
CHEMICAL ENGINEERING
June
2011
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A FIELD GUIDE TO
Flowmeters
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Facts at Your Fingertips: Reciprocating Pumps
Dynamic Information Tools
Column Internals
Cybersecurity for Chemical Engineers
Focus on Seals and Gaskets
GUIDE
Reduce Gas Entrainment in Liquid Lines
Maximizing Performance in Size Reduction
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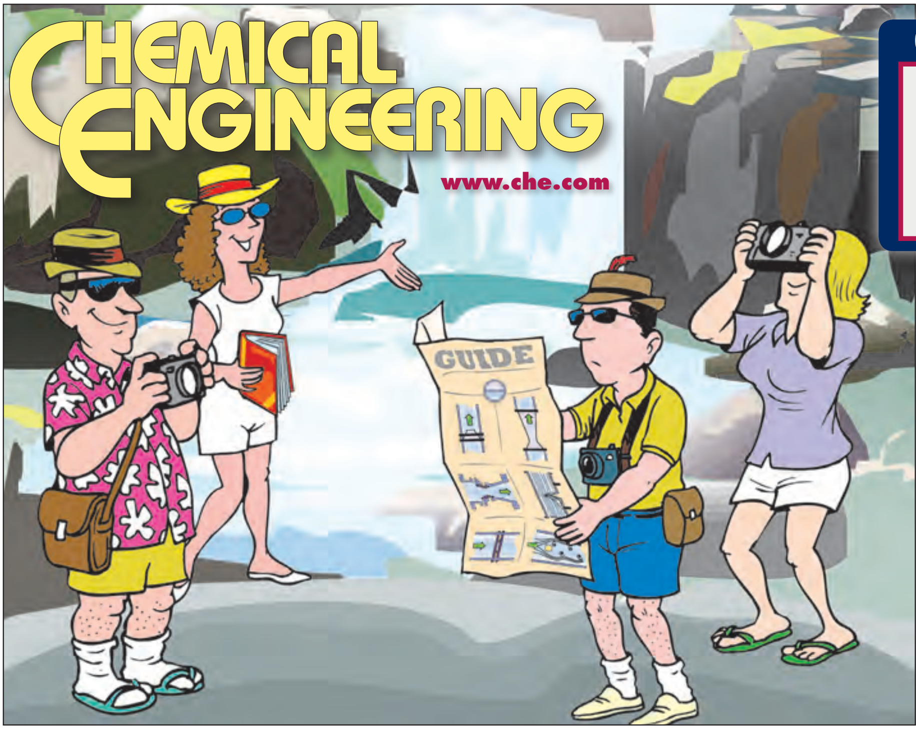

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COMING IN JULY

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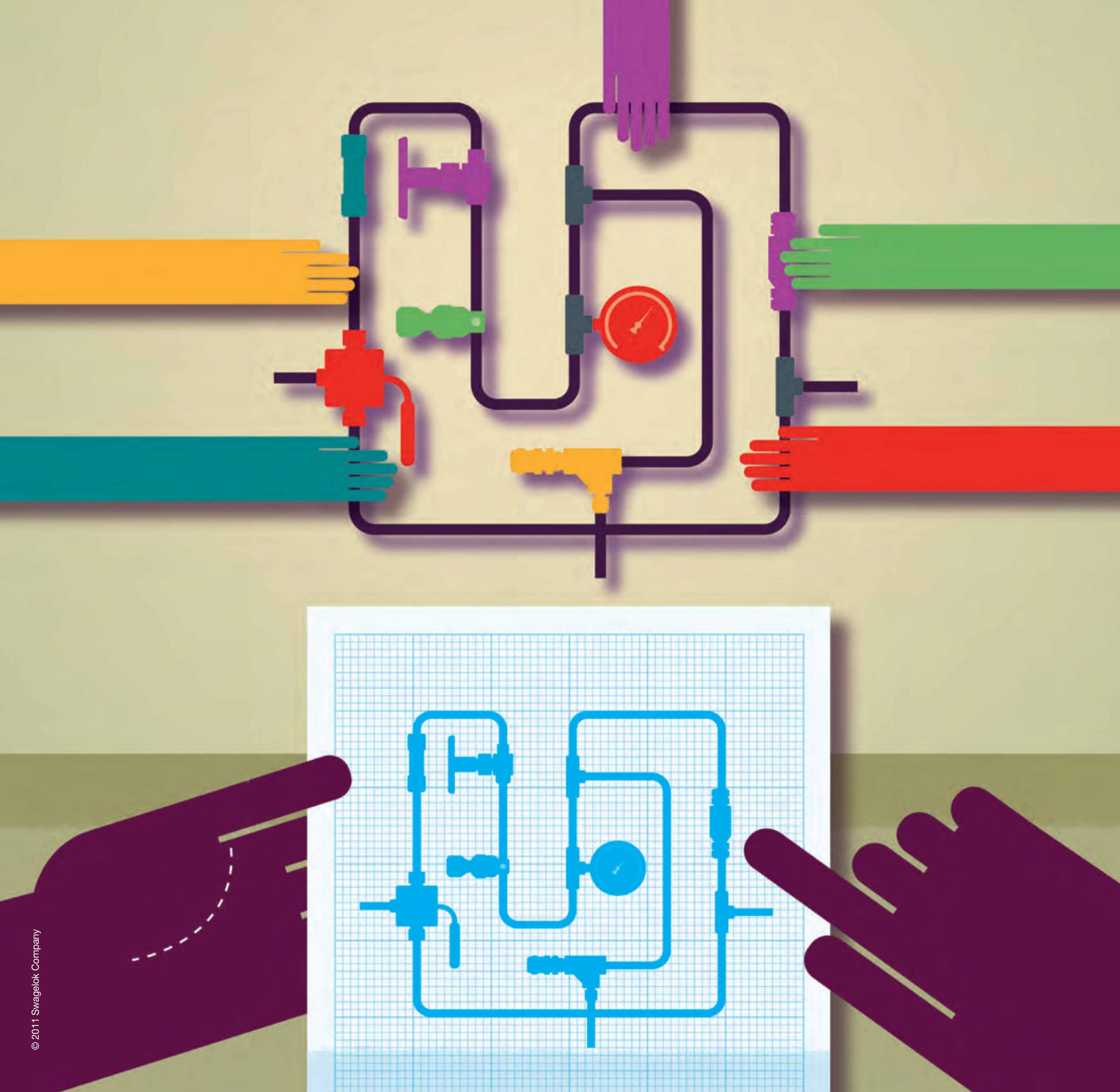
Cover: David Whitcher



