site in the future."

Mass transfer systems and beyond. The demand for pre-assembled, modular mass-transfer systems for distillation and liquid extraction that include not only the process equipment, but also the piping, instrumentation and electrical wiring, ranging in size from semi-units to full-scale production units recently has been expanding beyond single-operation units.

One of the areas of growth for systems that go beyond single operation, according to George Schlowsky, president with Koch Modular Process Systems, is in the biofuels industry. Startup firms producing biofuels often need more than just the distillation steps, explains Loftus. "So, in addition to the mass transfer, we are more often incorporating reactors, solids handling, filtration, drying and other processes that will support their chemical process into our modular construction. Because we are not experts in these other technologies, we leverage a network of existing specialists in these industries and work to procure their units and incorporate them into our modular construction. So, in addition to our expertise in system design and modular mass-transfer systems, we have become system integrators, which is a tremendous value to startup companies that don't have the engineering expertise to manage the overall processes in house."

Refineries. Most modular refineries are usually vacuum distillation units. Therefore, the throughput of the modular refinery is dictated by the size of the vacuum distillation column, which, when part of a modular refinery, is generally about 11 or 12 ft in diameter because it must fit within the skid. And, skids typically can't be more than 14 ft by 14 ft due to transportation limitations, Reynaud explains. With a column this size column, the largest modular refinery likely could be no more than a 20,000 barrel a day (bbl/d) facility.

FIGURE 4. An entire laboratory workspace is pre-engineered

The desire to go with a modular refinery is often due to the significantly reduced schedule. "Because many refineries are being built overseas, a modular approach can really shave time off the construction," he explains. "If you build on site in a foreign country, you have to ship all the raw materials, metal and pieces there. Think of it like buying a television that's already assembled versus the store shipping you a whole bunch of parts to be put together at your house. You aren't sure if all the parts arrive, the quality of your construction is probably not that of a skilled expert and it's going to take you a long time to get it right.

"Using that analogy, imagine the difference between constructing a modular refinery and a stick-built one," says Reynaud. "A modular refinery can be constructed in 12 months versus two years if built onsite."

Cleanroom laboratories. Hemco (Independence, Mo.; www.hemcocorp.com) provides an entire laboratory workspace, which is pre-engineered, including the structure, the furniture and fume hoods for the interior (Figure 4). While modular cleanroom laboratories afford many of the same time- and cost-saving opportunities as modular process systems, one of the biggest benefits of going this route versus traditional construction, according to David Campbell, vice president of sales with Hemco, is that the structure can be easily assembled, modified in the future, or disassembled and moved if needed.■

Joy LePree

TUNABLE ENZYMES AND THE LEANER, GREENER CPI

Manufacturers of biofuels, detergents and pharmaceuticals have more control than ever over enzyme and product properties

Novozymes

FIGURE 1. Enzymes play a key role in the production of cellulosic ethanol. First industrial-scale plants are now coming onstream, such as this one in Crescentino, Italy

Enzymes, nature's catalysts, have been used in industrial processes for centuries. Now, they are coming into their own in the chemical process industries (CPI). As green chemistry becomes an industry mantra, pressures to reduce product cost, facility carbon footprint and overall environmental impact are driving more companies to seek alternatives to traditional, catalyst-driven chemical syntheses.

Convincing skeptics is mounting evidence that, where feasible, enzymatic processes can increase product yield, dramatically reduce requirements for solvent and catalyst, as well as the number of steps and the overall costs of a chemical process.

Last year, the industrial enzymes market grew by 5% to \$3.7 billion, according to Novozymes (Bagsvaerd, Denmark; www.novozymes.com), a company that manufactures roughly half of the world's industrial enzyme output and currently pumps about 14% of its earnings back into research and development. By 2020, demand for green chemical processes could reach \$98.5 billion, and save global industries, including the CPI, over \$65 billion, according to a 2011 study by Pike Research, now part of Navigant Research (Boulder, Colo.; www.navigantresearch.com).

A sign of the times is the world's first large-scale commercial cellulosic-ethanol plants, some of which are just starting up in Europe (Figure 1) and the U.S. Dependent on enzymes, the facilities use biomass as feedstock and result in zero net carbon emissions.

Shrinking development time

Industrial enzyme suppliers are betting on a future fueled by continued demand for leaner, greener processes and products. Supporting market growth are ongoing improvements in protein engineering and techniques such as random mutagenesis, high-throughput screening and directed evolution, which make it much easier to predict and control the properties of individual enzymes.

Close work with customers and an applications-oriented approach are essential during the innovation cycle, says Wendy Rosen, global public affairs leader with DuPont Industrial Bioscience (Wilmington, Del.; biosciences.dupont.com). However, scientific advances in gene sequencing and developments such as polymerase chain reaction (PCR) technology have been instrumental in improving discovery, isolation and expression, says Lars Birch Mathisen, household care launch manager for Novozymes. "Years ago, it was pure guessing," he says. "Now, you can construct heat-stable organisms and target search much better from the beginning."

As a result, the time between the discovery of a new micro-organism and commercial production of a new industrial enzyme has shrunk significantly over the past few years. Today, the average time is five years, Mathisen says, but for some products it can even be shorter. Svend Licht, Novozymes' sales and business director, attributes that to better assay technology for screening. "What used to take over a year can now be accomplished in a few weeks or months," he says.

Another key change has been increased yields, enabled by continuous improvement of production strains,

FIGURE 2. This 30-million-gal biorefinery in Nevada, Iowa is expected to start up this quarter

says Licht. The result: closer control of the enzyme, and the product it is used to make, than ever before.

Alliances

To further improve that control, and shrink development time, CPI companies are working more closely with specialists in biocatalysis to bring new products to market, while enzyme manufacturers are working with experts in genomics and high-throughput screening. DSM N.V. (Heerlen, the Netherlands; www.dsm.com), a leading enzyme supplier, started this trend back in 2003, when it entered into a research agreement with Diversa [now Verenium Corp. (San Diego, Calif.; www.verenium.com), which became part of BASF in 2013].

In addition to Novozymes and DSM, industrial enzyme suppliers include DuPont, which bought Danisco's business in 2011, including the innovation-driven Genencor, founded in 1982 as a venture between Genentech and Corning. Also active is BASF SE (Ludwigshafen, Germany; www.basf.com), which acquired Henkel's detergents enzyme business last year. The company has linked up with Dyadic and Verenium, providing access to new discovery, expression and production platforms and an expanded genetic library based on organisms from extremely diverse environments.

Biofuels

Today, biofuels are a major CPI focus for industrial enzymes. In December, Novozymes introduced Eversa, the first enzyme process designed to convert waste cooking oils into biodiesel. This had been too difficult in the past, since many waste vegetable oils, apart from soy, palm and rapeseed, contain levels of free fatty acids that are too high to work in conventional conversion processes.

Currently, ethanol dominates activities in the biofuels enzyme sector, while detergents and pharmaceuticals are also key markets.

One surprise, given decades of stops and starts, has been the growing global demand for ethanol and the enzymes that are used to process it. "In 2015, we are expecting an export market of over 1 billion gallons," says Jack Rogers, global marketing manager for biofuels at Novozymes North America. Last year, the figure was around 650–700 million gal, and it was 300 million gal the previous year, he says.

Novozymes started up a corn biofuels enzyme facility in Blair, Neb. in 2011, and has developed enzymes that improve ethanol yield from corn. Over the past three years, Novozymes has introduced three new enzymes for ethanol production: Advantec, to improve conversion and hydrolysis; Spirazyme Achieve, a fiber-degrading glycoamylene, to release additional starch, and Olexa, designed to improve corn oil recovery by breaking down the binding oleozyme protein, explains Novozymes' Rogers.

Using the three enzymes together can increase ethanol yield from corn by up to 5%, boost corn oil extraction by 13% and energy savings by 8%, allowing customers to make more from less and substantially improve profit margins, according to Andrew Fordyce, executive vice president for Business Operations. For a typical 100-million-gal feed-grade corn ethanol plant in the U.S., that could translate into 45,000 tons of corn saved while maintaining the same ethanol output, generating up to $5 million in additional profits.

But corn is not the only possible feedstock. Recently, manufacturers have started up plants that will supply cellulosic ethanol, derived from agricultural waste, to fuel and other markets. Examples include DuPont Industrial Biosciences' 30-million-gal biorefinery in Nevada, Iowa (Figure 2), which is expected to start up this quarter, Novozyme's joint venture (JV) facility with Beta Renewables in Crescentino, Italy, which started up in October 2013 (Figure 1), POET-DSM's JV plant in Emmetsburg, Iowa, and Abengoa's plant in Hugoton, Kan.

The ethanol market is following different growth tracks in the U.S. and globally. Where ethanol demand in the U.S. has matured to about 10% of the gasoline market, exports are going strong, particularly to Asia, Europe and Latin America, says Novozymes' Rogers.

Environmental pressures are driving some of that growth, he says, but most of the increased demand currently stems from market economics. "The cost benefit of ethanol versus blended gasoline has reached record levels internationally," says Rogers, ranging from being "on par" to gasoline, to $1 less per gallon.

Observers have questioned whether lower oil prices in the U.S. and potential cutbacks in U.S. Environmental Protection Agency (EPA; Washington, D.C.) biofuel mandates might have an impact on future demand for cellulosic ethanol. Purdue University (West Lafayette, Ind.) agroeconomics professor Wallace Tyner, for one, in a recent article in *Technology Review*, has asked whether the entire market might vanish in the future.

Consumer products

Meanwhile, enzyme manufacturers are betting on continued consumer preference for products and processes that have less impact on the environment. This trend is occurring, not only in developed markets but in emerging economies with growing young, middle-class populations.

In addition, suppliers are passing along to their customers the ability to control and customize enzyme use to tailor products for specific applications. In October 2014, Novozymes launched a multi-enzyme solution called Medley to the European market, targeting the needs of small to mid-sized liquid detergents producers. The platform offers multiple enzyme activities, easily accessible to larger companies, to help smaller companies simplify production, free working capital and save money.

"We considered different needs throughout the world, and focused on the specific stain removal most needed in each region. This means that Medley is tailored to different geographies such as Europe, Asia, China and Africa — and the blends support that strategy," according to Novozymes' vice president Anders Lund. Included are a new amylase starch-removing enzyme that operates at lower temperatures and in liquid formulas, as well as a new lipase oil-degrading enzyme that is more stable in liquids, says Novozyme's Birch Mathison.

DuPont has also responded to the "green market" push by diversifying output. Its Nevada biofuels facility, for instance, will not only supply biofuel, using DuPont's new Accellerase biomass enzymes and process (Figure 3), but will also supply Procter & Gamble's Cold Water Tide detergent, which uses a coldwater protease jointly developed by DuPont and Procter & Gamble (P&G; Cincinnati, Ohio; www.pg.com), using new protein-engineering techniques.

DuPont and P&G estimate that moving to lower washing temperatures in the U.S. could reduce CO_2 emissions by 40 million metric tons per year, the equivalent of taking 6.3 million cars off the road.

The new coldwater protease enzyme would allow detergent cleaning performance at washing temperatures of 60°F to match what, in current formulations, requires temperatures of 90°F. Meanwhile,

DuPont Industrial Bioscience

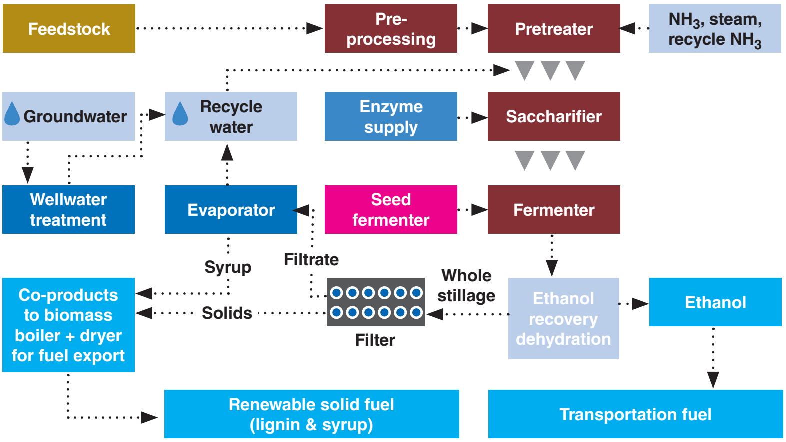


FIGURE 3. Enzymes play a central role in DuPont's fully integrated process for making ethanol from biomass

the Nevada biofuels facility would use 7,000 tons of agricultural waste, and reduce net greenhouse gas emissions by 100%.

Not only green considerations, but better economics are driving demand for enzymes in detergents, says Novozymes' Birch Mathisen. "By substituting enzymes for petrochemicals with volatile pricing, we get enhanced performance that was impossible just 10–15 years ago," he adds. "In addition, enzymes allow for more diverse performance profiles, and a secure price point."

Reducing pharma's E-factor

Pharmaceutical applications, which are notorious for their high E-factors, or impact on the environment, are another area of focus for industrial enzymes today. For Novozymes, today's biopharma focus is on biocatalysis, half-life extension, allowing for less frequent dosing, and hyaluronic acid, which is currently derived from roosters' combs in a rather hard-to-control process, according to Novozymes' Licht.

Drug companies are looking at ways to cut production costs, reduce chemicals and improve sustainability, says Licht, and biocatalysis and enzymes allow them to do this. Merck & Co., Inc. (Rahway, N.J.; www.merck.com), for instance, has a partnership with the enzyme specialist, Codexis, Inc. (Redwood City, Calif.; www.codexis.com), that helped it develop an enzymatic route to its blockbuster diabetes drug, Januvia, which had previously required rhodium, a rare metal catalyst.

The drug company GlaxoSmithKline (Bentford, England; www.gsk.com) has rolled out a formal plan to shift from synthetic chemistry to enzymatic reactions, a move that CEO Andrew Witty expects to reduce carbon footprint and manufacturing costs by 50%, according to a February 2013 Webcast.

As part of this program, GSK said it is using Novozymes' Veltis, an albumin designed to extend the half life of some drugs so that patients only need to take the drug once a month, once a week, or once every two weeks, instead of daily. Veltis is tunable, Licht says, so drug companies can adjust the enzyme in the formulation to provide exactly the half-life required. Veltis is being used in GSK's new diabetes drug, Tanzeum/Eperzan, while other companies including CSL and Epivax are evaluating the technology, Licht says.

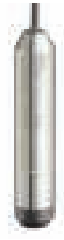
Currently, experts say that industrial enzyme suppliers and the CPI have just scratched the surface of potential applications. As new enzymes and applications continue to develop, the push to use them to reduce environmental impact and product cost promises to continue. ■

Agnes Shanley

FOCUS ON

Pressure Measurement & Control

Kobold Instruments



Siemens Industry Sector

Omega Engineering

GP:50

A small-diameter, submersible pressure transmitter

The Sitrans LH100 series pressure transmitter (photo) converts level-proportional hydrostatic pressure into a standardized 4–20-mA signal. Mostly used for measurement applications in the drinking water and wastewater industries, the Sitrans LH100 offers 0.3% accuracy and is available in a variety of measurement ranges. The transmitter is fully submersible, and has a slim 0.92-in. diameter, allowing it to be mounted in pipes as small as 1-in. in diameter. The instrument's stainless-steel housing and ceramic sensor provide resilience in harsh conditions. The Sitrans LH100 is fitted with an integrated humidity filter, permitting simple installation without the need for a junction box. — *Siemens Industry Sector, Erlangen, Germany*
www.siemens.com/industry

Compensated, unamplified sensors in a compact package

The TBP Series of basic board-mount pressure sensors have a millivolt output sensor that is compensated and unamplified, so that users can do their own amplification while retaining maximum resolution. The TBP Series features a wide pressure range of 1 to 150 psi, and has a very small footprint, occupying only 7 × 7 mm on the process-control board. A wide compensated temperature range of 0 to 85°C allows the sensors to operate in many types of applications. Low power usage enables use in battery operations. — *Honeywell Sensing and Control, Columbus, Ohio*
www.sensing.honeywell.com

Rugged pressure transmitters with many signal-output options

The Model 170/70/370/570 WECO Hammer Union Series of rugged pressure transmitters (photo) is engineered for installation in extremely demanding industrial environments, including those with shock and vibration. With stainless-steel housing and corrosion-resistant fasteners, these devices also incorporate a connector guard, which recesses the connector and eliminates breakage risks. The Series' four available signal-output options provide pressure-transducer compatibility with most control systems. An optional temperature output is also available, as well as an extended high-temperature rating of 350°F. — *GP:50 Corp., Grand Island, N.Y.*
www.gp50.com

These sensors measure differential pressure in filters

PMP differential pressure (DP) sensors (photo) are designed for controlling and measuring the DP of low-pressure air or non-corrosive gases in filters. A PMP sensor measures the pressure difference before and after the filter chamber. The need for a cleaning cycle can then be determined by an increased DP, at which point the instrument activates a programmable relay. A second relay produces an alarm if the DP continues to increase. PMP sensors can be customized to users' needs, as relay, hysteresis, time delay of the relays and analog output are programmable. — *Kobold Instruments Inc., Pittsburgh, Pa.*
www.koboldusa.com

These digital pressure gages are designed for marine applications

The new DPG409S Sanitary/Clean-In-Place (CIP) digital pressure gages (photo) incorporate a rugged stainless-steel (SS) enclosure and are designed for washdown and marine applications. With accuracy capabilities of 0.08%, these instruments are tested to industrial standards and can withstand very harsh environments. The DPG409S is available in various models, including: gage, absolute, compound gage, vacuum and barometric. Each model features an easy-to-read 25-mm backlit LCD display, with standard high and low alarms. The DPG409S has a long battery life, with data logging and charting software included. — *Omega Engineering Inc., Stamford, Conn.*
www.omega.com

This vacuum transducer is equipped for harsh conditions

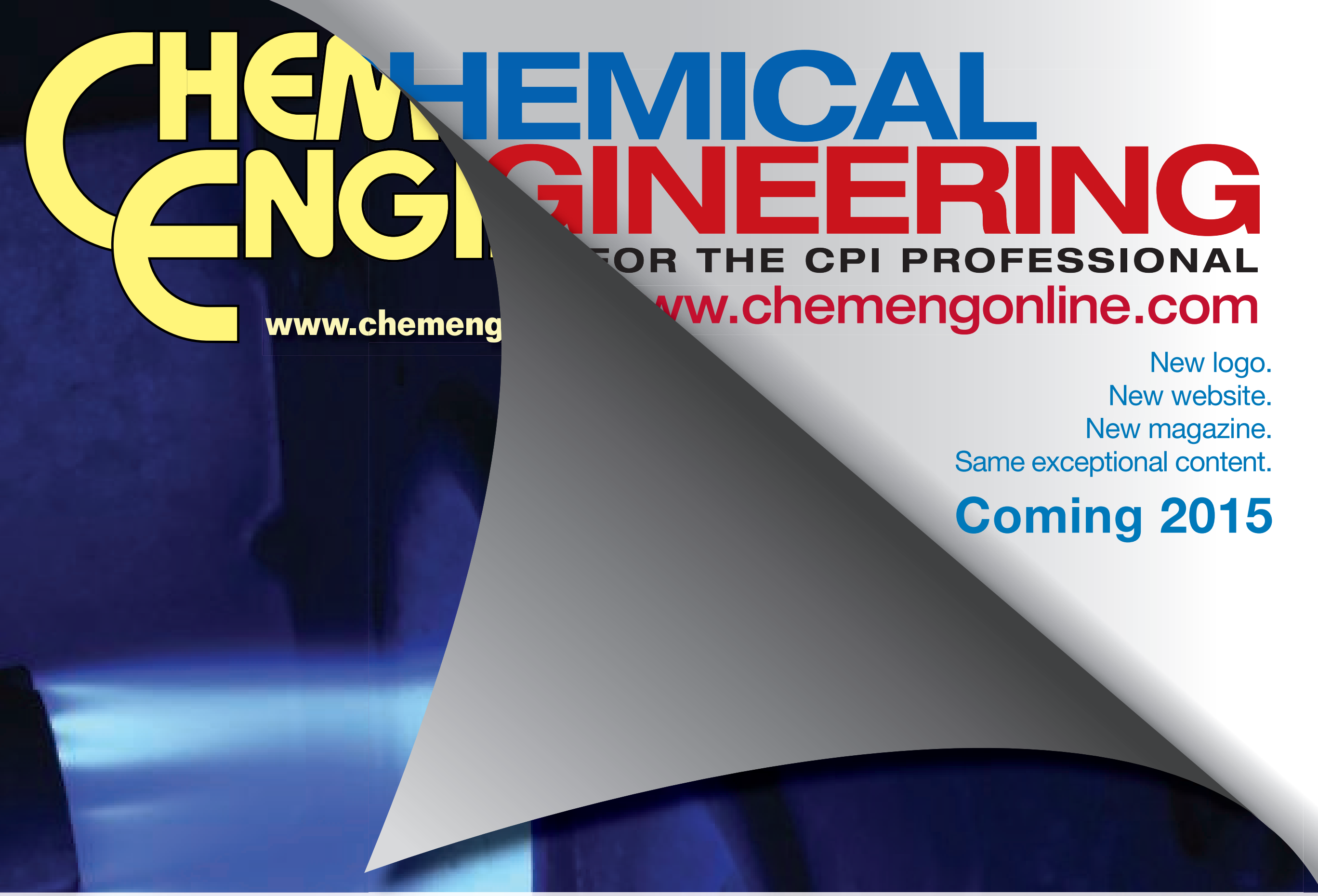
The 902B Absolute Piezo vacuum transducer is equipped with a microelectromechanical-system

Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

(MEMS) piezoelectric sensor with a metal-sealed, stainless-steel diaphragm and integrated electronics to provide seamless, gas-independent vacuum-pressure measurement between 0.1 and 1,000 Torr. Suitable for harsh processes and resistant to damage from air in-rush and vibrations, the 902B features up to three setpoint relays and a high bakeout temperature of 100°C. The 902B also provides both analog output and digital communication, an optional, integrated display and multiple analog output emulations. Its compact, single-unit design is mountable in any orientation. Applications for the 902B include semiconductor manufacturing, thin-film coatings, vacuum furnaces, freeze-drying, analytical instruments, medical devices and more. — *MKS Instruments, Andover, Mass.*
www.mksinst.com

This handheld calibrator features quick pressure generation
The DPI 611 handheld pressure calibrator improves upon its predecessor by doubling pressure-generation efficiency and pressure accuracy and tripling electrical accuracy, all in a more compact package. Designed for use throughout many industrial sectors, the DPI611 is said to be the first dedicated pressure calibrator to feature touchscreen swipe technology. The screen interface displays a comprehensive application dashboard, and a task menu allows for quick setup for pressure tests and calibration. Processes can be automated with the DPI 611, significantly reducing the time required for calibration. The instrument's pressure-generation capabilities have been significantly improved compared to previous models, with the DPI 611 able to create a 95% vacuum or generate a maximum pressure of 20 bars in just 30 s. — *GE Measurement & Control, Boston, Mass.*
www.ge-mcs.com

These pressure transmitters are now ATEX certified
This company's line of explosion-proof pressure transmitters has achieved ATEX certification for Class I Zone 0 hazardous locations. The non-sparking or non-incendive pressure transmitters are traditionally installed in applications requiring special materials, such as Alloy 718 or Alloy C276. Both the explosion-proof and non-incendive pressure-product families cover pressures from 1 to 20,000 psi. The transmitters can be ordered with compound pressure ranges for compressor applications, or bi-directional pressures for vapor-recovery systems. — *American Sensor Technologies, Inc., Mt. Olive, N.J.*
www.astsensors.com



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Dear *Chemical Engineering* Subscribers,

You may have noticed some enhancements over the last few months to *Chemical Engineering*. We've upgraded our *Chemical Engineering* Store Front, making it more user-friendly and easier to complete online transactions. We've also selected a new URL that we feel better reflects our brand: chemengonline.com.

In the coming months, we'll be adding even more upgrades to the *Chemical Engineering* brand, including:

- A responsive website
  The new responsive design will be more aesthetically pleasing and optimized for your desktop, laptop and mobile device.
- An improved logo
  For more than 113 years, *Chemical Engineering* has been the most widely respected global information source for the chemical process industries. As we unveil our new design, you'll see a refreshed and vibrant logo as a reflection of our enhanced brand.
- An enhanced magazine layout
  Chemical Engineering will remain the leading source for news, technology, and analysis. The new layout will be easier to navigate with an enhanced design and layout.

Thank you for providing your input and being a part of our continued success. There's still a lot of work to do in the coming months and we'll continue to update you on our progress.

Sincerely,

Chemical Engineering Staff

Automation Products Group

Yokogawa

Low-power model added to this family of transmitters

The DPharp EJA-E Series of differential pressure/pressure transmitters is now being offered in a low-power version (photo). The new low-power transmitter outputs both 1–5 V d.c. and HART signals, and consumes just 27 mW of power. Even with the device's decreased power usage, it still retains the accuracy and stability of standard-power models, with 0.555% accuracy. At the upper range limit, the transmitter can remain within ±0.1% for seven years. Installation is simple, as basic settings for the new DPharp transmitter can be done easily using a setting switch and an external adjustment screw on the transmitter. — *Yokogawa Corp. of America, Sugar Land, Tex.*
www.us.yokogawa.com

These transducers are easily zeroed in the field

Built with chemical compatibility in mind, PT-503 submersible pressure transducers (photo) feature polyvinyl chloride (PVC) housing that enables them to operate under prolonged exposure to harsh or corrosive materials, in temperatures ranging from –30 to 130°F and depths up to 450 ft. These transducers feature three different cables for compatibility with various chemicals, Teflon or ceramic transducer faces, built-in lightning protection and breathable hydrophobic vent-tube caps that filter out moisture. PT-503 transducers also allow for temperature compensation and are easily zeroed in the field. — *Automation Products Group, Inc., Logan, Utah*
www.apgsensors.com ■

Mary Page Bailey

JANUARY
New Products

Monitor sensor condition with these mobile meters

HandyLab 7 portable meters (photo) are used for sensor calibration, diagnostics, predictive maintenance and data logging. Using Memosens digital sensing, the meter records and tracks performance over a secure digital connection, providing a visual indication of sensor health. HandyLab meters interface with both Memosens digital and traditional analog sensors in many sensing applications, including pH, oxidation reduction potential (ORP), conductivity and oxygen monitoring. Various models are available, with different data-storage and connection options. An explosion-proof version is also available. — *M4 Instruments, Milford, Ohio*
www.m4instruments.com

Larger capacity now available for these double-wall tanks

The introduction of the new IMT 8850 model (photo) expands this company's line of double-wall storage tanks, providing capacity of up to 8,850 gal of liquid, which can accommodate two truckloads of most chemicals. Featuring a standard 24-in. hinged manway, the double-walled nature of these tanks eliminates the risk of spills without the expense of lined concrete containment. The IMT 8850's secure secondary-containment capacity encompasses over 110% of the primary tank's volume. A heavier-top sidewall and dome prevent dome collapse, while a primary inner tank and a secondary outer tank prevent chemical spills. — *Assmann Corp. of America, Garrett, Ind.*
www.assmann-usa.com

Comprehensive motor and drive protection with this dV/dt filter

The new dV Sentry motor-protection dV/dt filter offers comprehensive protection of variable-frequency drives (VFDs) and motors. The dV Sentry is intended for use

M4 Instruments

in heating, ventilation and air conditioning (HVAC), water and wastewater and irrigation applications. The patented Triple Defense Core technology allows the dV Sentry to protect against power distortion created over long-lead voltage power distortion, voltage spikes and common-mode voltage. The device has been shown to reduce common-mode voltage by over 50%, says the company, decreasing the risk of damage to motor bearings and insulation, as well as providing less erratic VFD behavior. The dV Sentry operates from –40 to 60°C, and creates little noise (less than 65 db) during operation. — *MTE Corp., Menomonee Falls, Wis.*
www.mtecorp.com

This magnetic level instrument provides realtime indication

1100 Series Magnetic Level Indicator (MLI) provides visual indication of liquid level within a larger, primary process vessel. Once the MLI is mounted to the vessel, the process liquid will flow freely up and down within the MLI chamber. Located inside the chamber is a specially designed float, which contains a powerful magnet that interacts with the non-invasive indicator assembly located on the outside of the chamber. The magnetic coupling between the float and the indicator allows the process level to be shown via the use

Assmann

of rotating flags housed inside the assembly. As the level rises and falls, these flags will change color and provide realtime indication of the liquid level. — *SOR Inc., Lenexa, Kan.*
www.sorinc.com

A valve for processing abrasive or corrosive substances

The new SKW (slurry knife wafer) valve was developed for applications where abrasive or corrosive slurries, powders or coarse substances are processed. The company has engineered its SKW valve at full-bore with no flow restrictions, allowing processes with abrasive or corrosive fluids — such as lime slurry or mineral slurries — to move without compromising performance. The main benefit to a full-bore design is that the SKW valve itself becomes an integral part of the pipe, and allows it to handle the same fluids in the harshest of conditions. — *Flowrox, Inc., Linthicum, Md.*
www.flowrox.us

Surface-mount accelerometers for vibration measurement

The Model 5150 Series of surface-mount, variable-capacitive accelerometers (photo, p. 28) offers general-purpose vibration measurements for a variety of aerospace, automotive, energy, industrial manufacturing, oil-and-gas, and testing and measurement applications. Design of the Model 5150 Series incorporates a micromachined variable-capacitive sensing element and custom

Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

New Products

Michael Smith Engineers

integrated circuit. The accelerometer produces two analog voltages, which vary proportionally according to measured acceleration levels. The devices are both nitrogen-damped and hermetically sealed. — *Silicon Designs, Inc., Kirkland, Wash.*
www.silicondesigns.com

This system optimizes firetubes for reduced consumption
The Automatic Secondary Air Control (ASAC) system (photo) reduces fuel consumption and emissions in a wide range of natural-gas-fired processing equipment. The patent-pending ASAC design optimizes firetube operation by monitoring and controlling the secondary air in the combustion chamber. Applicable to larger process-heating applications found in heaters, treaters and dehydrators, the ASAC system is now available for processes with pneumatic or electrical power, and can be installed prior to commissioning new equipment, or be retrofit onto existing equipment in the field. — *Engineered Concepts, LLC, Houston*
www.engineeredconcepts.com

This series of monitors sends machinery-health data sitewide
Allen-Bradley Dynamix 1444 condition-monitoring devices (photo, p. 29) are primarily used as machinery-protection systems for rotating and reciprocating equipment. To protect equipment, the Dynamix 1444 device measures and monitors a machine's critical dynamic and position parameters, and assures appropriate actions are performed. Information can be sent to plantwide and enterprise-wide databases for storage and trending. Dynamix 1444 Series monitors are

Silicon Designs

Engineered Concepts

rated for temperatures from –25 to 70°C and voltages of 18–32 V. The devices are also designed for use in hazardous environments and rated to marine standards for shock and vibration. — *Rockwell Automation, Milwaukee, Wis.*
www.rockwellautomation.com

Remotely control and monitor inaccessible actuators
Designed for use with this company's IQ3 actuators, the Remote Hand Station (photo) enables local monitoring and control for equipment in inaccessible locations. At distances up to 100 m from the valve, the Remote Hand Station provides the user with an exact duplicate of the actuator's own monitoring and control interface, which retains all of the actuator's functionality, including diagnostic data, such as valve torque and usage profiles, as well as service logs. Designed for wall- or pole-mounted installation, the Remote Hand Station is explosion-proof, and can be outfitted with a cover to prevent unauthorized interference. — *Rotork plc, Bath, U.K.*
www.rotork.com

Long- and close-coupled thermoplastic pumps
ARBO thermoplastic, mechanically sealed centrifugal pumps (photo) are available in polypropylene, polyethylene, polyvinylidene fluoride and polytetrafluoroethylene, making them resistant to the effects of aggressive chemicals, which can

Rotork

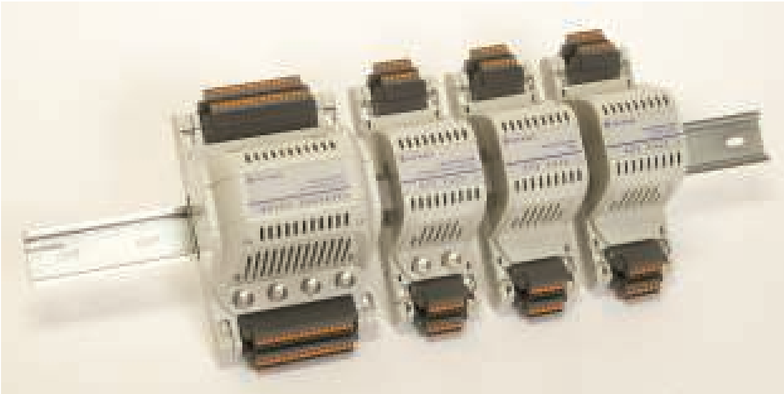
cause corrosion in metallic pumps. All wetted parts are manufactured out of solid block, without the need for injection molding, which eliminates the potential for stress-cracking. ARBO pumps can handle solid particles up to 3 mm, ensuring extended pump operation in the event of process upset. The pumps are available with either close-coupled or long-coupled design. In the close-coupled configuration, ARBO pumps can be specified in either horizontal or vertical mounting options. The long-coupled, horizontal version incorporates separate frame-mounted bearing support for the motor shaft. The complete long-coupled pump unit is assembled on a rigid glass-fiber-reinforced polyester baseplate. — *Michael Smith Engineers Ltd., Surrey, U.K.*
www.michael-smith-engineers.co.uk

This separator has advantages for beer production
To make the brewing process more cost-effective while still taking the quality requirements for beer products into consideration, this company continues to improve its workhorse AC separator line. The AC 2500 (photo, p. 29) offers gentle processing of beer and efficient clarification before filtration. The advantages include the following: cost reduction through process optimization; reduction in beer losses; avoidance of fluctuations; maximum yield with consistent beer quality; and reduced cleaning and wastewater costs. — *Flottweg SE, Vilsbiburg, Germany*
www.flottweg.com

Simultaneous horizontal and vertical shaft alignment
The RS5 sensor (photo, p. 29) is used for shaft alignment, with a mea-

Ludeca

Rockwell Automation



surement range that covers spans of up to 10 m. Its five-axis technology offers simultaneous tracking in both planes for machine corrections, allowing live monitoring of horizontal and vertical machine corrections at the same time, with the sensor at any rotational shaft position. Hundreds of measurement readings are automatically taken during shaft rotation, ensuring highly repeatable results, even in harsh conditions with vibration, and under unfavorable mechanical constraints, such as coupling backlash. The integrated ambient-light compensation ensures accurate measurements even in strong, direct sunlight. New battery technology enables longer sustained operation in the field. The RS5 laser and sensor are fully waterproof, shockproof and dustproof. — *Ludeca, Inc., Doral, Fla.*
www.ludeca.com

This adaptor allows wired devices to run wirelessly

The newly developed multi-function wireless adaptor (photo) enables wired devices that transmit or receive digital ON/OFF signals, or receive 4–20-mA analog signals, to function as ISA100 Wireless field devices. This increases the variety of devices that can be used with field-wireless systems, and is expected to lead to a wider use of such systems in plant operations. The adapter can be used with switches, solenoid valves, and other device types that utilize digital ON/OFF signals, and transmitters that utilize 4–20-mA analog input signals. An all-weather model that is

Yokogawa

waterproof and dustproof, and an explosion-proof model that can be used in inflammable-gas environments are expected to be released by the end of 2015. — *Yokogawa Corp. of America, Newnan, Ga.*
www.yokogawa.com/us

Expanded Scada software for recipe-based production

This company has added the WinCC/SES (sequence execution system) option to its Simatic WinCC Scada (supervisory control and data acquisition) system (photo, p. 30) for the sequential control of recipe-based and sequence-based operations in production plants. Such an addition is ideally suited to plants for which dosing, mixing and material transport are important process steps, such as in the food and beverage

Flottweg

industry. Thanks to the flexible sequential control, plant operators are able to define their production steps clearly and freely combine them into individual process sequences. Both step sequences and parameters can be adapted online at any time to meet ongoing production requirements. This means that production sequences can be re-adjusted quickly and simply in the event that the quality of natural raw materials fluctuates, or if another sequence of production steps is necessary to enable flexible routing through the production system. — *Siemens AG, Nuremberg, Germany*
www.siemens.com/wincc

New simulation software version with App builder

This company's newly released Multiphysics software version 5.0 (photo, p. 30) features extensive product updates, three new add-on products, and the new Application Builder. The Application Builder empowers the design process by allowing engineers to make available an easy-to-use application based on their Multiphysics model. Included with the Windows operating-system version of Multiphysics 5.0, Pepperl+Fuchs

Siemens

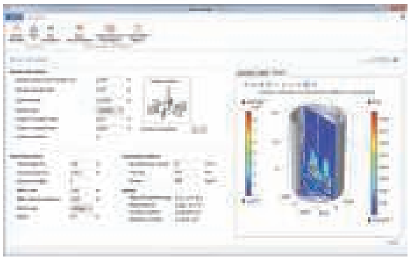
the Application Builder provides all the tools needed to build and run simulation apps. Any Multiphysics model can be turned into an application with its own interface using the tools provided with the Application Builder desktop environment. Using the Form Editor, the user interface layout can be designed, while the Methods Editor is used for implementing customized commands. — *Comsol, Inc. Burlington, Mass.*
www.comsol.com

An all-in-one vapor delivery solution

The Vapor Delivery Modules (VDM; photo) are compact sub-systems incorporating a liquid flow controller (thermal or Coriolis), one or two mass-flow controllers for carrier gas and a temperature-controlled mixing and evaporation device. The modules are equipped with a 1.8-in. thin-film transistor (TFT) display and push-buttons for local readout and control. The systems can also be operated via digital communication (RS232 or FLOW-BUS). Optionally, the units can be supplied with an additional mass-flow controller for dilution and with local or remote trace-heating temperature control. VDM-Series vaporizers are suitable for vapor deposition and coating processes for the production of semiconductor chips, displays and solar cells. — *Bronkhorst High-Tech B.V., Ruurlo, the Netherlands*
www.bronkhorst.com

Bronkhorst High-Tech

Comsol



A HART loop converter with autodetect function

The HART loop converter (HLC; photo) records up to four digital signals and converts them into analog 4–20-mA current signals. The new improved version automatically detects whether a different master is working in the same mode when querying the dynamic variables. The HLC enables direct access to all data from intelligent HART field devices without the need for additional field wiring. It captures up to four digital HART variables, three of which are converted into various analog 4–20-mA current signals and made available to various systems via signal splitting. — *Pepperl+Fuchs GmbH, Mannheim, Germany*
www.pepperl-fuchs.com ■

Mary Page Bailey, with Gerald Ondrey

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

The Impact of Off-BEP Pump Operation

Best-efficiency point (BEP), the flowrate at which a pump operates at its highest or optimum efficiency for a specific impeller diameter, is a key consideration when assessing pump performance. While most pumps do not consistently operate at their exact BEP, a pump that is properly sized will maintain a flow near peak efficiency (85–105% of BEP).

Operating a pump "off-BEP" means that the flowrate is either too far above or below the BEP for a sustained period of time, resulting in a number of negative consequences. This article outlines the consequences of operating pumps away from their BEP for extended periods, as well as the key questions to ask when assessing off-BEP pump operation.

Consequences of off-BEP operation

Vibration and noise. Noise and vibration can occur when a pump operates too far to the right of BEP, generating high-velocity eddy currents that contribute to the imbalance of pressure and shaft deflection. The resulting stress on the pump's internal components can lead to poor pump performance, excessive wear and increased risk of failure. The ideal noise/vibration point is approximately 90% of BEP.

Cavitation. Cavitation occurs when vapor bubbles continuously form and collapse, creating intense pressure (up to 10,000 psi) and shock waves (Figure 2). This is caused when the net positive suction head required ($NPSH_R$) increases beyond the NPSH available ($NPSH_A$), or when the $NPSH_A$ drops below the $NPSH_R$. In determining reliability, if the $NPSH_A$ in the system drops below the $NPSH_R$ by the pump, the pump will experience cavitation — eroding the impeller, vibrating the bearings and casings, and causing damage that can be quite severe. The fatigued metal breaks away, creating pitted surfaces, which become concentration points for further bubble collapse. $NPSH_R$ is typically based on test standards established by the Hydraulic Institute (www.pumps.org); the definition of it is based on a 3% total head drop (Figure 1). At that 3% ratio, a pump is already cavitating. That is why there are common practices in the industry that require a certain margin to be in place to make sure a pump is not running right at the $NPSH_A$, and thus, by definition, cavitating.

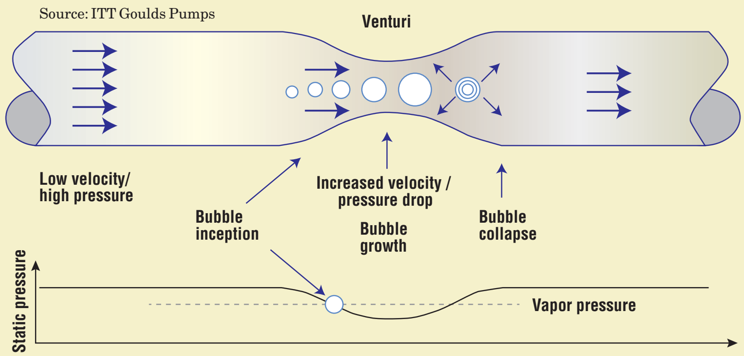


FIGURE 2. Cavitation can be created for demonstration purposes using a venturi

Bearing and seal failure. Bearing and seal failure accounts for more than 80% of all premature centrifugal pump failures, and occurs when a pump experiences increased radial and thrust loads during off-BEP operation. Pumps that have a single-volute casing design normally experience a rapid increase in impeller radial and thrust loads as the flow declines below BEP flow. Dual-volute casing designs help to balance radial loads and are essential for reliability when a pump must operate for a substantial period of time at flows considerably below its BEP flowrate. Modified concentric volute-casing designs are an alternative to single volutes — offering reduced radial loads in off-BEP operation, but giving up a little bit of pump efficiency in the process. The impeller loads that develop during off-BEP operation can lead to shaft deflection and mechanical seal failures, or overload the bearings with increased temperatures.

Discharge and suction recirculation. Discharge and suction recirculation happens when fluid does not flow through the pump as it was designed, causing small flow instabilities called eddies. The damage caused by eddies mirrors cavitation and can lead to catastrophic pump failure when portions of the impeller inlet or discharge vanes fatigue and fail by breaking off.

Temperature rise. Temperature rise is one of the more severe effects of off-BEP operation, because at its most extreme, human life can be lost. If a pump is allowed to run at shut-off for an extended period of time, enough energy can be applied to the fluid to cause the pressure in the pump to build to a point where it's greater than the yield strength of the casing, thus causing an explosion. Such explosions have been known to throw motors through concrete block walls. The chances of this happening are remote, yet real.

Key questions

The following application-related questions should be considered when assessing off-BEP pump operation:

- What type of damage can occur if a pump is run below the BEP?
- What type of damage can occur if a pump is run above the BEP?
- How does off-BEP operation affect a pump's mechanical seal?
- Why does vibration increase in off-BEP operation?
- What are some ways pump manufacturers use hydraulic design to minimize loads on bearings and increase bearing life?
- Are proper operational controls in place to prevent a catastrophic event?