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CHEMICAL ENGINEERING

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U.S. energy mix shifts

The U.S. Energy Information Administration (EIA; Washington, D.C.) recently released the complete version of its Annual Energy Outlook 2011 (AEO2011; www.eia.gov/forecasts/aeo), which includes projections for energy production, consumption, technology and market trends, and the direction they may take in the future for the world's second-largest energy user.

"EIA's projections indicate strong growth in shale gas production, growing use of natural gas and renewables in electric power generation, declining reliance on imported liquid fuels, and projected slow growth in energy-related carbon dioxide emissions in the absence of new policies designed to reduce them," says EIA Administrator Richard Newell. "But variations in key assumptions can have a significant impact on the projected outcomes." Key results highlighted in the AEO2011 Reference case include the following:

U.S. reliance on imported liquid fuels falls due to increased domestic production — including biofuels — and greater fuel efficiency. Although U.S. consumption of liquid fuels continues to grow through 2035 in the Reference case, reliance on petroleum imports as a share of total liquids consumption decreases. Total U.S. consumption of liquid fuels, including both fossil fuels and biofuels, rises from about 18.8 million barrels per day (bpd) in 2009 to 21.9 million bpd in 2035. The import share, which reached 60% in 2005 and 2006 before falling to 51% in 2009, falls to 42% in 2035.

Domestic shale-gas resources support increased natural gas production with moderate prices, but assumptions about resources and recoverability are key uncertain factors. Shale-gas production continues to increase strongly through 2035, growing almost fourfold from 2009 to 2035 when it is projected to make up 47% of total U.S. production — up considerably from the 16% share in 2009.

Although more information on shale resources has become available as a result of increased drilling activity in developing shale-gas plays, estimates of technically recoverable resources and well productivity remain highly uncertain, the report says. Over the past decade, as more shale formations have gone into commercial production, the estimate of technically and economically recoverable shale-gas resources has skyrocketed. However, the increases in recoverable shale-gas resources embody many assumptions that might prove to be incorrect over the longterm. Alternative cases in the report examine the potential impacts of variation in the estimated ultimate recovery per shale-gas well and the assumed recoverability factor used to estimate how much of the play acreage contains recoverable shale gas.

Assuming no changes in policy related to greenhouse gas emissions, carbon dioxide emissions grow slowly. Energy-related CO_2 emissions grow slowly, the report says, due to a combination of modest economic growth, growing use of renewable technologies and fuels, efficiency improvements, slow growth in electricity demand, and more use of natural gas, which is less carbon-intensive than other fossil fuels.