In pursuit of peak efficiencies and increased reliability (longer mean time between failures), pump adjustments are often made to align their BEP with the duty point of the pumping systems. Consider testing a pump if you are uncertain about its BEP for a specific application. ■

Editor's note: Content for this edition of "Facts at your Fingertips" was contributed by Rich Nardone, global product manager at ITT Goulds Pumps (Seneca Falls, N.Y.; www.gouldspumps.com).

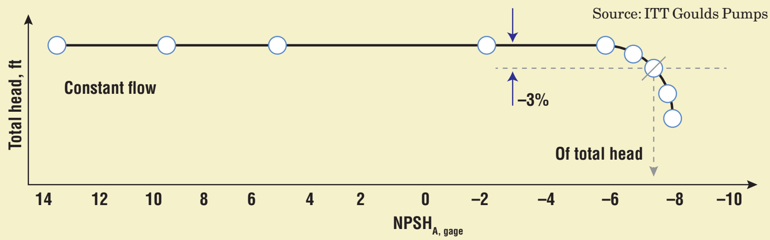


FIGURE 1. Shown here is an example of an NPSH test plot used to determine a pump's $NPSH_R$

Sugar Inversion

The substance known colloquially as table sugar is actually sucrose, a disaccharide composed of fructose and glucose. Sucrose is a major agriculturally derived product with an established industry for its extraction, processing and supply. It is mainly employed as a sweetener in industrial and domestic food applications, but also finds additional uses in the pharmaceutical industry, in chemical manufacturing, and as a feedstock for fermentation processes. For example, sugar is used as a feedstock for the manufacture of bio-based chemicals, such as bio-succinic acid.

Sugar generally exists commercially as a solid granular product. However, some food manufacturers prefer to use sugar in a liquid form, due to the ease of handling a liquid product. One commercially available liquid-sugar product is liquid invert sugar, also known as invert syrup. It is produced from the inversion of sucrose, which refers to the hydrolysis of the disaccharide molecule into its constituent parts, the monosaccharides glucose and fructose. The result of this reaction is a product with greater sweetening power and improved microbiological stability, when compared to sucrose.

Invert syrups are commercialized with different combinations of invert sugar and sucrose contents, depending on the degree of inversion performed. Also, invert syrups can be produced by three different inversion processes: acid hydrolysis with mineral acids; enzymatic hydrolysis; or hydrolysis by cation ion-exchange resin. The latter process is described in this column.

The process

The process for sucrose inversion by ion-exchange resin shown in Figure 1 is similar to the one presented in U.S. Patent 8,404,109, published by European Sugar Holdings S.a.r.l. (Capellen, Luxembourg). An important feature of this process is the removal of ash from the solution in the ion-exchange columns.

Sucrose dissolution. Water and steam are mixed to form a hot water stream. Part of this stream is added to raw sugar (sucrose) before it is fed to a screw conveyor, which directs wet sucrose to an agitated vessel. The remaining hot water is fed into the vessel, forming a 60 wt.% sucrose solution.

Sucrose inversion. The sucrose solution is fed to a cation-exchange column, where some ash is retained and the pH is lowered, allowing the inversion reaction to occur. Then, part of the inverted solution is fed to an anion-exchange column, where some ash is removed and the pH of the solution is increased. Finally, the fully inverted solution is concentrated to 70 wt.% dry matter, forming the final product.

Economic evaluation

An economic evaluation of the sugar-inversion process was conducted, taking the following assumptions into consideration:

- A facility producing 585,000 ton/yr of invert syrup from raw sugar. The facility was assumed to be located on the U.S. Gulf Coast in the same location as a plant operating a fermentative process that uses invert syrup as feedstock
- A raw-sugar warehouse with storage capacity equal to 20 days of operation
- Utilities facilities and product storage were not considered in the analysis

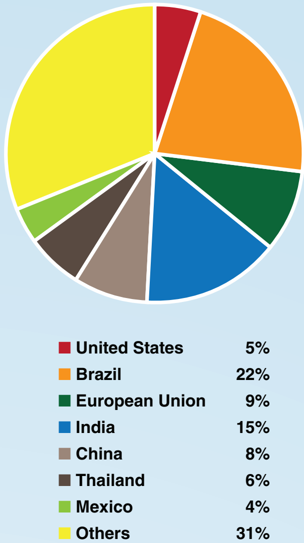


FIGURE 2. World sugar production by country or region in 2013

The estimated total fixed investment for building such a plant is about $40 million.

Global perspective

Sucrose can be produced either from sugarcane or sugarbeet plants, depending on climate conditions. Sugarcane is cultivated in tropical and subtropical regions, while sugarbeets are more suitable in temperate zones.

In 2013, world sugar production was about 177 million tons (in raw sugar equivalent). About 80% of global sugar production is derived from sugarcane, and about 20% is from sugarbeets.

Brazil, the world's largest sugar producer, accounts for about 22% of global sugar production, with all of its sugar production originating from sugarcane.

The world's main sugar producers are shown in Figure 2. The U.S. is the only country among them that produces sugar from both sugarcane and sugarbeet in significant amounts. As the world's sixth-largest sugar producer, the U.S. produces 56% of its sugar from sugarbeets, while the remaining 44% comes from sugarcane. ■

Editor's Note: The content for this column is supplied by Intratec Solutions LLC (Houston; www.intratec.us) and edited by *Chemical Engineering*. The analyses and models presented are prepared on the basis of publicly available and non-confidential information. The content represents the opinions of Intratec only. More information about the methodology for preparing analysis can be found, along with terms of use, at www.intratec.us/che.

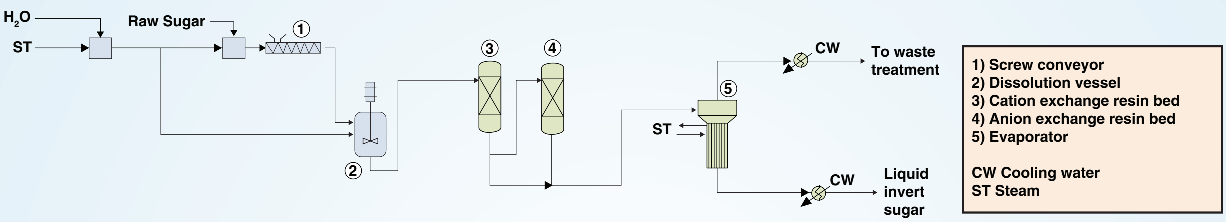


FIGURE 1. The sugar-inversion process shown here uses ion-exchange resins

Controlling Suspension Rheology

The physical characteristics of dispersed particles have a large impact on overall rheological properties

John Duffy
Malvern Instruments

Many important products of the chemical process industries (CPI) exist as suspensions or dispersions of particles in liquid media. Examples range from adhesives, ceramics, paints and inks to food-and-beverage, personal care and pharmaceutical products. The physical properties of the dispersed particles in such systems — including particle size, particle-size distribution, concentration, electric charge and even particle shape — can all strongly influence the overall (bulk) rheological properties of a suspension, thereby defining product behavior and functionality. Understanding these interactions is crucial for achieving the desired product performance. This could mean, for example, the stability of a paint or medicine, or the visual appeal of a shower gel or drink.

This article examines the impact of particle loading on suspension viscosity, and more broadly, on overall rheological behavior. It looks in some detail at how particle size and shape influence critical aspects of suspension performance, such as viscosity and stability. One central focus of the article is to provide practical guidance for measuring the rheological properties of suspensions and to show how particle properties can be manipulated to tailor and control product performance.

Industrial suspensions

Suspension products are ubiquitous in everyday life, as well as within industrial manufacturing. Examples from the domestic sphere range from indigestion medicines and nasal sprays to shower gels with eye-catching suspended active ingredients, and low-fat foods that mimic the performance of their high-fat counterparts. Paints, inks, coatings, ceramic slurries and abrasives exemplify suspensions in industrial use. Rheological properties are critical in defining the performance of all suspension products, most especially their stability and flow characteristics.

Consider, for example, the underlying characteristics that impart high performance to paints, which are actually suspensions of pigments and other ingredients in a liquid continuous phase. Paints are stored in a low-stress state, subject only to the influence of gravity. These same stresses apply following the application of paint to a surface. A paint that is highly viscous at low shear will tend to resist sedimentation or settling, and therefore be very stable. Having a high viscosity under low shear will also make a paint less likely to slump or curtain on the substrate to which it is applied, producing a desirable smooth finish.

However, when it comes to the use of paints, the shear stresses applied are relatively high and the viscosity target changes, too. In this environment, there are benefits to low viscosity, since it aids the even distribution of the product over the surface. Paint therefore offers a good example of a suspension where there is a need to engineer a specific viscosity profile — in this case, shear-thinning behavior — which is where viscosity decreases with applied shear stress. A paint formulation that shear-thins will deliver the low shear, high viscosity required for stability and a good surface finish, coupled with the low viscosity at high shear needed for easy, low-energy-input application.

The formulation of pharmaceutical suspensions provides a contrasting example, where stability is the defining focus. Stability in a medicine equates to uniform dosing, so if the active ingredient does sediment (settle) out, it must be easily resuspended on shaking. A stable suspension addresses any concerns about this issue by reducing the risk of sedimentation. In the formulation of medicines, engineering rheology to deliver the required stability is crucial, but there may be less need to ensure that viscosity is closely controlled over a wide range of shear stresses.

Rheological properties

These examples draw attention to the way in which viscosity can change as a function of shear, and the need to understand those changes within the context of the conditions applied to the product during use (see also *Chem. Eng.*, August 2009, pp. 34–39). However, viscosity can also exhibit time-dependent behavior, known as thixotropy. For example, a shear-thinning paint that is thixotropic will take an appreciable time to regain high viscosity following a reduction in the shear stress. This can be a useful characteristic. If a brushed paint instantly regains high viscosity when brushing stops, then brush marks are likely to be visible in the finish forever. A product with some thixotropy will allow these marks to flow away into a smoother finish.

One further viscosity-related characteristic that is also used to impart defined properties to a suspension product is yield stress (often termed apparent yield stress). Suspensions with a yield stress change relatively abruptly from solid-like to liquid-like behavior at a certain point. Below this point (the yield stress), such suspensions behave in a solid-like or gel-like way; above it they flow like liquids. Yield stresses arise from underlying macro- and micro-structural characteristics in a material and can be usefully engineered into many products.

For example, mayonnaise with an appreciable yield stress will hold its form when spooned from a jar or when sitting on a plate, enhancing perceptions of quality. High-quality tomato ketchup will not drip from a plastic bottle, but will flow well when the bottle is squeezed. The term "apparent yield stress" arises because some materials can appear to behave like a solid on short timescales but, over longer periods of applied stress, can flow or creep.

A number of suspension parameters can be varied in order to refine rheological properties to meet formulation goals, within the constraints of meeting other targets relating to, for example, appearance. These parameters include particle loading, particle size, particle size distribution, particle morphology and, for sub-micron particles, zeta potential. Focusing on viscosity, the following section examines how these different parameters can be manipulated and managed to reach formulation goals.

The impact of particle loading

At the beginning of his career, physicist Albert Einstein studied and described the flow field around a single hard sphere in a liquid. His conclusions remain of value for systems containing very low particle concentrations. However, in many industrial suspensions, particle loadings are relatively high, with particles in far closer proximity to one another. The consequence of this is a much more inhibited flow field that results in higher suspension viscosities and greater sensitivity to incremental changes in particle concentration. The Krieger and Dougherty relationship, expressed in Equation (1), describes the relationship between particle loading or concentration and viscosity in this regime of higher particle concentrations:

$$\frac{\eta}{\eta_{medium}} = \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m} \qquad (1)$$

Where η is the viscosity of the suspension; η_{medium} is the viscosity of the medium; ϕ is the volume fraction of solids in the suspension; ϕ_m is the maximum volume fraction of solids in the suspension (the maximum amount of particles that can be added to the suspension); and $[\eta]$ is the intrinsic viscosity for spheres (a dimensionless number with a value of 2.5)

Figure 1 shows how the viscosity behavior of a suspension changes as the volume fraction of particles increases, relative to the maximum volume fraction. At low volume fractions, where ϕ/ϕ_m is less than 0.1, the particles have room to flow freely, a situation closer to the one considered by Einstein. The suspension exhibits the Newtonian response of the continuous phase, which means that viscosity is independent of the shear rate.

At slightly higher volume fractions, when ϕ/ϕ_m lies in the range 0.1 to 0.5, particle-particle interactions start to become significant. These interactions inhibit the freedom with which particles move, and give rise to an increase in viscosity. However, because the strength of particle-particle interactions is relatively low, they are broken down as shear rate is increased. This effect is compounded by the influence of Brownian motion, especially in suspensions containing relatively fine particles, where Brownian stresses can be relatively high. Brownian motion opposes an applied shear stress, acting to maintain randomized particle movement. However, this effect is overcome at higher stresses, at which point particles rearrange into a more efficient packing structure. As a result of both of these mechanisms, suspensions in this regime exhibit non-Newtonian shear-thinning behavior. Viscosity is no longer independent of shear rate (Newtonian behavior) but decreases as shear rate is increased.

At high particle loadings, once ϕ/ϕ_m exceeds 0.5, there is minimal room for the particles to move. Now the particles are not only interacting with each other, they are physically inhibiting the motion of one another. As shear increases, this inhibition of movement becomes more and more limiting and so the suspension exhibits non-Newtonian, shear thickening behavior; viscosity increases with shear rate.

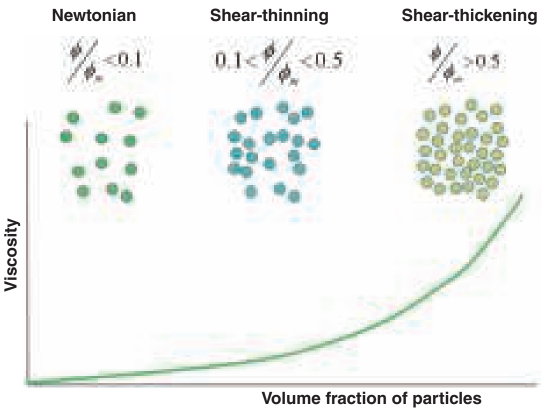


FIGURE 1. Increasing the volume fraction of particles in a suspension increases viscosity and also influences whether a suspension will exhibit Newtonian or non-Newtonian behavior

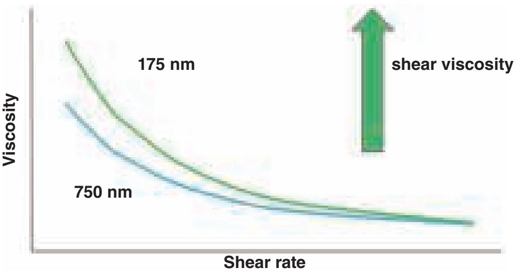


FIGURE 2. Decreasing particle size may lead to an increase in low shear viscosity, for a constant volume fraction of particles, if colloidal interactions are significant

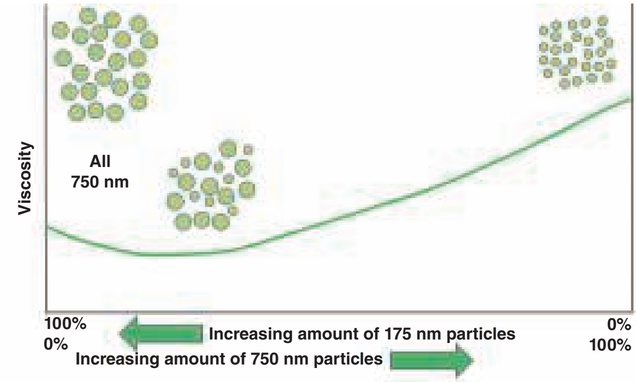


FIGURE 3: The impact of polydispersity and particle size can produce competing effects and, in the system above, produces a minimum viscosity value

The actual values of ϕ/ϕ_m that mark the transition from Newtonian to shear-thinning and then to shear-thickening behavior are system-specific, but those included here provide a good guideline for most cases. Changing the particle loading is clearly a productive strategy for altering not only the viscosity of a suspension, but also its Newtonian/non-Newtonian characteristics. Varying not only the amount, but also the properties, of the particles added is a complementary approach.

Particles and viscosity

Optimizing particle properties can provide a means to control the viscosity profile of a suspension.

Particle size. For a constant volume fraction, decreasing particle size will increase viscosity. If volume fraction is kept constant, then decreasing particle size leads to an increase in the number of particles present. This is especially the case with sub-micron-sized particles. For such particles, the effective hydrodynamic size may be substantially increased by any surface charge, hydration or adsorption layers that surround each core particle. This will result in a higher effective volume fraction for a given particle loading, thereby increasing the viscosity of the suspension. For larger particles, which are fewer in number, this effect is greatly reduced.

Figure 2 shows data for latex particles in a pressure-sensitive adhesive that illustrate this effect. Because interparticle (colloidal) interactions are dominant at low shear rates, the effect is more pronounced in this range, with smaller particles giving rise to higher viscosities due to their higher effective volume. At high shear rates, interparticle forces are broken down and hydrodynamic forces dominate. A consequence of this phenomenon is that the effective volume fraction becomes less dependent on particle size and viscosity values converge.

Polydispersity. For a constant volume fraction, increasing polydispersity will decrease viscosity.

Polydispersity is the span or range of the particle-size distribution. A particle-size distribution with a wide span contains dissimilarly sized particles — some large, some small — and tends to pack better than if particles are of uniform size (a narrow distribution; small polydispersity). This superior packing makes it easier for an equivalent volume of particles to move around, leading to lower viscosity. Again, in terms of the Krieger and Dougherty relationship, increasing polydispersity increases the maximum volume fraction, thereby lowering viscosity. Conversely, this means that narrowing the particle-size distribution can increase viscosity, a change often associated with increased stability.

The effects of polydispersity and particle size can at times be competing, so particle size and particle-size distribution can be used in combination to engineer system viscosity. Returning to the example of using either 175-nm particles or 750-nm particles (see Figure 2), a bimodal distribution of these two particles results in a minimum viscosity (see Figure 3). For a given volume fraction, suspension viscosity with only 750-nm particles is lower than with 175-nm particles because the use of finer particles increases the effective volume. However, the inclusion of a relatively small fraction of 175-nm particles in a binary mixture reduces, rather than increases, viscosity. The impact of these finer particles on packing behavior — an effect that decreases viscosity — more than offsets the increase in viscosity caused by a greater number of particle-particle interactions.

Convexity. Smoother particles result in suspensions with lower shear viscosities than those with low convexity.

Convexity is a measure of the regularity or sharpness of the perimeter of a particle — a descriptor of particle shape. Particles with low convexity (see Figure 4) have a convoluted outline that increases the likelihood of mechanical resistance to flow in a suspension. Furthermore, relative to equivalently sized smooth particles, particles with low convexity may have a higher specific surface area, increasing the strength of any particle-particle interactions. Both of these effects tend to be more marked at high solids loadings.

More generally, however, particles with higher surface roughness cause greater deviation of the liquid flow fields around them, a phenomenon that also acts to increase viscosity. As a result, the viscos-

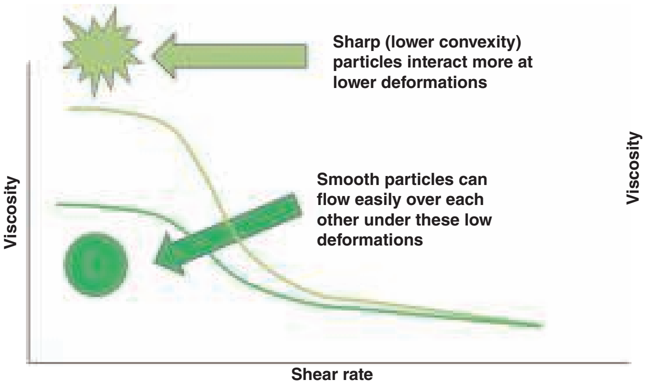


FIGURE 4. Sharper particles (those with lower convexity) give rise to suspensions with higher viscosity, all other factors being equal

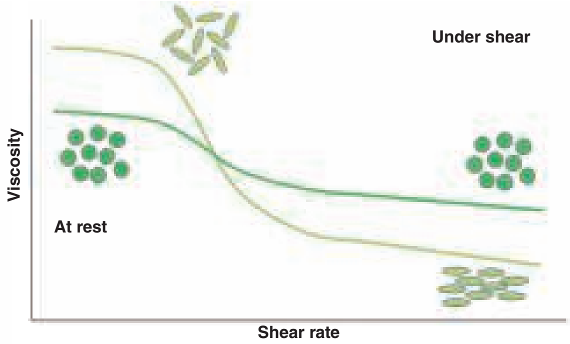


FIGURE 5. As a result of orientation at high shear rates, the viscosity of suspensions with elongated particles has a different profile compared to that of a suspension containing spherical particles of equivalent size

ity of a suspension can often be reduced by using smoother, more regular particles. Although once again, any impact on viscosity is usually more marked at low shear rates and high volume fractions.

At low shear forces, elongated particles produce higher viscosity than spherical ones, although the converse is true at high shear, where elongated particles are associated with lower viscosity than spherical analogs.

Elongated particles produce a different suspension viscosity profile than spherical analogs (Figure 5). Particle-particle interactions between spherical particles typically break down as shear increases, and this gives rise to shear-thinning behavior. Elongated particles are generally randomly oriented at low shear, thus occupying larger volumes, but at high shear, will tend to orient in way that is parallel to the direction of flow, resulting in more efficient packing. As a result, suspensions with elongated particles also shear-thin, but far more markedly that those containing spherical particles.

At low shear forces, a suspension that contains particles with elongated shapes typically has higher viscosity than one that contains spherical particles of equivalent size. At high shear, however, this situation is reversed, and the suspension with spherical particles will have higher viscosity than those with elongated particles of equivalent size.

Electrical charge zeta potential

The preceding analysis of how particle size and shape impact viscosity has shown that these physical characteristics influence how easily particles within a suspension can move, relative to one another. One further parameter that can also influence particle movement, and consequently viscosity and stability, is the electrical charge on particles within a system. One way of measuring this charge is to quantify zeta potential.

Zeta potential quantifies the magnitude of the electrostatic repulsion or attraction in a system. It is a measure of particle charge at the edge of the slipping plane between the particle and associated double layer, and the surrounding solvent (Figure 6). The fact that zeta potential is not the charge on the surface of the particle, but rather at the edge of the particle's "sphere of influence," makes it highly relevant to suspension behavior. If a suspension has a large negative or positive zeta potential, then the particles within it will tend to successfully repel each other. Low zeta-potential values increase the likelihood of flocculation or agglomeration (the joining together of discrete particles).

In sub-micron colloidal systems, particles tend to move under Brownian motion and the influence of gravity is low because particle mass is small. Here, increasing the zeta potential causes particles to repel one another, inhibiting movement and increasing viscosity, especially at low shear rates (see Figure 7), when the particles exhibit a larger effective hydrodynamic volume. A zeta potential of sufficient magnitude (around ±30 mV) will maintain particle separation. In these systems, gravitational forces only become large enough to cause sedimentation if the particles grow in mass by a process of agglomeration. Keeping particles separate therefore ensures stability.

In a suspension with larger particles, zeta potential may be controlled in order to deliver a quite different effect. For particles of significant mass, gravitational forces are sufficient to induce sedimentation. Here, engineering a high zeta potential to maintain the particles as discrete entities does not produce a stable suspension. Counterintuitively, the opposite can work. In certain systems reducing the zeta potential induces partial agglomeration of the particles, creating a networked gel that can give appreciable viscosity to a suspension. Reduction in zeta potential also induces an apparent yield stress in these cases.

Rheology measurement

Clearly, a number of strategies can be used to refine rheological properties to meet performance targets for a specific suspension. However, the driver for such formulation optimization is analytical data. Laser diffraction and dynamic light scattering (DLS) are well-established techniques for measuring particle

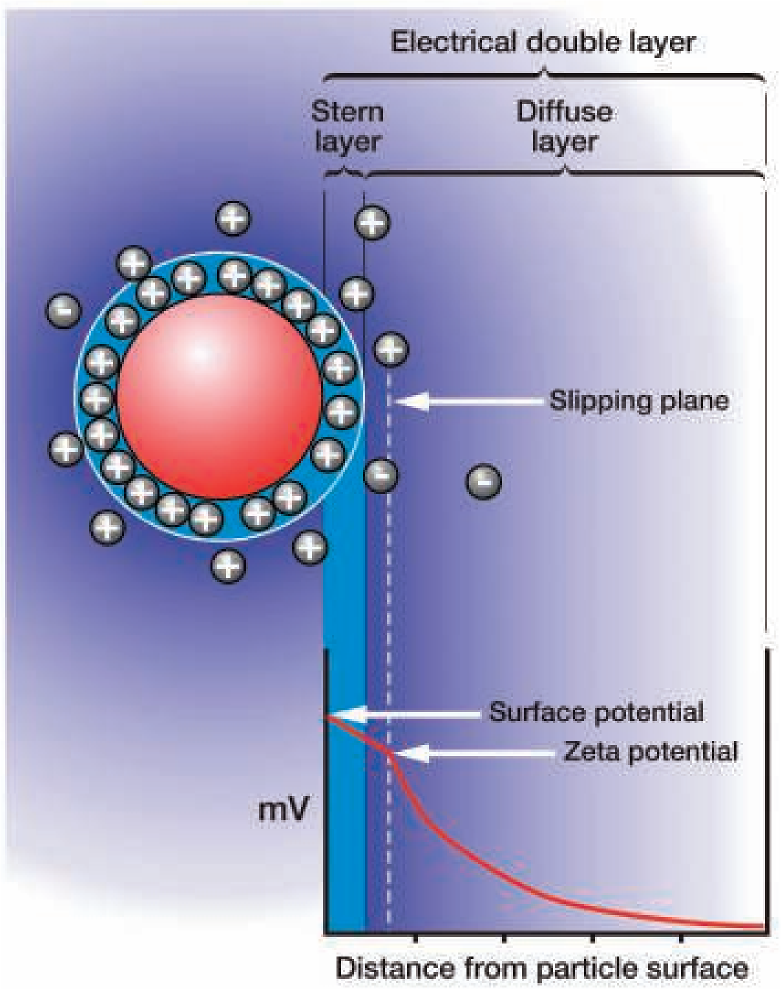


FIGURE 6. Zeta potential influences whether particles will repel or attract each other when held in suspension

size distributions centered in the micron and sub-micron ranges, respectively. Zeta potential can be measured by electrophoretic light scattering, a technique that is complementary to DLS and is often integrated into DLS systems, while automated imaging brings rapid, statistically relevant analysis of particle shape.

This leaves the actual measurement of rheological parameters. Here, there are multiple options but often some confusion as to which instrument and methodologies to employ. A defining requirement in rheological characterization is to make measurements under conditions that are relevant to the application. Understanding the capabilities of different rheometers helps to identify the best choice for specific uses and materials.

Rotational rheometer / viscometer. These instruments work by loading samples between two plates (or other similar geometry, such as cone-and-plate, or alternatively, a cup-and-bob system). Applying a torque to the top plate exerts a rotational shear stress on the material and the resulting strain or strain rate (shear rate) is measured. Rotational rheometers and viscometers share the same operating principle, but the former have far greater functionality. This is most evident in the accuracy and range over which shear stress can be applied, their facility for oscillatory testing and the level of control over the normal force applied during rotational testing.

Rotational rheometers are arguably the most versatile rheological-measurement tools available. They can be configured for a number of different rheological methods, all of which probe the structure and performance of suspensions. Test types include the generation of simple viscosity flow curves (plots of viscosity against shear) over many decades of torque, yield-stress measurement and precise sequences that simulate the chewing of food. Modern, sophisticated instruments enable close matching of the test method to the specific process or in-use environment of the product. Innovative software products are increasingly helpful in allowing even novice rheologists to generate and interpret relevant data.

Rotational rheometers are used for a broad range of sample types, from pastes and gels to the most weakly structured liquids. Applied shear can be precisely controlled into the very low shear-stress region, making these instruments suitable for stability studies and for the measurement of yield stress. However, rotational rheometers are optimized for operation across many a wide range of torque levels rather than for the precise differentiation of viscosity in low-viscosity, weakly structured fluids. In addition, rotational rheometers face mechanical limitations in the high-shear region for low viscosity or highly elastic materials.

Capillary rheometry. In capillary rheometry, a sample is forced to extrude through a barrel or die of well defined dimensions under high pressure. The pressure drop across the barrel or die is measured to give pressure-flowrate data for the fluid, from which viscosity is calculated. Temperature and shear rate can be closely controlled to simulate the processing environment of interest.

Originating in the polymer industry, capillary rheometry is useful for measuring the viscosity profiles of suspensions and slurries containing relatively large particles, at high particle loadings. Industrial examples include polymer melts, ceramic slurries, foodstuffs, inks and coatings. Capillary rheometers can apply very high force, which enables the exploration of behavior at far higher shear rates than is possible with rotational rheometry. High-shear-rate performance is pertinent in many industrial processes, such as extrusion and spraying. For certain applications, the sample size required for capillary rheometry — around one liter for the generation of a flow curve — can be a limitation.

Microfluidic rheometry. A relatively new form of mechanical rheometry, microfluidic rheometry is closely aligned to capillary rheometry, since it is similarly based on the determination of viscosity from measurements of how pressure drop varies as a function of flowrate. However, with this technique, the sample is forced down microfluidic channels and the resulting pressure drop is measured using micro-electro-mechanical-system (MEMS) pressure sensors embedded within the channel. This method delivers highly accurate measurements. The scale of testing is small, but extremely high shear rates can be applied.

Microfluidic rheometry characterizes low-viscosity, dilute suspensions containing relatively small particles (less than 20 microns), especially at ultra-high shear rates, in excess of 1,000,000 s^{-1}. Instruments that use this technique offer completely enclosed measurement, which is helpful for the safe and reliable analysis of highly volatile or environmentally sensitive samples. Microfluidic rheometry instruments can generate accurate viscosity data using volumes as low as 50 µL. Compared with rotational rheometry, microfluidic rheometry more sensitively differentiates samples with low viscosities and enables testing under higher-shear-rate conditions. Relative to capillary rheometry, microfluidic rheometry requires orders of magnitude less sample, and more easily accommodates low-viscosity materials.

These capabilities make microfluidic rheometry especially useful for measuring the viscosity behavior of products, such as inkjet inks, specialty chemicals, personal care products and food and beverages, under the shear conditions that exist during product use. The small sample size can be particularly helpful during early development work, when the supply of material may be limited.

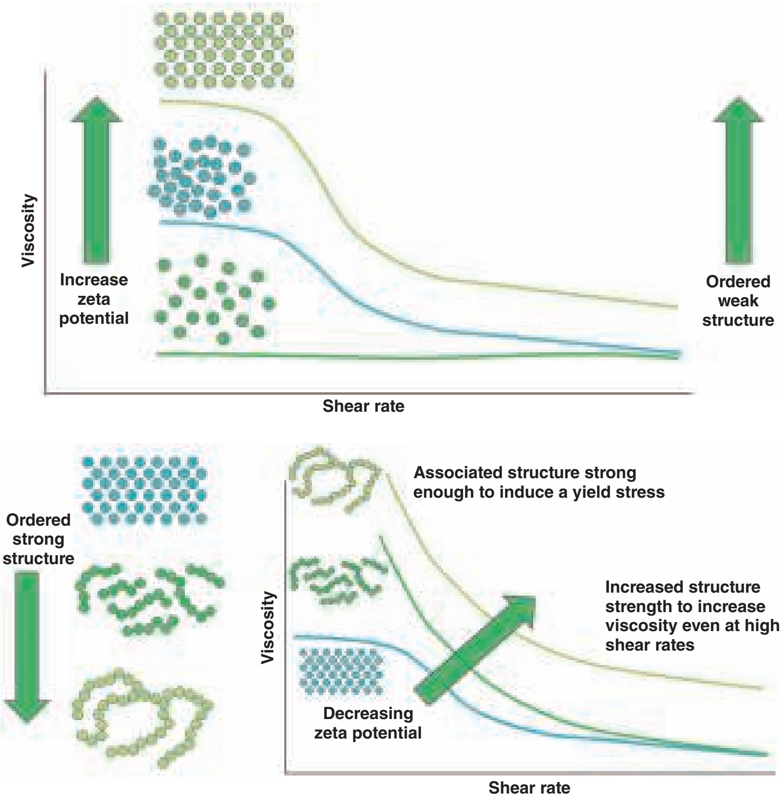


FIGURE 7. In a colloidal suspension with sub-micron particles, increasing zeta potential increases viscosity at low shear stress (top). In contrast, decreasing zeta potential can induce a flocculated particle gel with an apparent yield stress (bottom)

Concluding remarks

Formulating a suspension to have specific rheological characteristics is essential when it comes to commercializing products with consumer appeal and competitive advantage. Generating reliable rheological data to support product formulation is essential to the effort, and this relies on choosing a rheometer that can measure effectively under the conditions that will prevail during product use. A robust rheological characterization strategy provides a secure platform from which to address the optimization of suspension formulation, which involves tuning particle loading, size, shape and charge, to meet specific performance targets. ■

Edited by Scott Jenkins

Author

John Duffy is product marketing manager for rheology products at Malvern Instruments Ltd. (Grovewood Road, Malvern, Worcestershire, WR14 1XZ, UK; Phone: +44-1684-892456; Email: John.Duffy@malvern.com). Duffy holds a Ph.D. from the University of Nottingham (U.K.), where his research in the School of Chemical and Environmental Engineering involved rheological studies of the microstructure of molten coal. Duffy has previously worked with both Boots and Unilever, and has a wide range of experience on the role of rheology in household and personal care products.

Feature Report

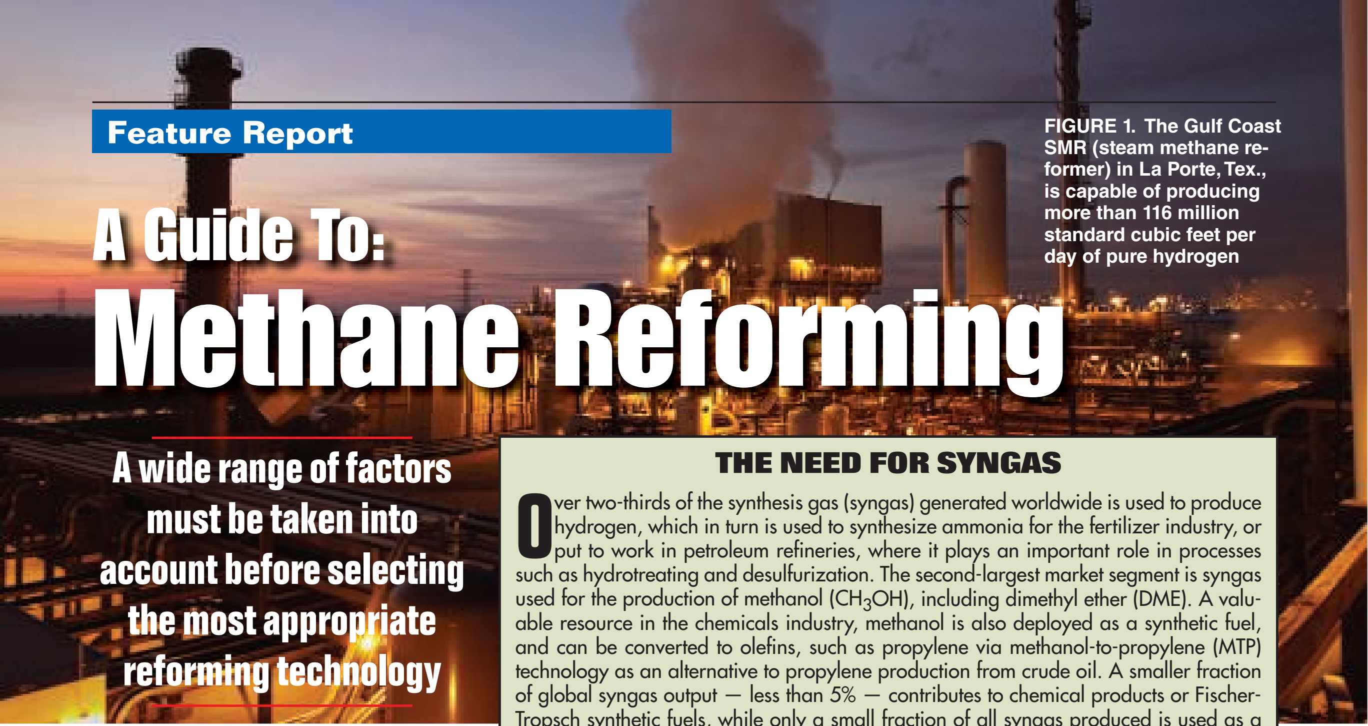


FIGURE 1. The Gulf Coast SMR (steam methane reformer) in La Porte, Tex., is capable of producing more than 116 million standard cubic feet per day of pure hydrogen

A Guide To: Methane Reforming

A wide range of factors must be taken into account before selecting the most appropriate reforming technology

Dieter Ulber
Air Liquide Global E&C Solutions Germany GmbH

THE NEED FOR SYNGAS

Over two-thirds of the synthesis gas (syngas) generated worldwide is used to produce hydrogen, which in turn is used to synthesize ammonia for the fertilizer industry, or put to work in petroleum refineries, where it plays an important role in processes such as hydrotreating and desulfurization. The second-largest market segment is syngas used for the production of methanol (CH_3OH), including dimethyl ether (DME). A valuable resource in the chemicals industry, methanol is also deployed as a synthetic fuel, and can be converted to olefins, such as propylene via methanol-to-propylene (MTP) technology as an alternative to propylene production from crude oil. A smaller fraction of global syngas output — less than 5% — contributes to chemical products or Fischer-Tropsch synthetic fuels, while only a small fraction of all syngas produced is used as a substitute for natural gas (SNG) or in integrated gasification combined cycles (IGCC) for power production.

Demand for syngas is rising across the board, in large part driven by a growing need for H_2 in many sectors. For example, H_2 plays an essential role in petroleum refineries and the broader petrochemical industry. Against the background of ever-more-stringent environmental legislation, it is a key ingredient in desulfurization and in the hydrocracking methods used to convert crude oil into ultra-clean diesel fuel. Moreover, the general trend toward processing heavier, lower-grade oil is leading producers to turn to new refining schemes that require large volumes of hydrogen. Plus, H_2 is fast gaining prominence as a transportation fuel, deployed in fuel cells for electric vehicles. ❑

From the agrochemicals sector to steel production, from petroleum refineries to chemicals production — many sectors of the chemical process industries (CPI) would grind to a halt overnight without one crucial ingredient: syngas. Short for "synthesis gas," syngas describes a blend of primarily hydrogen and carbon monoxide. Highly versatile, syngas forms the basis for diverse end products that are deployed in a wide range of industrial scenarios (see box).

Broadly speaking, syngas is generated by one of two ways: using a methane reforming process, based on a gaseous reaction principle; or applying a gasification technique, centered around a heterogeneous reaction. It cannot be claimed that one method is categorically better than the other; rather, the technology chosen will depend on the availability of feedstock and the intended downstream application. In terms of feedstock, reforming techniques are ideal for gases and light hydrocarbon liquids, while gasification is generally reserved for heavier liquids and solids, such as coal and biomass. In this context, methane reforming technology is growing in popularity as the spread of hydraulic fracturing contributes to a fall in the price of natural gas.

When it comes to the downstream application, on the other hand, the ratio of H_2 to CO in the final syngas will vary depending on the process used. The rule of thumb is that reforming techniques yield a higher H_2 content, while gasification tips the balance in favor of CO. For example, reforming natural gas can generate an H_2-to-CO ratio of up to 5.5, while the corresponding figure for entrained-flow coal gasification hovers between 0.35 and 0.8. Considering that the bulk of syngas manufactured worldwide is used to produce H_2, as outlined above, this article focuses on methane-reforming technologies as the most efficient way of generating H_2.

Overview of CH_4 reforming

The reforming process itself, however, comes in a number of different guises. And the choice of technology is crucial, as it will have implications for all other aspects of the syngas production process.

Regardless of the generation method deployed, the journey from feedstock to syngas comprises a number of basic steps. First, the feedstock is pre-treated to remove sulfur. Depending on downstream processing requirements, it may also undergo a pre-reforming stage. The feedstock is now ready to begin the transformation into syngas, by means of a reforming process — and it is here that significant differences between the various techniques become apparent, as will be discussed below. After reforming, the syngas is conditioned to adjust the ratio of components as required, before being purified in a final step. Again, the choice of reforming process will impact on the options available in these final two stages.

The following section outlines in more detail the four main technologies used in the all-important reforming stage. These can be broken down into two categories: three catalytic models — steam methane reforming (SMR), heat exchange reforming, and autothermal reforming — and the non-catalytic partial oxidation process.

TABLE 1. CARBON TO HYDROGEN RATIO OF DIFFERENT FEEDSTOCK IN KG/KG

C/H in kg/kg	Hydrogen
1.5–3.0	Refinery offgas (H_2-rich)
3	Methane
3.0–3.3	Natural gas
3.0–4.0	Refinery offgas
4.3	Natural gas (CO_2-rich)
4.5-4.8	LPG
5.0-6.0	Naphtha
6.0-8.0	Biomass
7.0–10.0	Oil residue
18.0–32.0	Petcoke
10.0–50.0	Coal, petcoke
	Carbon

Steam methane reforming. A good place to begin is with the most common syngas generation technology: SMR, also referred to simply as steam reforming. This process is based on an endothermic reaction. After blending the desulfurized feed with steam, the mixture is superheated before being routed to a primary reformer. This unit comprises a number of tubes containing a catalyst. As heat is applied to the tubes externally from the surrounding furnace, the catalyst sets off a reaction between the feedstock and the steam, transforming the methane and water into a syngas comprising H_2, CO, CO_2, residual CH_4, N_2 and H_2O.

Heat exchange reforming. Closely related to SMR is heat exchange reforming. This term describes technologies such as gas-heated reformers and post-reformers, which recover process heat to catalyst tubes. This energy — which would otherwise contribute to steam production — is used to trigger a further reforming reaction, resulting in greater thermal efficiency. The heat exchange reactor can be arranged in series or parallel to other reforming technologies. Conditions and limits are similar to SMR, and a wide range of reactor designs are available. Many heat-exchange reformers are essentially heat exchangers with a catalyst on the tube or shell side. However, recent innovations include the potential to perform heat exchange inside an SMR tube, reducing equipment cost and making the technology an attractive option for low-steam co-production and zero-steam H_2 generation, while simultaneously cutting CO_2 emissions.

Autothermal reforming. Like SMR and heat exchange reforming, authothermal reforming (ATR) is a catalytic process. However, it differs fundamentally from these two methods in terms of how the reforming reaction takes place. The feedstream of hydrocarbon and steam is fed into a refractory-lined pressure vessel, where a top-mounted burner adds oxygen to the mixture. The exothermic reaction of feedstock and reformed gas with O_2 triggers partial combustion to begin the transformation to syngas. This is completed by means of an endothermic reforming reaction in the catalyst bed.

The addition of O_2 and the higher temperatures involved in ATR mean that the chemical composition of the resulting gas is different from that generated by means of SMR or heat exchange reforming. While an air-blown autothermal reformer is preferred for conventional ammonia production, for other applications (such as syngas for methanol production), a pure O_2-blown autothermal reformer is applied. In this article, the term ATR is used to refer to syngas production by ATR using pure O_2.

Partial oxidation. The final reforming technique that will be considered is partial oxidation (GasPOX). In marked contrast to the previous three processes, partial oxidation does not require the use of a catalyst. Instead, the reaction is instigated by blending the feedstock directly with O_2 and combusting the mixture in a reactor at an extremely high temperature. This exothermic process converts the input material into a syngas with a different composition to that resulting from SMR, heat exchange reforming or ATR.

Selection considerations

Each of the reforming technologies described above offers certain benefits for certain applications. As mentioned previously, there is no single best way to generate syngas — the method used will depend on a number of factors. The following section of this article examines a number of key aspects at various stages of the process chain: beginning with feedstock and general process parameters, before moving to end-product characteristics, conditioning and separation options, and cost considerations.

Feedstock. When choosing a generation technology, the availability, price, and properties of the feedstock are key considerations. The hydrogen-to-carbon ratio in the final syngas will vary depending on the feedstock selected, with lighter gases resulting in a higher H_2 content and heavier gases tipping the balance toward CO (Table 1).

It is also important to keep in mind that different feedstocks will have different heating values, which has consequences for steam production, utility consumption and system design. Against this background, certain feedstocks are a naturally good fit for specific reforming methods. For all four of the methane reforming technologies discussed here, natural gas is the principle starting point. However, heavier input materials such as liquified petroleum gas (LPG) and naphtha are often used as an alternative in SMR units. Of course, natural gas composition can vary significantly in terms of the proportion of CO_2, N_2 and heavier hydrocarbons. These differences will directly impact technology selection, depending on the required gas ratio in the end product, as will be discussed in more detail below.

Process parameters. When designing a syngas-generation plant, a number of key parameters must be carefully considered. Although these differ from technology to technology, they are closely related to one another within a single system — with the result that a change in one parameter will often have consequences for the others.

Pressure. Process pressure varies between syngas generation systems, with the most important distinction existing between SMR/heat exchange reforming and ATR/GasPOX. In SMR and heat-exchange reforming units, heat is applied to the feedstock indirectly from outside the reforming tubes, limiting the gas pressure within. With the O_2-based processes ATR and GasPOX, on the other hand, the heat comes from an exothermic reaction within a refractory-lined vessel, meaning pressure levels can be much higher. Greater pressure during reforming will translate into lower levels of H_2 and higher levels of CH_4 in the gas at the reformer outlet.

High pressure can deliver other benefits in terms of the overall process, too. For example, high feedgas pressure can minimize power requirements for downstream product compression, saving costs. Moreover, it can reduce pipe size in large plants, and makes it possible to supply the end product at higher pressures without the need for an additional compressor. Also, greater pressure provides more options in terms of downstream product separation, as will be discussed later in this article.

Temperature. The temperature at which reforming takes place will directly affect the composition of the syngas generated: the lower the temperature, the greater the proportion of H_2; the higher the temperature, the more CO is created and the more CH_4 is converted. Once again, the endothermic nature of SMR and heat exchange reforming places limits on how high process temperatures can be — once a certain point is passed, there is a danger of melting the metal reforming tubes. During GasPOX reforming, in contrast, temperatures can soar as high as 1,500°C.

Catalyst. Another important consideration is whether or not the reforming process requires a catalyst. Of the four main technologies discussed here, GasPOX is the only one where a catalyst is not necessary. As catalysts are easily damaged by impurities in the feed material, GasPOX systems are therefore capable of handling heavier, lower-grade materials. Nevertheless, it is essential to track any unwanted trace components: it should be evaluated whether these will have a negative impact on downstream units, and such impurities must be eliminated during gas separation to ensure they do not appear in the final product. Without a catalyst, the temperature must be higher for the reaction to take place, resulting in greater levels of CO in the final syngas.

Oxygen. As ATR and GasPOX reforming both revolve around reactions that require O_2, the availability and price of this element will play a role when considering these technologies. Oxygen impacts on the reforming process in a number of ways. By adjusting the amount of O_2 added, it is possible to directly control the reforming temperature. And the more steam admixed or the higher the inert content in the feed, the more oxygen will be necessary to reach the required temperature. Indirectly, these higher O_2 levels will lead to increased formation of CO_2 in the output gas — something that is important to keep in mind in terms of downstream processing and costs. It is perhaps interesting to note, however, that the syngas generated by a GasPOX system will contain less CO_2 than that produced by ATR — despite the fact that GasPOX requires more O_2 in the feedstream. This is because the temperatures involved in this process are so much higher that much of the CO_2 is shifted to CO during the reaction, cancelling out the effects of the increased O_2 levels.

Steam. Process steam is another important parameter that can affect the generation process in a number of ways. First of all, the more steam admixed during reforming, the higher the H_2-to-CO ratio in the final syngas and the lower the level of export steam co-produced. However, as the volume of steam added increases, an ever-smaller proportion of the steam fraction actually reacts with the hydrogen in the feedstock. A point is reached where the additional steam is no longer adding value — it is simply being heated up only to be cooled down again later in the process, impacting negatively on the overall thermal efficiency of the plant. At the same time, this unconverted steam will require greater heat input, a larger reformer and a larger heat recovery section, all of which have cost implications.

The steam-to-carbon ratio will differ for each reforming technology, depending on the amount of steam required in the process. This ratio ranges from up to 3.0 mol/mol for SMR to just 0.1 mol/mol for GasPOX. In many cases, minimizing the steam-to-carbon ratio can improve the overall thermal efficiency of the plant, lowering costs. For example, by applying pre-reforming in an adiabatic reactor at low temperature upstream of an SMR unit, it is possible to convert higher hydrocarbons in the feed to natural gas, lowering steam-to-carbon ratios.

A minimum steam-to-carbon ratio exists for each reforming method, determined by the reaction kinetics of hydrocarbon cracking during heating and reforming. It is essential not to exceed these limits if carbon formation is to be avoided in the reforming process. Of the four reforming technologies discussed here, the steam-to-carbon ratio limit is lowest for the GasPOX method. As a result, trace amounts of soot are formed during generation; this impurity must subsequently be washed out of the syngas and will also limit the options for re-using process condensate.

It is important to note that a minimum steam flow may be required for downstream units, for example if an iron-based catalyst is used. However, these limits have been relaxed by the introduction of new catalyst products for high- and medium-temperature CO shift.

A final consideration is that increasing co-production of steam can enhance efficiency: depending on plant design, a higher flow of steam, boiler feedwater and demineralized water can be used to capture and reuse more heat energy.

Downstream considerations

Of course, the most important consideration when generating syngas is the downstream application: what will the final gas be used for? Depending on requirements, producers will look to create a mixture with a specific ratio of H_2 to CO, and each technology will produce a different result (Table 2). In general, SMR is the most flexible in this regard. It can yield the highest H_2 content, but also enables different ratios for applications in the chemicals and metallurgy sectors. ATR and GasPOX, on the other hand, result in a syngas with a larger CO content, due to the higher temperatures and the O_2 used in the process.

The following section discusses in more detail the important points to consider when designing a system to generate the following products: H_2, CO and synfuels.

Hydrogen. To generate H_2, the feedstock chosen will ideally exhibit an inherently high hydrogen-to-carbon ratio, such as natural gas. It is also possible to produce H_2 from more carbon-heavy fuels like naphtha; in this case, the heating value of the feed helps to extract H_2 from the steam during the reforming process. However, the overall levels of H_2 will be lower and the additional steam must be taken into account in plant design.

For each of the four reforming technologies discussed here, the syngas generated will contain differing levels of H_2. With SMR, the resultant gas exhibits the highest H_2-to-CO ratio (up to 5.5). At the other end of the scale, the ratio with GasPOX is in the range of 1.5–2.0. Of course, it is possible to change this balance by adding a CO shift unit downstream of the reforming process.

Carbon monoxide. Where the required end product is CO or oxogas, GasPOX can deliver the highest CO levels. CO can, however, also be generated using SMR: in this case, almost all the carbon in the feed is converted to CO, by taking the CO_2 and unconverted CH_4 remaining in the reformed gas and recycling it back to the feedstream, thereby lowering the H_2-to-CO ratio from around 4.5 to 3.0. Moreover, if CO_2 is available from an external source, and more than 50% of the CH_4 feed molar flow is replaced with CO_2, then it is possible to produce H_2 and CO in the reformed gas at a ratio of 1. However, it is important to observe the thermodynamic limit in order to avoid carbon formation in the reforming stage.

Synfuels. When manufacturing synthetic fuels, CO_2 in the syngas will also be converted to fuel. As such, the optimum syngas composition is expressed in terms of a stoichiometric number, which describes how much CO and CO_2 will react with H_2 to form methanol or Fischer-Tropsch products. The optimum stoichiometric number can be achieved by deploying more than one technology simultaneously. A combination of SMR and ATR — a process known as combined reforming — is often chosen to produce methanol and synthetic fuels. When using the combined method, the steam reformer is operated at higher pressure (~40 bars) and lower temperature (~750°C). The lower level of methane conversion in the SMR stage (primary reforming) is then compensated by the downstream ATR system (secondary reforming). The required stoichiometric number can be achieved by adjusting the SMR and ATR feed flow ratio, and by separating H_2 from the purge gas following methanol synthesis and recycling it back to the upstream syngas generation system.

Combining syngas streams. Another option for large-scale syngas production is to combine syngas streams from different sources — for example, from entrained-flow coal gasification and from a methane reforming unit — to achieve the required product flowrates. This scenario allows the individual syngas production units to run at maximum efficiency, while the mixing process ensures the optimum product-ratio adjustment.

Conditioning and purification

Syngas generation does not end with the reforming process, as the gas created will always contain several unwanted components. First of all, even where a CO shift unit has been deployed, it is never possible to achieve complete conversion to H_2 due to the chemical equilibrium at the necessary reaction temperature. Moreover, methane is not fully converted during reforming, and all nitrogen in the feed and in the oxygen stream will end up as N_2 in the reformed gas. And of course, the CO_2 created as a byproduct will need to be removed in the majority of cases. A number of downstream gas-conditioning and product-separation systems can be used to produce pure gases or gas mixtures. The methods chosen will vary depending on the required end product.

The cost and effort of CO_2 extraction will depend on the level of CO_2 present and the syngas flow, and the CO_2 fraction in the reformed gas will vary in line with the generation technology deployed (Table 3). There are two main reasons for this: differences in the carbon-to-hydrogen ratio for individual feedstocks, and variances in the outlet temperature of the reforming unit in question.

When it comes to product separation, there are three main options downstream of methane reforming: a cryogenic or cold box unit, polymer membranes, or pressure swing adsorption (PSA). The choice of one technology over the other will be influenced by a number of factors. For cryogenic processes, for example, it is important to keep in mind that a higher reforming temperature — as in a GasPOX plant — will contribute to higher methane conversion and lower methane slip. As a result, when separating CO from a syn-

TABLE 2. H_2-CO-MIXTURE FOR DIFFERENT PRODUCTS

Hydrogen	
100% H_2	Hydrogen
100% H_2	Ammonia
75% H_2	SNG
67% H_2	MeOH
≤ 67% H_2	Fischer Tropsch / synfuels
~62% H_2	Direct reduction gas
60% H_2	DME
50% H_2	Oxoalcohol
26-41% H_2	Power (integrated gasification combined cycle)
100% CO	Pure CO (acetic acid)
100% CO	Polyurethanes (MDI/TDI)
Carbon monoxide	

TABLE 3. SYNGAS TECHNOLOGY COMPARISON

*: items in brackets, {}, optional		Steam Methane Reforming (SMR)	Heat Exchange Reforming	Auto-thermal Reforming (ATR)	Partial Oxidation (GasPOX)	Residue Gasification (MPG)	Entrained Flow Coal Gasification (ETF / dry feed)	Fixed Bed Coal Gasification (FBDB / dry ash)	Entrained Flow Biomass Slurry Gasification (Bioliq)
Principles	Reaction	Gaseous	Gaseous	Gaseous	Gaseous	Heterogenous	Heterogenous	Heterogenous	Heterogenous
	Catalytic	yes	yes	yes	no	no	no	no	no
	Heat supply	indirect (firing)	indirect (heat exchange)	direct (O_2)	direct (O_2)	direct (O_2)	direct (O_2)	direct (O_2)	direct (O_2)
Feed		Natural gas, refinery offgas, LPG, naphtha	Natural gas, refinery off-gas, partially reformed gas	Natural gas, refinery off-gas, partially reformed gas	Natural Gas, Refinery Offgas	Heavy Oil Residue contaminated with sulphur and heavy metals	Fine high-rank bituminous coal or lignite, low ash content, low ash fusion temperature	Low-rank lignite or high-rank reactive coal, lump coal, high moisture and ash content, high ash fusion temperature	Biomass including highly viscous feed, high water and oxygenate content
Feed pretreatment*		Hydro-desulfurization, {Pre-reforming}	Hydro-desulfurization, {Pre-reforming}	Hydro-desulfurization, pre-reforming, fired heater	{Hydro-desulfurisation}, fired heater	Fluidization, pumping & atomization	Coal grinding and drying, pulverized fuel quality, dry feed, lock hopper	Coal screening, lock hopper	Biomass preparation, pyrolysis,slurry feed
Reforming	Equipment	Externally heated catalyst filled tubes in a furnace	Heat exchanger filled with catalyst	Refractory lined reactor	Refractory lined reactor	Refractory lined reactor	Cooling screen	Refractory lined reactor with internals for coal distribution and ash removal	Reactor with cooling screen
	Pressure, barg	15–45	30–40	40–100	40–100	50–80	25–40	25–60	40–80
	Temperature, °C	750–950	750–880	950–1,050	1,200–1,400	1,200–1,350	1,300–1,600	230–600	1,200–1,500
	Steam/carbon ratio, mol/mol	1.8–3.0	1.8–3.0	1.0–2.0	0.1–0.5	0.3–0.5	1.2–1.5	1.0–1.7	0.1–0.5
	H_2/CO in syngas in mol/mol	3.5–5.5	3.5–5.5	2.5–3.5	1.5–2.0	0.85–1.0	0.35–0.8	1.5–3.3	0.6–1.0
	CO_2 in syngas, mol%	7–12	7–12	8–10	2–4	3–6	3–8	23–34	15–40
	CH_4 in syngas, mol%	3–30	6–10	2–3	0.2–1	0.2–1	0.25–1	5–16	0.2–1
Condensate handling		Internal recycle	Internal recycle	Internal recycle	Soot water recycle and blowdown	Soot, ash (metal) removal	Slag removal, Soot water recycle and blowdown	Waste water treatment, ash lock and handling	Slag removal, Soot water recycle and blow-down, waste water treatment
Syngas cleaning		-	-	-	Soot scrubbing/ washing	H_2S removal Rectisol, sulfur unit	H_2S removal Rectisol, sulfur unit	Liquor separation, tar/ oil/phenol/ NH_3 recovery, Rectisol, sulfur unit	H_2S removal Rectisol, sulfur unit
Product separation of typical products		PSA (H_2), Liquid methane wash coldbox (CO), syngas for synfuels	PSA (H_2), syngas for synfuels	Liquid methane wash coldbox (CO), membrane (H_2 + CO), syngas for synfuels	Partial condensation coldbox (CO), membrane (oxogas), syngas for DRI	Methanation (H_2, NH_3), liquid nitrogen wash (NH_3), syngas for synfuels	Combined cycle (power), syngas for synfuels	Methane synthesis (SNG), syngas for synfuels, syngas for DRI	Combined cycle (power), syngas for synfuels

gas with a methane component of 1 mol% or lower following GasPOX reforming, a partial-condensation cold box must be chosen rather than a methane-wash cold box, as the latter requires that the feed gas have a CH_4 content of greater than 1.5 mol%. However, the choice of cold box will also depend on the required end product. For example, oxogas can be made readily available from the first column of a partial condensation cold box, while a methane-wash cold box can provide H_2-rich gas at high pressure.

Polymer membranes can be an effective means of product separation if quality specifications are lower, or where byproducts are to be recycled. Membrane technology is particularly advantageous in scenarios where the

TECHNOLOGY CHOICE IN PRACTICE

This case study illustrates many of the points discussed in the main text, by outlining how a technical solution was chosen to meet a more complex set of requirements. The plant in question specializes in large-scale production of carbon monoxide for the chemicals industry [toluene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI)]. At the same time, the operator wishes to generate hydrogen as an additional source to feed an existing pipeline network, for over-the-fence gas supply to several customers. The required product ratio of CO to H_2 is 2.5:1, and a variety of natural gas sources are available as feed and fuel. As the plant serves multiple customers with fluctuating requirements, a decision is made to implement a flexible system that allows the ratio of H_2 to CO in the syngas to vary between three and six. In addition, co-produced superheated steam at 53 barg can be exported as required at almost steam fuel value.

The technologies implemented along the process chain are as follows: pre-reforming, steam methane reforming, and amine wash CO_2 removal — with a downstream serial arrangement of a methane-wash cold box, pressure swing adsorption, and CO_2 and methane recycle compression. For this system design and the given product ratio, it is not necessary to operate a parallel CO shift train downstream of the reforming unit. In the PSA unit, the purity of the H_2-rich gas from the cold box is increased from 97.8 to 99.99%. The H_2 is compressed from 23 barg to the specified product pressure of 44 barg. And by deploying a feed ejector driven by process steam, feed compression can be avoided. The remaining H_2-rich tailgas from the PSA stage is used as fuel in the reformer. Moreover, the plant design can facilitate the import of CO_2, should a suitable source become available in the future — providing scope to reduce natural gas consumption.

The solution is implemented using a tailor-made combination of proven, standardized technology units, and the construction of the plant is based on pre-fabricated modules. As a result, it is possible to not only overcome the challenge of selecting the right methane reforming technology, but also to combine the technologies and adjust the parameters of each individual unit in such a ways as to maximize overall plant performance. ❑

process pressure is high, as is the case in GasPOX plants, for example.

Where the aim is to achieve as pure a H_2 stream as possible, PSA is the separation method of choice — enabling H_2 recovery of up to 90%. Recently, a new technology has been launched that compresses the remaining tailgas from the PSA process, removes CO_2 using cryogenic technology, and recycles the hydrogen back to the PSA via membranes. In addition to lowering CO_2-capture costs, this method can increase H_2 recovery to over 98%. If using partial oxidation, it can be advantageous to perform conventional CO_2 removal followed by methanation to achieve a H_2 recovery close to one. This can be the case in instances where the H_2 product-quality specification allows for it and the upstream reforming technology requires a syngas cleaning unit for H_2S and CO_2 anyway.

A note on CO_2 emissions

When generating H_2, every carbon atom in the feed will be converted into CO_2. As such, the more natural gas consumed, the larger the volume of CO_2 produced. Any calculation of total CO_2 emissions, however, must also take into account the indirect emissions from power production or air separation.

If CO_2 removal has been integrated into the technology chain, the capture rate of CO_2 from syngas will be higher for those technologies that consume less carbon-containing fuel. Where opportunities exist to recycle CO_2 — as in the CO process chain — it is also possible to reduce CO_2 emissions. The fuel for the SMR or fired heater will, in this case, primarily comprise H_2 extracted from the syngas during product separation.

Cost considerations

Needless to say the cost factor will loom large when making decisions on which syngas technology to choose. A number of aspects are of relevance: thermal efficiency, the potential for economies of scale, reliability of the equipment chosen, and plant design.

Thermal efficiency. For all methane-reforming technologies, thermal efficiency is determined by the limitations that exist on the use of low-temperature heat in flue and process gas. Losses can be minimized by optimizing process parameters to reduce fluegas flow and by maximizing the use of internal process heat, for instance, by deploying a pre-reformer or heat exchange reformer. Moreover, technologies designed to use low-temperature heat in reforming plants are becoming more attractive, as they have become more advanced and less expensive in recent years.

The point at which improvements in thermal efficiency outweigh the advantages of higher hydrogen conversion will depend on utility cost factors, particularly steam value and the ratio of feed to fuel cost. This can be calculated by means of an overall utility cost assessment. To take an example, minimizing the steam-to-carbon ratio and lowering methane conversion will not be an attractive option if feed is more expensive than fuel.

In contrast to coal gasification, where high up-front expenditure (capex) is required, the bulk of the total cost breakdown for gas-reforming plants is for operating expenses (opex) — attributable to feed, fuel, oxygen, steam, power and other utilities. This is particularly true of large gas reforming plants, where economies of scale can shift the opex-to-capex ratio to as high as 80:20.

For the four technologies discussed here, it should be noted that they differ in terms of the economies of scale that can be achieved. In the case of steam methane reforming, for example, the relationship of cost to capacity for the system's tubes and burners is almost linear. However, the SMR furnace and header system scales at a rate of less than one. For ATR and GasPOX reactors, the overall cost-scaling exponent is also below one. This is one of the main reasons why ATR and combined reforming are often chosen for large-scale methanol and synfuel production.

For large-scale synfuels projects, the capital cost of the air separation unit (ASU) must be taken into account, whereas for smaller GasPOX or ATR projects, the price of the O_2 will add to operating expense.

Reliability. When calculating the total cost of operating a reforming site, it is essential to take into account the reliability of the plant. What will the price of unforeseen downtime be and what impact will this have on subsequent interruption to product flow? These costs can vary from technology to technology, largely due to the differing effect of downtime on individual downstream production systems. In a petroleum refinery, for example, an interruption to H_2 supply can almost lead to a complete shutdown. The same is true of downstream chemical conversion in a CO-production-process chain. A back-up product buffer or a pipeline network connecting several production units and consumers is essential in such cases.

Catalysts and tubes. The critical components in terms of reliability and availability will vary for each reforming technology. For catalytic processes, the catalyst volumes of reactors must be sized in line with planned turnaround periods. Ensuring a well designed plant front-end and steam system will be money well spent, as these measures will prevent catalyst poison traces entering from internal or external sources. In an SMR unit, the steam reformer tubes are the critical component. These are typically designed for a lifetime of 100,000 hours, based on the creep of the centrifugally cast material as it is exposed to high temperatures. A number of steps can be taken to maximize tube lifetime at a competitive cost: for example, by opting for state-of-the-art control systems, over-firing protective functions, automatic SMR start-up sequences and load change functions, proper heat distribution, and advanced design tools.

Burners. For O_2-based processes, on the other hand, the main priority is to ensure that the burner is well designed and exceptionally safe. To ensure a long burner lifetime, it is important to first pay close attention to how the feedstock, steam and O_2 are fed and mixed at the burner nozzle; second, to minimize the exposure of the burner front to radiation from the high flame temperatures that result from the O_2 combustion reaction; and third, to choose carefully the cooling principle of the burner during operation and after plant shutdown.

Whichever generation technology is used, it is imperative to eliminate single points of failure in the control and plant emergency shutdown system. Plant vulnerability studies can define compressor redundancy and identify critical components that require the implementation of online maintenance functionality. Based on this analysis and the required turnaround cycle, a decision can be made on how many redundant reactors are required in a partial oxidation unit, for example, or what number of capital spares (for example, burner and rotor of induced or forced draft fans for the furnace or heater) are necessary for an SMR, ATR or gasPOX system.

Outsourcing. Of course for many manufacturers working with syngas, the cost and effort of operating a plant to generate the gas themselves might be too high. In such cases, sourcing syngas from a third-party operator can be an attractive option. By working with syngas specialists in this way, it is also possible to benefit from a global industrial management system and extensive practical expertise. Moreover, by integrating a feedback loop, some providers are in a position to ensure that lessons learned on the ground are immediately communicated to the engineering design team for implementation.

Final remarks

Ultimately, the choice of technology chain for a specific project is made on the basis of a total cost evaluation that takes into account capital expenditure, feed, fuel, oxygen and other utilities, steam value, and additional opex, such as the cost of catalysts. The development engineers tasked with design have the important job of systematically comparing the modules available and narrowing down the process-chain options using the criteria discussed above. Teams with extensive experience can feed this knowledge into the decision-making process, helping them to find the most cost-effective solution.

To master this challenging task, providers nowadays offer end-to-end portfolios to address the entire process chain. And some even go a step further. For example, innovative planning solutions are available that enable a process simulation to calculate and optimize utility costs, and automatically prepare piping and instrumentation diagrams (PIDs), providing reliable estimates of capital expenditure. These kinds of services can help save costs before any construction work has even begun.

As outlined in the box on p. 40, the majority of syngas produced worldwide is currently used to generate H_2 for the petroleum-refining and fertilizer industries. The suitability of SMR units for producing H_2 means that this is the most widely used of the methane reforming technologies. However, it is worth noting that as the synfuels market continues to expand, combined reforming methods are set to grow in importance. Moreover, the abundant availability of coal is leading to a rise in the popularity of coal gasification units for MTP, MTO and SNG processes — in China and India, in particular. If this trend continues, such methods of syngas production could soon catch up with those based on natural gas. ■

Edited by Gerald Ondrey

Author

Dieter Ulber is director of technology, HyCO Product Line at Air Liquide Global E&C Solutions Germany GmbH (Olof-Palme-Straße 35 60439 Frankfurt am Main, Germany; Phone: +49- 69-5808-0; Fax: +49-69-5808-1109; Email: dieter.ulber@airliquide.com). Since joining the company in 2002, Ulber has been a process engineer for a number of the company's projects in Malaysia and China. He holds a bachelor of engineering degree from the Thayer School of Engineering, Dartmouth College (Hanover, N.H.) and a doctoral degree in mechanical engineering from RWTH (Rheinisch-Westfälische Technische Hochschule) Aachen (Germany).

Temperature Effects for High-velocity Gas Flow

Guidelines are presented to better understand the temperature profiles of high-velocity gases

Aubry Shackelford
Inglenook Engineering, Inc.

NOMENCLATURE	
Variables	
Cp	Specific heat capacity at constant pressure
H	Specific enthalpy
M	Mach number
P	Pressure
Pr	Prandtl number
r	Recovery factor
Re	Reynolds number
T	Temperature
U	Mean velocity
Subscripts and superscripts	
a	Under adiabatic constraint
aw	At the pipe wall under the adiabatic constraint
w	At the pipe wall
y	Coordinate system in the direction normal to the pipe wall (radial)
¤	At stagnation conditions
»	At flowing conditions (static) outside of the boundary layer
*	Reference condition for estimatiing fluid properties within the temperature gradient

In high-velocity gas flows, such as those that may occur within the discharge piping of a pressure-relief or depressurization valve, the temperature experienced at the wall of the pipe through which the gas is flowing can be much higher than the flowing stream's "static" temperature. In fact, the wall temperature approaches the stagnation temperature, which is the temperature that would be obtained if the fluid were brought adiabatically and reversibly (isentropically) to rest.

Experimental work in aeronautical engineering has established this effective adiabatic wall temperature, and correlations have been proposed to determine the "recovery factor" as a function of the Prandtl number (*Pr*) of the fluid. It has been found that the adiabatic wall temperature is about 90% of the difference between the stagnation and static temperatures for a turbulent gas having a Prandtl number of 0.7, which is typical for many gases. When performing heat-transfer calculations between the pipe and the gas, or when specifying temperatures for piping material selection, this recovery factor is important, and should be accounted for.

Recent investigations into the potential for fluid temperatures to exist below the embrittlement temperature of relief-valve discharge piping have shown that low-flowing temperatures can exist for a wide variety of systems, including: flashing liquids or two-phase flow; autorefrigeration and Joule-Thompson cooling in response to pressure drops; and high-velocity gas flow [*1*].

There is evidence that some systems exhibiting these behaviors have resulted in metal embrittlement and failure. However, there is an apparent lack of evidence supporting embrittlement failures involving high-velocity gas flow, and there is some suspicion that the flowing temperatures experienced in high-velocity gas flow may not be realistic, as evidenced by a common refrain — "if the gas was getting this cold, I would be seeing ice on the pipes." Some attempt to reconcile this anecdotal evidence with the "intuition" that the pipe (or vessel) wall temperature can approach the bulk fluid temperature given a long enough pipe and a low enough convective loss to ambient from the pipe is needed. This article provides guidance in determining the wall temperature for high-velocity gas systems.

Boundary layers

Before attempting reconciliation of the various notions related to wall temperatures, it is useful to recall Prandtl's theory of the boundary layer, which envisions a small layer of fluid close to the pipe wall in which the viscous forces are significant due to the velocity gradient. However, outside of this layer, the core fluid flow approaches that of an inviscid fluid. The velocity gradient is established by the known boundary condition of zero velocity at the wall, as real fluids will "stick" to the pipe wall, and the maximum velocity is approached in the center of the pipe. For turbulent flow, this boundary layer consists of a laminar sublayer, a logarithmic outer layer and a buffer zone of some nominal thickness that transitions continuously between these sublayers [2]. The resultant velocity profile for a constant-area pipe in fully developed turbulent flow is shown in Figure 1. All variables, subscripts and superscripts presented in the equations and figures are defined in the Nomenclature section.

It is also useful to remember that the majority of resistances to flow within a pipe — the frictional losses themselves — are actually due to effects of this boundary layer, and that the friction factor is used as a means to determine these losses as a function of the mean velocity in the pipe. In addition, while a rigorous analysis of the energy and momentum balances that includes the boundary-layer effects would find that a slight modification of the terms would be required for turbulent flow (for instance, a momentum-correction factor of 1.018 for the logarithmic-law profile in turbulent flow), these correction factors are commonly ignored in engineering calculations. They tend to cancel out from mathematical expressions, and are minor when compared to the loss terms [2]. As a result, the typical energy and momentum balances as employed in engineering hydraulic calculations are still valid, even when recognizing the actual velocity profile.

For present purposes, we are concerned with the temperature profile that exists as a result of this actual velocity profile. However, before evaluating this, it is useful to also address heat-transfer considerations. For heat transfer within a pipe, a temperature gradient exists between the wall and the center of the pipe. In general heat-transfer calculations, it is convenient to define a bulk temperature. The bulk temperature is generally defined as the effective temperature across the gradient that drives the heat transfer with a wall of a given

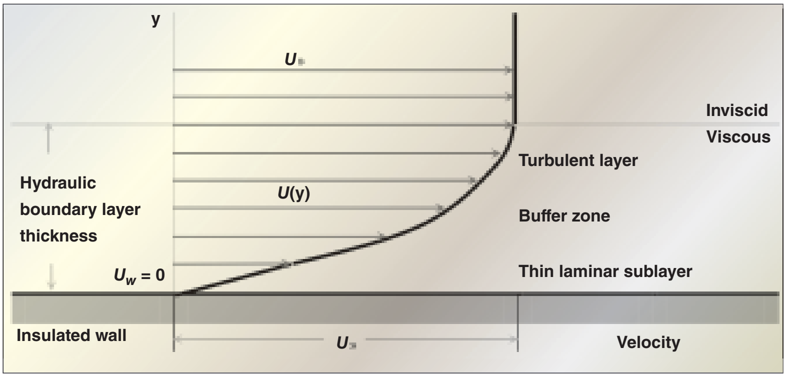


FIGURE 1. The velocity profile near the wall of a pipe shows that both turbulent and laminar conditions are present [2]

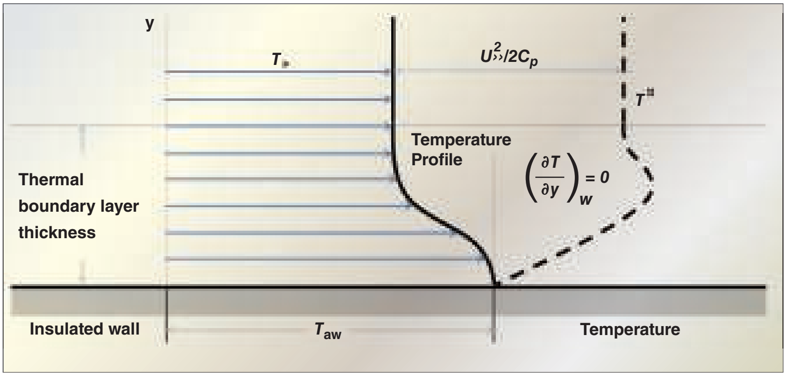


FIGURE 2. The temperature profile near the pipe wall is affected by the velocity gradient within the pipe [5]

temperature. The normal calculations then proceed using this bulk temperature, and general experience is based on the most common heat-transfer situations — those that deal with phase transitions (in which case the effective temperature is essentially fixed at the saturation temperature) or liquid flow (in which case the effective temperature is taken as the average of the flowing temperatures). Heat transfer in gas flow is not as common, and when it does occur, the velocity is typically reduced. As a result, the accumulation of experience with heat-transfer design at petrochemical processing facilities does not typically include heat transfer with high-velocity gas streams.

Adiabatic wall temperature

An area of practice that does offer experience with this situation is aeronautical engineering. A summary of the cumulative theoretical and experimental work in this area, provided by Eckert [3, 4], indicates that for high-speed gas flow, the fluid temperature at the wall is significantly greater than the static (flowing) temperature. Also described in literature by Shapiro [5], is the phenomenon of the temperature profile of a gas in response to the actual velocity profile, where the steady-state temperature distribution shows an adiabatic wall temperature T_{aw} being greater than the free-stream temperature $T_{»}$, yet less than the free-stream stagnation temperature, $T_{¤}$. This temperature profile is shown in Figure 2.

The experimental work in this area has confirmed that the adiabatic wall (recovery) temperature approaches, but does not reach, the stagnation temperature. A recovery factor is thus defined as the amount of the stagnation temperature that is recovered as the fluid decelerates to zero velocity at the wall, based on the actual temperatures achieved [3]. Equation (1) shows an expression for the recovery factor, *r*.

$$r = (T_{aw} - T_{»}) / (T_{¤} - T_{»}) \qquad (1)$$

The subscripts aw, », and ¤ are for the adiabatic wall, static and stagnation temperatures, respectively. The recovery factor, *r*, has been found to be dependent on Pr, and for $0.5 < Pr < 5$, the recovery factor is estimated as shown below in Equations (2) and (3) for laminar and turbulent flow, respectively [3].

$$r = \sqrt{Pr} \text{ for laminar flow} \quad (2)$$

$$r = \sqrt[3]{Pr} \text{ for turbulent flow} \quad (3)$$

A detailed analysis of the turbulent boundary layer, presented by Shapiro [5], finds that the adiabatic-wall recovery factor is a function of Pr and the ratio of velocities between the laminar sublayer and the edge of the boundary layer. While admittedly, this velocity ratio is not accurately known for compressible flow, it does indicate the boundaries for r when $Pr < r < 1$. Development of a more accurate expression for the recovery factor is further complicated by the difference in the hydraulic and thermal boundary-layer thicknesses. Nonetheless, Shapiro presents an analytical expression [5], which has been further developed by Tucker and Maslin [6], and shows that this expression approaches the expression for turbulent flow shown in Equation (2) at high Reynolds number values and Mach numbers less than one.

The computation of Pr requires the selection of a reference temperature, T^*, at which to evaluate the fluid properties, and Eckert's work states that the constant-property calculations could be used with a reference temperature defined as in Equation (4) below [3].

$$T^* = T_s + 0.5(T_w - T_s) + 0.22(T_{aw} - T_s) \quad (4)$$

For adiabatic flow, T_w is equivalent to T_{aw}; therefore, the reference temperature is given by Equation (5).

$$T_a^* = T_s + 0.72(T_{aw} - T_s) \quad (5)$$

Further research at Mach numbers much greater than one found that an enthalpy approach (as opposed to the temperature approach) was needed. However, the present discussion is limited to flowing velocities having Mach numbers less than or equal to one.

The difference between the stagnation and static temperatures can be expressed as a function of the velocity and the specific heat capacity at constant pressure (evaluated at the reference temperature [3]), based on the fluid specific enthalpy, as defined in Equations (6), (7) and (8).

$$H_o = H_s + 0.5(U_s^2) \quad (6)$$

$$H_o - H_s = C_p^*(T_o - T_s) \quad (7)$$

$$r = (T_{aw} - T_s) / (U_s^2/2C_p^*) \quad (8)$$

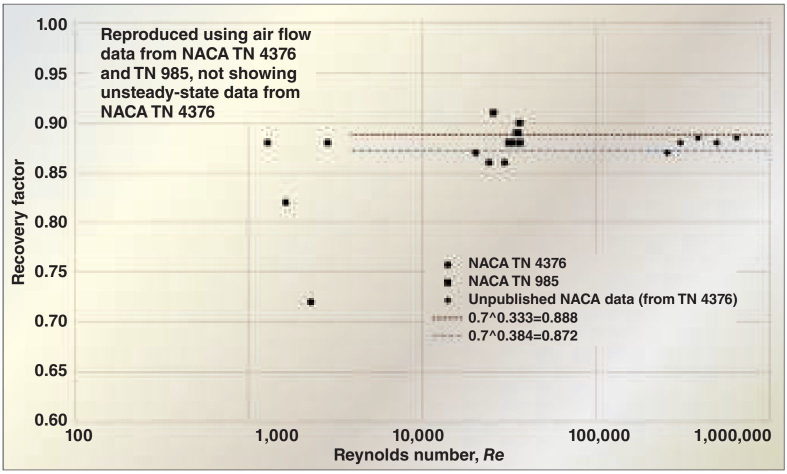


FIGURE 3. The variation of recovery factor (r) at the tube exit with Reynolds number is shown [8]

The experimental and theoretical work outlined by Eckert [3, 4] is based on high-velocity gas flow relative to flat plates; nonetheless, additional work for the now-defunct National Advisory Committee for Aeronautics (NACA) [7,8] experimentally determined the recovered wall temperatures in adiabatic and diabatic airflow in pipes at a range of Reynolds and Mach numbers. Figure 3 is adapted from NACA Technical Note (TN) 4376 [8] and shows how the recovery factors vary with changing Reynolds number values.

NACA Technical Note 4376 states that "In the turbulent flow region (Reynolds numbers above 3,000) the temperature recovery factor is nearly independent of Reynolds number. The average value is 0.88, which agrees with values for flow parallel to flat plates." The experimental evidence for pipe flow was found to be in substantial agreement with the experimental evidence for flat plates.

The development of the adiabatic-wall-temperature recovery factor for turbulent flow to this point has been focused on flat plates or flow within pipes, and it is not obvious whether this analysis applies in situations involving a significant change in the fluid flowing direction, such as at an elbow or a tee. The velocity at the wall is still assumed to be zero, but the boundary layer is not developed in the same way as with flat plates at a given angle of attack or for pipes. Experimental work on the heat transfer for jets impinging on surfaces may provide some guidance in this evaluation, although much of the focus is on the effects on heat transfer when changing the distance or angle of attack between the jet source (nozzle, orifice or end of pipe) and the flat plate. In the jet-impingement studies found by the author, the discharge is directed at a flat plate having a large surface area, without restriction or redirection of the flow, so it is not directly applicable to configurations like a tee in pipe flow — nonetheless, some temperature recovery occurs. Per work by Goldstein and others [9], the recovery factor for the impingement of air on a surface is independent of the jet Reynolds number, but is dependent on the jet to impingement plate spacing. In this work, a minimum recovery factor of 0.7 was determined, which is the approximate value of Pr for air.

It would appear that the prudent course of action would be to use the bounds of the recovery factor depending on the goals of the analysis. For the case of the determination of the adiabatic wall temperature for use in the low-temperature estimate for material specification, the lower bound of the recovery factor would provide this estimate, as shown in Equation (9).

$$r = \sqrt{Pr} \text{ for lowest recovery} \quad \textbf{(9)}$$

In addition, in the evaluation and development of the adiabatic-wall-temperature recovery factor, only noncondensable gases have been considered. It is conceivable that a vapor stream may experience flowing temperatures below its dewpoint, thus possibly condensing within the core stream. It is possible that at the wall, the shearing work and frictional heating is sufficiently high to ensure that there are no liquid droplets touching the wall, and the flow behaves as an annular two-phase flow that can be treated as a gas for practical purposes. On the other hand, it is possible that the condensed liquid droplets can contact the wall, which may result in additional cooling at the wall as the liquid is vaporized. The evaluation of the adiabatic wall temperature for high-speed condensable vapor flow remains as further work.

Application and examples

One of the direct applications of this information would be the screening of potential low-temperature issues caused by low-flowing temperatures in all-gas flow systems. The recovery factor for these cases can be determined as a function of *Pr* at the reference temperature T^* as described by Eckert [*3*, *4*], or perhaps in the more detailed analysis of Shapiro [*5*]. This recovery factor can then be used to determine an actual adiabatic wall temperature. The recovery temperature should then be compared to the minimum design metal temperature (MDMT) of the piping system for identification of potential low-temperature cases. In addition, any analysis that is being performed involving heat transfer between the fluid and the pipe should be based on the effective temperature differential between the pipe wall temperature and this adiabatic wall temperature.

A practical application of the adiabatic wall temperature evaluation can be found in natural-gas processing facilities, where discharges from pressure-relief or depressurization valves may involve high-velocity noncondensable gas. Evaluations of discharge piping that are performed assuming adiabatic flow yield flowing temperatures and velocities. These flowing conditions can be used to determine the stagnation enthalpy, and thus the stagnation temperature, which can then be used in the calculation of *r*.

Calculation example

As an example of wall-temperature determination, consider the flow of 25,000 lb/h of methane at 400 ft/s within an 8-in. Schedule 40 pipe having a stream temperature of –20°F. The following steps were performed, using the equations defined previously in this article, as well as the properties of methane obtained from the National Institute for Standards and Technology's (NIST) standard reference data program, Refprop v. 9.0 [*10*]:

- Use the velocity and flowing enthalpy to determine the stagnation enthalpy per Equation (6)
- Perform an enthalpy-entropy flash at the stagnation enthalpy and flowing entropy to obtain the stagnation temperature
- Iterate on the reference temperature to obtain the specific heat capacity at constant pressure, viscosity and conductivity for use in determining *Pr*
  - The stagnation temperature is used as the adiabatic wall temperature for the first step in the iteration in this example, but a better estimate can be determined using an estimated recovery factor of 0.88 and Equation (8)
  - The reference temperature is calculated based on Equation (5) at each step
  - The fluid properties are re-evaluated at the reference temperature and the flowing entropy, and *Pr* is recalculated
  - Calculate *r* based on Equations (2), (3) or (9). Equation (3) was used in this particular example
  - Calculate an adiabatic wall temperature based on Equation (1)
  - Iteration is continued until the solution converges on an adiabatic wall temperature

In this case, an adiabatic wall temperature of –14.3°F is calculated. Table 1 gives a summary of the parameters used in this example for the iterative determination of the adiabatic wall temperature. One will find that by using an estimated recovery factor of 0.88 to generate the reference temperature from Equa-

TABLE 1. CALCULATION OF ADIABATIC WALL TEMPERATURE

Area	ft^2	0.348	
Volumetric flow	ft^3/h	500,000	
Mass flow	lb/h	25,000	
Density	lb/ft^3	0.05	
Flowing enthalpy	Btu/lb	341	
Flowing entropy	Btu/lb°R	1.49	
Stagnation enthalpy	Btu/lb	344.125	
Stagnation temperature	°F	-13.7	
Reference temperature iterations			
Iteration		1	2
Wall temperature	°F	-13.7	-14.3
Reference temperature	°F	-15.46	-15.89
Specific heat capacity	Btu/lb°R	0.51185	0.51177
Viscosity	cP	0.00936	0.00935
Conductivity	Btu/h-ft°F	0.01576	0.01574
Prandtl number		0.736	0.736
Recovery factor		0.903	0.903
Adiabatic wall temperature	°F	-14.3	-14.3

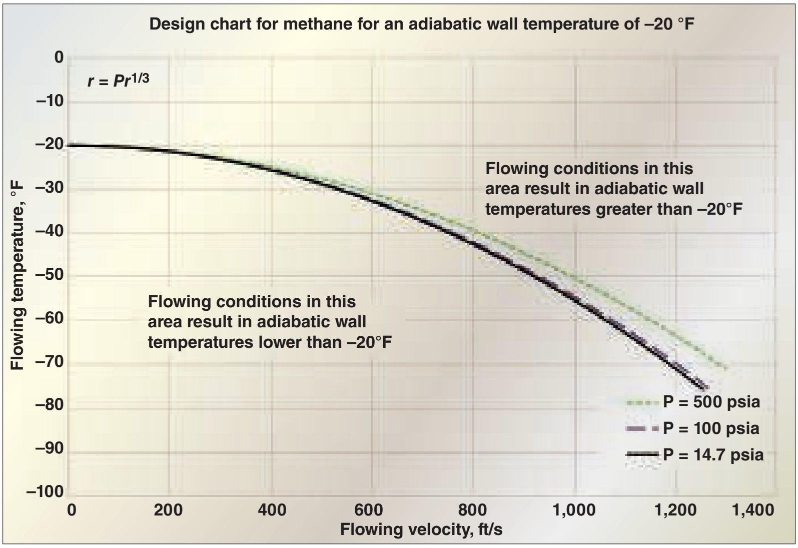


FIGURE 5. This design chart for methane shows a very minor dependence on pressure at an adiabatic wall temperature of –20°F

tion (8), iteration is generally not needed, as *Pr* does not vary significantly over the temperature range.

Design chart for methane

Alternatively, design charts can be prepared for a specific gas and material specification to speed the screening of potential low temperatures. Using the fluid properties of methane, obtained by means of the NIST Refprop program [*10*], the locus of flow conditions that would result in an adiabatic wall temperature of –20°F were identified for the Eckert estimate for turbulent pipe flow using Equation (3), as well as the low temperature estimate using Equation (9), with the reference temperature evaluated using Equation (5). As shown in Figure 4, flow conditions above the line result in adiabatic wall temperatures greater than –20°F, while conditions below the line result in adiabatic wall temperatures less than –20°F.

The properties of methane in the regions investigated are primarily dependent on temperature; however, there is some pressure dependence. The design chart as described above is generated for other static (flowing) pressures, using the turbulent recovery factor of Equation (3), and is shown in Figure 5. One will note the minor effects of pressure on the design charts. Design charts, along with the correlations described in this article, are effective ways of determining adiabatic wall temperature in high-velocity gases. ■

Edited by Mary Page Bailey

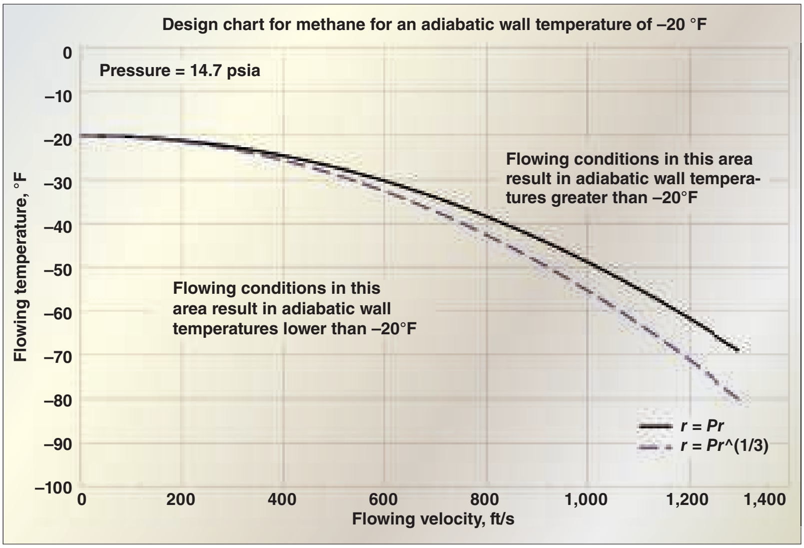


FIGURE 4. A design chart for methane shows the corresponding flowing velocities for adiabatic wall temperatures

Acknowledgment

The author would like to thank Georges A. Melhem and Dale L. Embry for their review of the content of this manuscript.

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Author

Aubry Shackelford is president and principal engineer at Inglenook Engineering, Inc. (15306 Amesbury Lane, Sugar Land, TX 77478; Phone: 713-805-8277; Email: aubry@inglenookeng.com). He has over ten years of experience in process safety management in general, with particular emphasis on pressure-relief design. Shackelford has also helped author several guidelines related to pressure relief for the American Petroleum Institute (API), the International Organization for Standardization (ISO) and the Center for Chemical Process Safety (CCPS). He has a B.S.Ch.E. from Northeastern University and holds affiliations with AIChE, NSPE and SPE.

Plot Plan Design: Process Requirements

It is important to conceptualize plant layout in terms of both ideal location and optimal geographical positioning of equipment components

Mohammad Toghraei
Engrowth Training

For any chemical process facility, the cost of improper or sub-optimal plant layout can be enormous. Designers are generally well aware of safety constraints, but there is often less recognition about other process requirements that will impact the design. This article discusses key elements of plant layout and plot plan design, in two important levels:

- *Level 1. Plant location.* This step involves selecting the best location
- *Level 2. Plant layout.* This step involves the placement of units and equipment relative to each other, in an effort to optimize all safety, operations and maintenance objectives

Each requires a certain chain of decision making that can impact the success of all efforts (Figure 1).

An integrated effort

Level 1. During Level 1, engineers seek to identify the optimal location for the plant. Generally speaking, a chemical process industries (CPI) plant should be in a location that allows it to easily receive raw materials and have access to utilities, such as water and power. Other key considerations are related to access to the infrastructure needed, such as roads, rail lines and shipping options, to enable both the shipment of products (and side-products) and the disposal of waste streams.

Other than material resources, any CPI facility also needs access to a good supply of human resources. When plants are established in desirable locations, they have access to a broad pool of qualified, skilled people for operation, maintenance and management of the plant.

Plant location should also be selected to minimize the potential environmental impact of plant operations. For instance, establishing a plant in an area that is surrounded by mountains is often not a good decision, due to potentially poor air-flow characteristics in the area. Similarly, if the treated wastewater of a plant needs to be injected into a disposal well, the plant cannot be very far from an area that has a suitable underground geological structure.

Economic parameters are also important when scouting possible plant locations. Ideally, stakeholders want to locate plants in locations with minimum land costs and minimum applicable taxes.

Level 2. During Level 2 efforts, stakeholders work to identify the best method for laying out the different units within the facility. One overarching objective of a plot plan (but not necessarily the most important one) is to minimize the length of equipment-connecting elements, such as pipes that convey liquids, gases and bulk solids. Material conveying systems, such as screw conveyors, belt conveyors, also fall within this category.

During the development and design of a plot plan, requirements and limitations are identified and decisions are made with regard to the following considerations:

- Process requirements, such as the need to support equipment

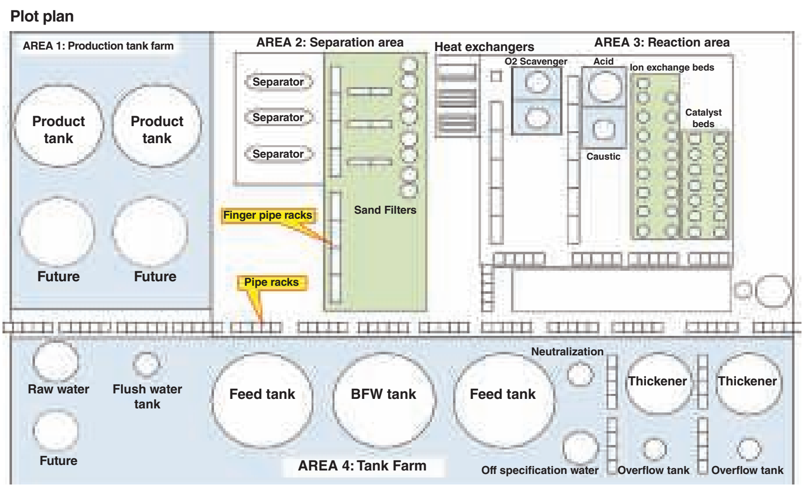


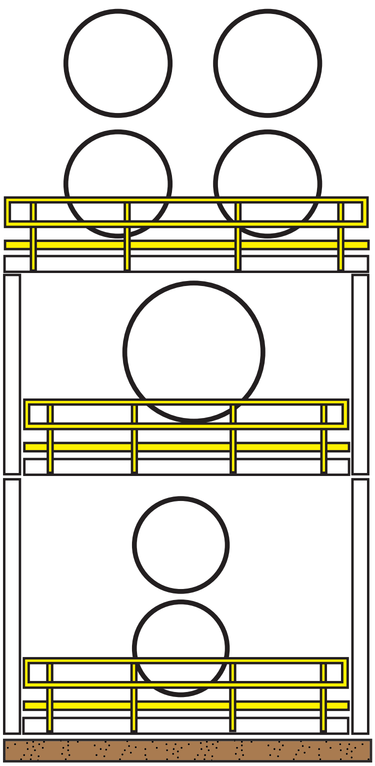
FIGURE 1. Shown here is a typical plot plan

- Suitable performance
- Safety requirements, such as the need to ensure the proper distance between the furnace and oil-storage tanks
- Construction requirements, such as the need to provide enough access area to allow construction equipment (such as cranes and lifts) to maneuver around the equipment
- Operation, inspection and maintenance requirements, to ensure easy accessibility for operators to reach each component, system or monitoring console
- Logistics requirements, to ensure easy accessibility for service companies and their vehicles, including chemical-delivery trucks

If the team follows the basic rule of seeking to minimize pipe length wherever possible, it will undertake efforts to minimize the length of both process piping and utility piping. To minimize the process piping length, equipment must be placed in the order of the process flow diagram (PFD) arrangement. However, the effort to minimize the utility piping length often forces designers to lay down the developed "string" of equipment based on the PFD along the perimeter of a circle with shared utility units in the center. Although other requirements (such as those related to safety and logistics) will usually result in changes to this preliminary arrangement, it will be a useful exercise to group equipment components that are using common utilities, in a first attempt to minimize the utility pipe lengths.

The designer not only needs to try to minimize the pipe length but also to minimize the pipe rack length and the number of finger pipe racks. Doing so requires effort to develop common routes for different pipes, as much as possible.

Safety requirements call for segregating areas within a plot plan in a way that groups equipment and units with common hazardous characteristics. To minimize the risk of releasing flammable, toxic, or lethal liquids from storage tanks, they should be grouped based on hazardous classification areas and then put within different containments or diked areas.



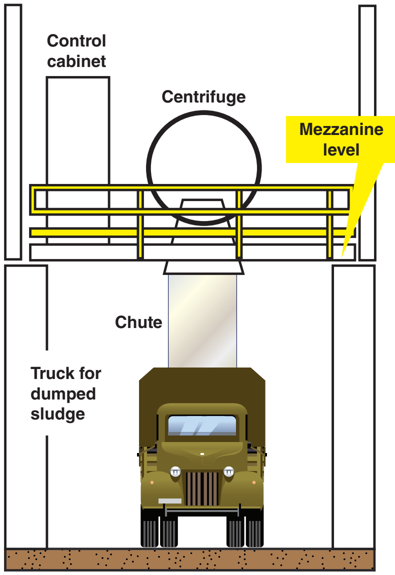


FIGURE 2. In many cases, it makes good engineering sense to incorporate vertical designs, to take advantage of gravity-based flow, limited footprint area in the facility, and other engineering considerations

Prevailing wind direction at the target location also affects the location of equipment. Thus, a furnace, for instance, can be placed at the edge of a plant against the direction of the prevailing wind to make sure any potential flammable leaked fuel gases would move away from the plant. This same logic is why flares are typically placed far from human activity.

Another group of safety considerations could be better classified as "nuisance issues." For instance, even though engineering controls are often used to manage noise and fugitive emissions, units that are inherently noisy or odorous should be placed in areas with little human presence.

Construction requirements are equally important during the development of a plot plan. Ease-of-construction rules typically call for a plant with a regular shape, preferentially with right angles.

Meanwhile, specific installation requirements associated with certain equipment must also be taken into account. For example, air coolers are usually installed in a horizontal direction, at some height above the ground. Such an installation will require an additional support structure. The added expense of this typically leads the plot plan designer to locate all the air coolers in one location, to economize.

The concept of constructability can affect the location of equipment, too. For instance, a piece of equipment may be placed relatively far from the main part of the plant — in a less-congested area against all other requirements — to satisfy the need for ease of access for construction vehicles, such as large cranes.

Operation and inspection requirements will also impact the location of equipment. Such considerations often require that operator-intensive equipment be grouped and placed in easily accessible areas. There must be specific clearance around each piece of equipment, to provide enough room for operators.

Specific maintenance requirements may require wider clearance around one or all sides. For example, a floating bundle shell-and-tube heat exchanger needs a clearance of about 1.5 times the tube length in front of the heat exchanger as an area for bundle removal. Similarly, plate-and-frame heat exchangers need enough clearance to allow for plate removal.

Some equipment — raw material tanks, silos of additives, chemical-injection skids that may need frequent fillings by trucks — is considered "logistic-intensive" in the sense that it may affect the logistics if placed in non-suitable locations. Placing such units in a poorly considered spot could also be unsafe or might interfere with an operator's daily duties because of the increased truck traffic that would be needed to transfer products or raw materials. To address these potential issues, such units are usually placed near the edge of the plant.

Another aspect of plant design to consider is where to place ponds such as storm water ponds that are often used in plants to collect rain water. Placing such ponds in the middle of a plant will decentralize the other units and will lengthen intra-plant travel time for personnel, so it best to place them at the periphery of the overall layout.

Key elements to consider

The following elements should be reconciled during the development of the plot plan:

1. Indoor versus outdoor installations. If the outside ambient temperature is not extreme (and the variation in temperature over time is not significant), then the least expensive decision is often to place all of the equipment outdoors. However, this option is not available everywhere.

The indoor-versus-outdoor decision is important because of the added cost of providing buildings to house the equipment. The first choice is always to locate the equipment outdoors unless the equipment is sensitive to very low or high temperatures, or the equipment is very operator-intensive. In these cases, it makes more sense to locate the equipment indoors.

Higher costs are associated with indoor installation not just because of the cost of buildings, but also due to added costs required to meet jurisdictional building codes (which tend to be more explicit, and thus more costly, for indoor facilities).

Polymeric membrane systems, for example, usually cannot tolerate temperatures greater than 40–50°C or very low temperatures. As a result, they are usually placed indoors.

The main group of operator–intensive equipment includes equipment used in semi-continuous, intermittent or batch operation. Although many batch operations are designed to be operated fully automatically, frequent operator checks are still necessary.

Consider the case of filtration. It is popular to place pressure filters indoors even though the filtering media (such as sand or anthracite) are not temperature-sensitive.

Any equipment that, for whatever reason, is not monitored by instruments — and thus requiring more operator attention — is usually placed indoors. For example, equipment for which taking samples is important should be placed indoors to ensure a suitable environment for the operator to be able to take the samples. However, some companies may opt to utilize another option, which is to use an expensive, automatic grab-sampling system for some equipment so that they can locate it outdoors.

The other consideration during plot plan development is the need for clean rooms, which are used to protect processes for which even trace amounts of impurities could impact the quality of the product. Examples of such processes are pharmaceutical and microchip manufacturing plants. In general, clean rooms need to be located indoors.

It is not the case that only two options — indoor or outdoor — are available. Having equipment partially indoors is one option to achieve a compromise between cost and operability. For example, in some cases, the side of the equipment that has all the sampling points can be located indoors while the rest of the equipment could be left outdoors. Similarly, when equipment has tall towers, instead of raising the roof of the building, the tower portion can be left above (that is, outside) of the building.

Another interim option is placing equipment inside of a "shed" or walk-in cabinet. The downside to this approach, however, is that not all provisions associated with an indoor building will be available. For example, in a small walk-in cabinet, a full firefighting system will not be available. Selecting this interim option should be considered very cautiously, making sure that all safety measures are considered carefully.

In very cold areas, such as northern Canada, the plot plan of indoor equipment sometimes needs to ensure that certain sensitive equipment components are not located near doors or windows, to minimize the chance of freezing. In such areas, frequent opening of doors and gates can increase the chance of freezing for the equipment near the door, especially if there is no hot-air curtain available.

2. One story versus multi story plant. The decision must be made as to whether or not the plant should be designed on one level, or whether some equipment should be placed on a second or third floor. The default option is to maintain the entire plant on one floor to minimize the cost, however, that may not be possible.

Having the plant built on more than one story increases the cost because of additional required structures and supports to hold all equipment systems, especially when the equipment is dynamic rather than static, and reciprocating rather than rotary. For example, placing a small tank on a mezzanine level could be less expensive than placing a centrifugal pump or mixer on that level.

However, in some cases having a multistory plant is preferable and justifiable (Figure 2). Consider the case for plants involved with solids handling, such as those whose raw materials, products or interim products are in bulk, granulated or powdered form. Solids conveying is typically carried out by pneumatic conveying systems, belt conveyors, screw conveyors, bucket conveyors and related systems. One way to reduce the need for some modes of pneumatic or mechanical conveyance (and hence reduce energy requirements) is to arrange the equipment vertically and use gravity.

In some cases, vertical arrangement can ease cleaning, especially

for sticky materials. In this approach a simple chute can sometimes replace a more complicated, mechanical solid-conveying system.

Another common example of plants that benefit from vertical arrangement are those that deal with liquids in the boiling temperature range (or in the bubble-point range for non-pure liquids). In such cases, the designer usually prefers to have a vertical arrangement to prevent unwanted evaporation or flash of the liquid. It is common to see a "stack" of heat exchangers that operate at temperatures close to the boiling temperature of liquid, to suppress the flash of liquid caused by the weight of the column of liquid (Figure 2).

3. Pipe length in the suction side of pumps. All pumps, either centrifugal or positive-displacement types, are sensitive to low suction pressure. This sensitivity can be quantified using the required net positive suction head ($NPSH_R$) term for centrifugal pumps, and the required net positive inlet pressure ($NPIP_R$) term for positive-displacement pumps. $NPSH_R$ is essentially the required effective liquid column in the suction side of the pump to guarantee proper operation with minimum cavitation.

This sensitivity can be addressed by ensuring an adequate margin on top of $NPSH_R$ exists to provide a suitable available net positive suction head ($NPSH_A$). The goal is to make sure $NPSH_A$ is higher than $NPSH_R$ with enough margin. This can be done by minimizing the suction pipe length and the number of fittings used. Doing so forces the designer to place the source container and the pump as close as possible on the plot plan.

Although reciprocating pumps are typically less sensitive than centrifugal pumps toward suction pressure (in other words, they could have lower $NPIP_R$ than equivalent $NPSH_R$), their pulsational operation, or the fact that pressure in their suction (and discharge side) can go much below average suction pressure makes them vulnerable. The effect of pulsation in their suction side is quantified in the "suction acceleration head" term, which needs to be added to the NPIP by the manufacturer. The magnitude of acceleration head is a function of the speed of reciprocation, the volume of cylinder(s) and the length of suction pipe.

4. Chemical compatibility. Different equipment handles different chemicals, which are not necessarily compatible. In an ideal world, various chemicals are bound by their respective equipment or containers. However, there is always a chance of leakage in an accident or via controlled release as the primary step of maintenance. Plot-plan development must consider the impact of the presence (and potential co-mingling) of all site-specific fluids, in any given location.

One specific concern is sumps. Sumps can receive different liquids and must be designed to store them safely for a limited time. The compatibility of any liquids that could end up in a given sump should be checked to make sure no uncontrolled reactions can occur. If fluids are not compatible, the respective equipment could be moved to another building, or a dedicated sump could be considered.

Another issue related to potential incompatibility of chemicals is electrical area classification. The electrical devices in each area should be compatible with the nature of the chemicals in each area. For example, a conventional electrical device that may generate sparks during its functioning is not suitable to be installed in any area in which highly flammable liquids may be present. This requirement is generally addressed by designating an "electrical area class" for each area, depending on the type of chemicals in that area.

It should be considered that one area with a less-stringent electrical class should not be pushed to a more-stringent electrical area class only because of a few units that are located (unwisely) in the area and require more-stringent electrical area classification. With proper plot plan design, engineers can avoid the poor (and costly) practice of classifying a big area or building with more severe electrical classification level only because of one or a few units that are handling flammable fluids.

5. Inline mixing with or without static mixers. When two or more streams will be mixed in line (pipe) rather than a mixing tank, requirements associated with the static mixer should be defined by the plot plan. The aim of any mixing effort is to produce a fairly homogenous mixed fluid at the inlet of the downstream equipment.

If the downstream equipment can be placed far from the mixing point, a homogenous fluid can often be attained via regular pipe flow even without a static mixer. If this is not the case, then a static mixer is needed. As a rule of thumb, when dealing with relatively watery liquids (viscosity <20 centipoise), a pipe length of 100–150 times the pipe diameter is usually sufficient and removes the need so that a static mixer can achieve the desired homogeneity.

6. Handling time-sensitive fluids. As noted, the relative location of equipment affects the pipe length between units. This could be critical for time-sensitive fluids. Although the travel time in specific sections of pipe is a matter of minutes, it could still be important for very sensitive fluids.

For example, in some flotation vessels, the bubbles are generated outside of the flotation vessel and then bubble-laden liquid is transferred to the vessels. If the distance between the bubble-generating mechanism and the flotation vessel is too large, bubbles will coalesce with each other. And at the vessel inlet, instead of having a liquid with small bubbles, there could be liquid with big slugs of gas. This reduces the separation efficiency of the flotation vessels.

7. Process gravity-flow pipes. When flow from one equipment component or container to another occurs only by gravity, some other issues should be considered. In two interconnecting containers, the liquid level in the second (downstream) container is partly adjusted by the pressure drop in the connecting pipe. This shows the importance of gravity-pipe pressure drop and its length in the design and operation of a unit. The pipe pressure loss can be minimized by placing these containers as close as possible and using the minimum number of elbows and other fittings on the connecting pipe.

If the gravity pipe is placed with a slope toward the second interconnected container, the importance of minimizing the pipe length becomes more obvious. If the pipe is long, the second downstream container may need to be placed in a pit to be able to provide the required slope. This is not an ideal situation, because dealing with equipment in a pit provides some difficulties for operators.

8. Hydraulic transferring of critical solids. One method of transferring powders, granules or beads is through the use of hydraulic transfer systems. Hydraulic transferring can be done by air, water or other fluids. If the integrity of solid beads is important, this operation should be done carefully and the design should minimize attrition. One requirement in such systems is to minimize the transfer line length and use specific fittings, such as long-radius elbows. This requires the source and destination units to be placed as close to each other as possible, which will affect the plot plan.

9. Symmetric piping. Providing a symmetrical piping design to the inlet of two similar equipment components is one passive way to split a stream equally to both of them. The need for symmetric piping can force the designer to relocate or rotate equipment in the plot plan. As a rule of thumb, any need for symmetrical piping around equipment should be identified early, as it will impact the plot-plan design efforts.

10. Future plans. The basis for future modifications in the plant could be economic or technical, and they may be either planned or unplanned. While the designer of the plot plan cannot leave room for the unplanned modifications, he or she should try to reserve enough room in suitable locations to accommodate those future modifications that can be planned or anticipated in some way. ■

Edited by Suzanne Shelley

Author

Mohammad Toghraei is an instructor and consultant with Engrowth Training (Web: www.engedu.ca; Phone: 403-808-8264; Email: moe.toghraei@engedu.ca), based in Calgary, Alta. He has more than 20 years of experience in the process industries, and has published articles on different aspects of process operations. His main expertise is in the treatment of produced water and wastewater from the oil-and-gas industries. Toghraei received a B.Sc. in chemical engineering from Isfahan University of Technology (Iran), and an M.Sc. in environmental engineering from Tehran University (Iran). He is a member of the Assn. of Professional Engineers and Geoscientists of Alberta (APEGA), and is a professional engineer, P.Eng., in the province of Alberta.

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Rudy Teng
Sales Representative
Chemical Engineering;
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Hsinchu 30055 Taiwan
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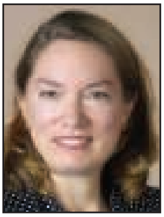
Diele-Braun


Wagner


Aitken


Ray

Greene's Energy Group LLC (Houston), a provider of testing services, equipment rentals and specialty services for the oil-and-gas industry, names *Robert Fraser* regional business-development manager, based in Dubai.

Philippe Sauquet becomes president of refining and chemicals, and a member of the executive committee, for **Total S.A.** (Paris).

Archroma (Reinach, Germany), a producer of color and specialty chemicals, makes the following two announcements: *Valerie Diele-Braun* becomes president, paper solutions, succeeding *Helmut Wagner,* who becomes chief purchasing officer.

Amyris (Emeryville, Calif.), a renewable products company, appoints *Raffi Asadorian* chief financial officer. The interim CFO *Paulo Diniz*, becomes chairman of **Amyris Brasil**.

Scott Aitken becomes managing director for the European water business for engineering, procurement and construction firm **Black & Veatch** (Redhill, U.K.).

Cashco (Ellsworth, Kan.), a manufacturer of control valves and other equipment, promotes *Dan Ray* to director of engineering, procurement and construction management.

Adept Technology (Pleasanton, Calif.), a provider of intelligent robots, autonomous mobile robot solutions and services, welcomes *Michael Jellen* vice president for North America. ■

Suzanne Shelley

BUSINESS NEWS

PLANT WATCH

Bayer MaterialScience inaugurates TDI plant in Dormagen

December 9, 2014 — At its site in Dormagen, Germany, Bayer MaterialScience AG (Leverkusen, Germany; www.materialscience.bayer.de) has started up a new production plant for toluene diisocyanate (TDI). Valued at around €250 million, the new plant was under construction for 30 months, and replaces a smaller TDI production unit.

Air Liquide will construct a new air-separation unit in Port Neches

December 9, 2014 — Air Liquide (Paris, France; www.airliquide.com) broke ground for a new air-separation unit (ASU) that will produce oxygen (O_2), nitrogen (N_2) and argon (Ar) in Port Neches, Tex. The new ASU will produce 2,400 metric tons (m.t.) per day of O_2 and 2,600 m.t./d of N_2, tripling O_2 production capacity and doubling N_2 production capacity at the Port Neches facility. Commercial operations are expected to begin by the end of 2015.

BASF starts up emulsion polymers plant in Freeport

December 8, 2014 — BASF SE (Ludwigshafen, Germany; www.basf.com) began operations at a new emulsion polymers plant at its integrated site in Freeport, Tex. The acrylic emulsion polymers manufactured at this plant are used for architectural coatings, construction chemicals and adhesives, as well as applications in the paper-chemicals industry. Construction of the plant began in February 2013.

Yara to build new nitric acid plant, increase ammonium nitrate capacity

December 5, 2014 — Yara International ASA (Oslo, Norway; www.yara.com) will invest $220 million to expand production capacity of technical ammonium nitrate (TAN). The investment includes construction of a new nitric acid plant, which replaces an existing plant. The total TAN capacity after the upgrade will be approximately 450,000 m.t./yr.

Airgas to construct new liquid-hydrogen plant in Kentucky

December 4, 2014 — Airgas, Inc. (Radnor, Pa.; www.airgas.com) has announced plans to build a new liquid-hydrogen plant in Calvert City, Ky. The new facility is targeted to be onstream in the summer of 2016 and will complement the company's nearby ASU, also slated for a 2016 startup.

Solvay boosts production capacity for polyaryletherketone resin in India

December 3, 2014 — Solvay S.A. (Brussels, Belgium; www.solvay.com) is increasing production capacity of polyaryletherketone resin by 25% at its plant in Panoli, Gujarat, India to support demand for its ultra-high-performance polymers. Healthcare, electronics and energy are among the key markets for these polymers.

Showa Denko and UOP open high-silica zeolite plant in Japan

December 3, 2014 — Union Showa (USKK), a joint venture (JV) between Showa Denko K.K. (SDK; Tokyo, Japan; www.sdk.co.jp) and UOP LLC (Des Plaines, Ill.; www.uop.com) has completed the construction of a new high-silica zeolite plant at SDK's Higashi-nagahara Plant in Aizu-Wakamatsu City, Fukushima, Japan. High-silica zeolite is an adsorbent used for the removal of volatile organic compounds (VOCs).

Tecnimont awarded EPC contract for Illinois fertilizer plant

December 1, 2014 — Maire Tecnimont S.p.A. (Milan, Italy; www.mairetecnimont.com) was awarded a $1.5-billion engineering, procurement and construction (EPC) contract by Cronus Chemicals, LLC to build an ammonia and urea plant in Tuscola, Ill. The plant will have a production capacity of 2,200 m.t./d of ammonia and 3,850 m.t./d of urea, as well as the equipment necessary to produce diesel exhaust fluid.

Verdezyne to produce bio-based diacids at newly announced Malaysian facility

November 20, 2014 — Verdezyne Inc. (Carlsbad, Calif.; www.verdezyne.com) will build a commercial-scale renewable chemicals plant in Nusajaya, Malaysia. Construction will commence in 2015. The plant is designed to produce, from plant-based feedstock, 13,600 m.t./yr of bio-based diacids, including dodecanedioc acid (DDDA), and is said to be the world's first plant for the bio-based production of DDDA.

Dow plans polyethylene capacity expansion in Argentina

November 14, 2014 — Starting in 2015, The Dow Chemical Company (Midland, Mich.; www.dow.com) plans to expand capacity at its four polyethylene (PE) production units located in Bahia Blanca, Argentina. The project will upgrade Dow's low-density, gas-phase, slurry and solution PE units at the site.

MERGERS AND ACQUISITIONS

Solvay to acquire Brazilian specialty-esters manufacturer Dhaymers

December 9, 2014 — Solvay S.A. is acquiring Dhaymers (www.dhaymers.com.br), a Brazilian manufacturer of specialty esters. Dhaymers' specialty esters are used in skin-care products, mining emulsions and lubricants for the metal-working industry.

Indorama to acquire manufacturing operations from Performance Fibers Asia

December 8, 2014 — Indorama Ventures Public Co. (Bangkok, Thailand; www.indorama.net) has acquired the Asian manufacturing operations of Performance Fibers (PF) Asia, a producer of polyester tire-cord (PTC) fabric. PF Asia has plants located in Kaiping City, China that produce 41,000 m.t./yr of PTC fabric and 48,000 m.t./yr of PTC yarn.

Vertellus acquires sodium borohydride business from Dow

December 5, 2014 — Vertellus (Indianapolis, Ind.; www.vertellus.com) has acquired Dow's sodium borohydride (SBH) business. SBH is used in the synthesis of fine chemicals, such as pharmaceutical ingredients and agrochemicals. The transaction is expected to close in the first quarter of 2015.

Lubrizol creates Oilfield Solutions segment with Weatherford acquisitions

December 1, 2014 — The Lubrizol Corp. (Wickliffe, Ohio; www.lubrizol.com) has acquired the oilfield-chemicals and drilling-fluids businesses from oilfield services company Weatherford (Houston; www.weatherford.com) for $825 million. The acquired businesses will form a new segment within Lubrizol, called Oilfield Solutions.

Synalloy acquires carbon-pipe distributor Specialty Pipe & Tube

November 25, 2014 — Synalloy Corp. (Spartanburg, S.C.; www.synalloy.com) has acquired Specialty Pipe & Tube, Inc., a distributor of seamless carbon pipe. The transaction is valued at $31.5 million.

BASF divests omega-3 production plant in Norway to Marine Ingredients

November 24, 2014 — BASF SE plans to sell its manufacturing facility for omega-3 oils in Brattvåg, Norway to Marine Ingredients, a manufacturer of marine-based ingredients and customized products. The transaction is expected to close in early 2015. ■

Mary Page Bailey

FOR ADDITIONAL NEWS AS IT DEVELOPS, PLEASE VISIT WWW.CHEMENGONLINE.COM

January 2015; VOL. 122; NO. 1

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2012 — 2013 — 2014

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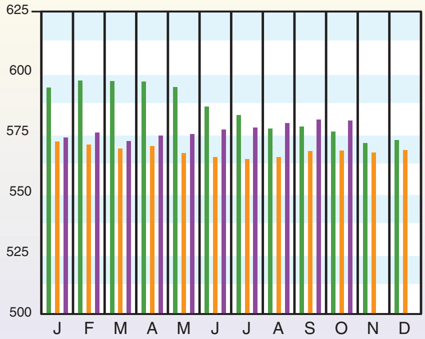
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Oct. '14 Prelim.	Sept.'14 Final	Oct.'13 Final
***CE* Index**	579.8	580.1	567.5
Equipment	704.1	704.6	686.6
Heat exchangers & tanks	652.3	650.9	620.0
Process machinery	666.9	668.1	655.7
Pipes, valves & fittings	876.4	877.4	874.5
Process instruments	411.9	413.4	411.8
Pumps & compressors	941.1	939.0	924.7
Electrical equipment	516.0	515.7	513.8
Structural supports & misc	769.1	775.1	744.1
Construction labor	324.4	323.9	321.6
Buildings	547.2	546.3	533.7
Engineering & supervision	320.3	321.4	324.4

Annual Index:

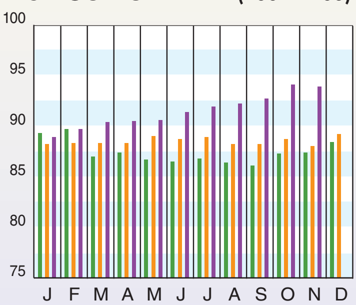
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6
2013 = 567.3



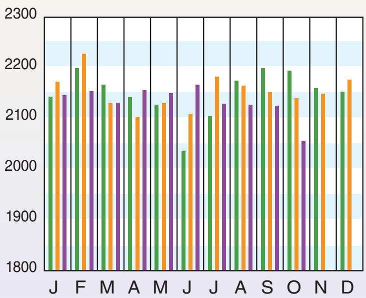
CURRENT BUSINESS INDICATORS*

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2007 = 100)	Nov.'14 = 93.9	Oct.'14 = 93.1	Sept.'14 = 92.9	Nov.'13 = 89.1
CPI value of output, $ billions	Oct.'14 = 2,056.1	Sept.'14 = 2,114.6	Aug.'14 = 2,123.6	Oct.'13 = 2,137.9
CPI operating rate, %	Nov.'14 = 78.7	Oct.'14 = 78.1	Sept.'14 = 77.9	Nov.'13 = 75.5
Producer prices, industrial chemicals (1982 = 100)	Nov.'14 = 283.4	Sept.'14 = 293.2	Aug.'14 = 296.6	Nov.'13 = 290.0
Industrial Production in Manufacturing (2007 = 100)	Nov.'14 = 102.2	Oct.'14 = 101.1	Sept.'14 = 100.7	Nov.'13 = 97.6
Hourly earnings index, chemical & allied products (1992 = 100)	Nov.'14 = 157.4	Oct.'14 = 156.2	Sept.'14 = 157.0	Nov.'13 = 157.4
Productivity index, chemicals & allied products (1992 = 100)	Nov.'14 = 107.8	Oct.'14 = 107.8	Sept.'14 = 107.9	Nov.'13 = 106.8

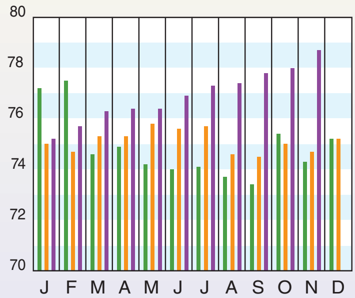
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



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

HIGHLIGHTS FROM RECENT ACC ECONOMIC DATA

The American Chemistry Council (ACC; Washington, D.C.; www.americanchemistry.com) released its "Year-end Chemical Industry Situation and Outlook" report in late December. The report says that despite facing global headwinds, the American chemical industry expanded at a 2.0% growth rate in 2014, and is expected to reach a 3.7% gain in output in 2015, before hitting 3.9% in 2016. The report's consensus is that U.S. chemical output will continue to expand well into the second half of the decade, exceeding that of the overall U.S. economy. Other key highlights of the Situation and Outlook report include the following:

- Light vehicle sales ($3,500 of chemistry per unit) grew 5.2% in 2014
- Housing starts ($15,000 of chemistry per start) grew 7.5% in 2014
- Basic chemicals were hard hit from recessions in Japan and Brazil
- During the second half of the current decade, U.S. chemical industry growth is expected to expand at a pace of more than 4% per year on average, exceeding that of the overall U.S. economy
- A trade surplus of $77 billion is expected by 2019
- More than 215 new chemical production projects valued at over $135 billion have been announced in the U.S., helping capital spending to surge nearly 12% in 2014 to more than $33 billion

Globally, the ACC reported that the Organization for Economic Cooperation and Development's (OECD; Paris; www.oecd.org) composite leading indicator pointed to stable growth momentum for the OECD regions as a whole. ❑

CURRENT TRENDS

The preliminary value for the October *CE* Plant Cost Index (CEPCI; top; the most recent available) declined slightly (0.05%) from the final September value, reversing the increasing trend that has been observed for the past six months. The Equipment subindex saw a very small decline in October, as did the Buildings and Engineering & Supervision subindices, while the Construction & Labor subindex saw a small increase. The overall October PCI value stands at 2.2% higher than its value from October 2013. Meanwhile, updated values for the Current Business Indicators (CBI) from IHS Global Insight (middle) show that the CPI output index was up slightly from the previous month, while the value of output declined. ❑

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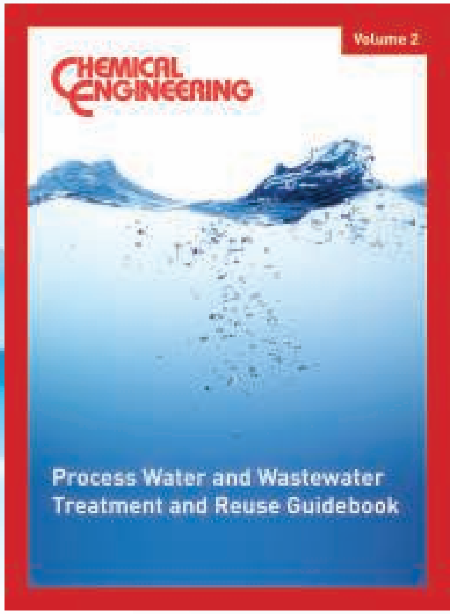

This guidebook contains how-to engineering articles formerly published in *Chemical Engineering*. The articles in Volume 2 provide practical engineering recommendations for process operators faced with the challenge of treating inlet water for process use, and treating industrial wastewater to make it suitable for discharge or reuse.

There is a focus on the importance of closed-loop or zero-discharge plant design, as well as the selection, operation and maintenance of membrane-based treatment systems; treating water for use in recirculated-water cooling systems; managing water treatment to ensure trouble-free steam service; designing stripping columns for water treatment; and more.

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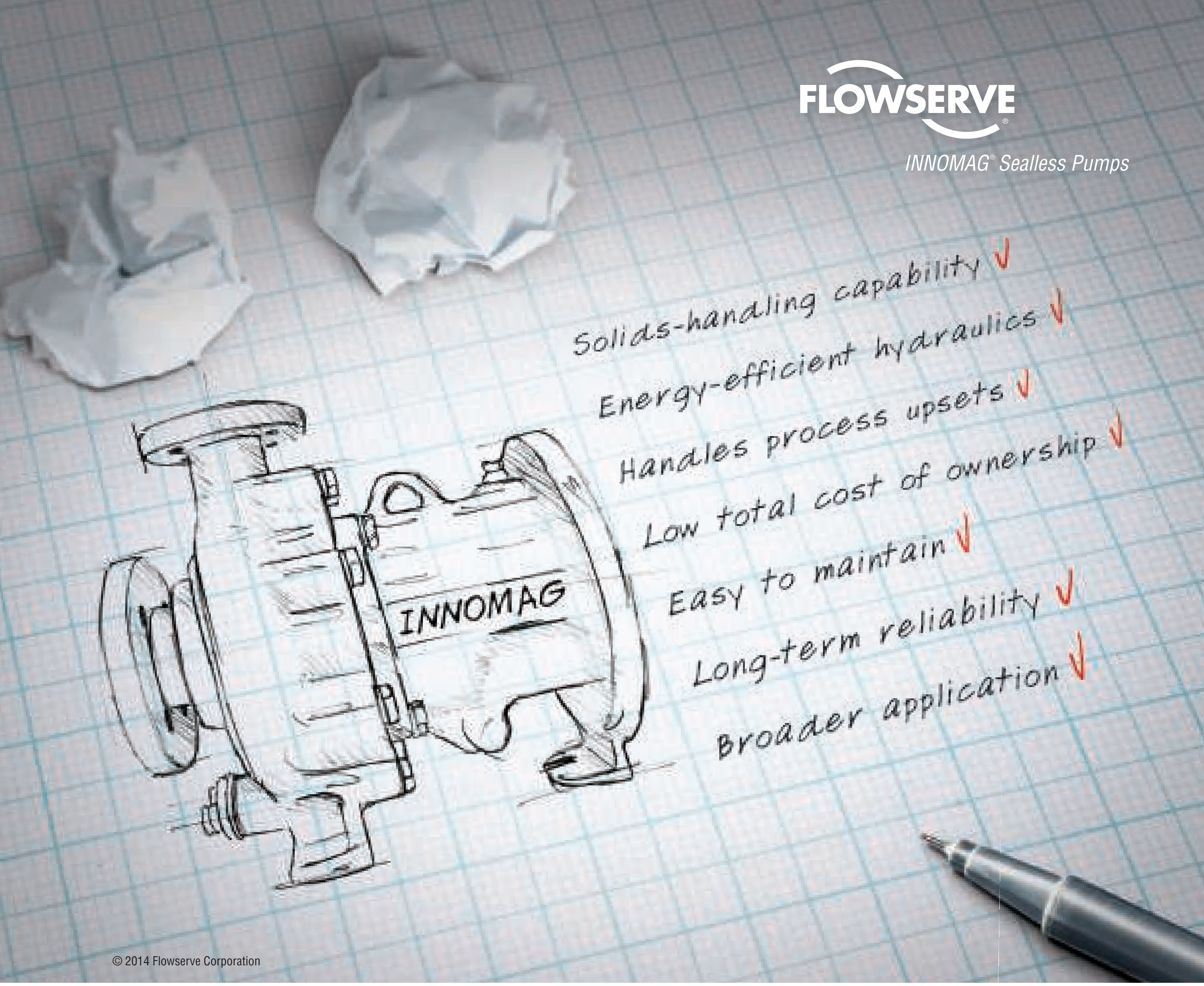

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