In the Reference case, which assumes no explicit regulations to limit greenhouse gas (GHG) emissions beyond vehicle GHG standards, energy-related CO_2 emissions do not return to 2005 levels (5,996 million metric tons) until 2027, growing by an average of 0.6% per year from 2009 to 2027, or a total of 10.6%. CO_2 emissions then rise by an additional 5% from 2027 to 2035, to 6,311 million metric tons in 2035. The projections for CO_2 emissions are sensitive to many factors, including economic growth, policies aimed at stimulating renewable fuel use or low-carbon power sources, and any policies that may be enacted to reduce GHG emissions, all of which are explained in sensitivity cases. ■

Rebekkah Marshall

Letters

Standards for protective clothing

Your March 2011 article Chemical Protective Clothing promoted the existence of an international standard (ISO 16602) for testing and evaluating chemical protective clothing. The article tells your readers that there is no comprehensive standard in North America that quantifies the performance of protective garments. As chairman of the International Safety Equipment Association's (ISEA) Protective Apparel Group, I would like to correct this erroneous information. In October 2010, ISEA received approval of a new standard, ANSI/ISEA 103-2010, American National Standard for Classification and Performance Requirements for Chemical Protective Clothing. The standard was drafted by ISEA members who are global leaders in the manufacturing and supply of protective clothing. Prior to receiving recognition as a new national standard, the document underwent a formal consensus review by key stakeholders including those in the chemical, waste management and handling, and hazards environmental industries.

The ANSI/ISEA 103-2010 standard includes all of the salient points made in the article pertaining to whole-suit testing, minimum performance levels, six types of chemical hazards, and requirements for mechanical, barrier, and basic flammability properties. Meanwhile, it avoids circumstances where complete harmonization with an international standard would not be permissible and would conflict with other U.S. regulations. For example, the Type 2 Classification in the ISO 16602 standard clearly is in conflict with NIOSH here in the U.S. and would not be the appropriate standard in this country. I encourage your audience to contact ISEA (www.safetyequipment.org) with any questions.

Brian Lyons, vice president sales & marketing
International Enviroguard, Mesquite, Tex.

Author responds: The objective for writing this article was to help those in the chemical process industries (CPI) who have responsibility for employee safety by making them aware of a well-established performance standard for chemical protective clothing (CPC). Any meaningful discussion about global consensus standards for CPC must include ISO 16602. The ISO 16602 standard has been in place since 2007 and has been adopted in almost every region of the world with significant CPC usage.

As an active participant in the ISEA protective apparel committee, DuPont was fully aware of the development status of the ANSI/ISEA 103 standard. It is important to note that the issuance of the ANSI/ISEA 103 standard in October 2010 does not conflict with the intent or benefits of ISO 16602. In fact, the vast majority of the performance types and classifications in ISO 16602 are in harmony with the ANSI/ISEA 103 standard. While it may be advantageous for those who work in the CPI to be aware of the ANSI/ISEA 103 standard, we chose to focus this article on the established ISO 16602 standard rather than point out the subtle differences between the two standards. We are not aware of any CPC manufacturers that have garments certified to meet the new requirements of ANSI/ISEA 103.

Susan Lovasic
DuPont Protection Technologies


ABB

Calendar

NORTH AMERICA

AWMA Annual Conference & Expo. Air & Waste Management Assn. (Pittsburgh). Phone: 412-232-3444; Web: awma.org
Orlando, Fla. **June 21–24**

BioPlastek 2011. Schotland Business Research (Skillman, N.J.). Phone: 609-466-9191; Web: bioplastek.com
New York, N.Y. **June 27–29**

BIO 2011. Biotechnology Industry Organization (Washington, D.C.). Phone: 202-962-6655; Web: bio.org
Washington, D.C. **June 27–30**

2011 Chemical Sector Security Summit & Expo. SOCMA and the U.S. Dept. of Homeland Security (Washington, D.C.). Phone: 202-721-4122; Web: socma.com
Baltimore, Md. **July 5–7**

Scaleup of Chemical Processes. Scientific Update Consulting (East Sussex, U.K.). Phone: +44 1435 873062; Web: scientificupdate.co.uk
Boston, Mass. **July 11–13**

Semicon West 2011. Semiconductor Equipment and Materials International (San Jose, Calif.). Phone: 408-943-7988; Web: semiconwest.org
San Francisco, Calif. **July 12–14**

ChemEd 2011. Western Michigan University (Kalamazoo, Mich.). Phone: 269-387-4174; Web: chemed2011.com
Kalamazoo, Mich. **July 24–28**

Biomass 2011. U.S. Dept. of Energy's Office of Energy Efficiency and Renewable Energy (Washington, D.C.). Phone: 202-586-5188; Web: www1.eere.energy.gov/biomass/biomass_2011.html
National Harbor, Md. **July 26–27**

2nd International Conference on Nanotechnology: Fundamentals & Applications. International Academy of Science, Engineering and Technology (Nepean, Ont.); Web: icnfa2011.international-aset.com
Ottawa, Ont. **July 27–29**

Drug Discovery & Development Week. IBC USA Conferences (Boston, Mass). Phone: 941-554-3500; Web: ibclifesciences.com/drugdisc/overview.xml
San Francisco, Calif. **August 1–3**

2nd Annual ChemInnovations 2011 Conference and Exhibition, co-located with ISA's Houston Section Annual Conference & Exhibition, the Texas A&M University Turbomachinery Laboratory's 40th Turbomachinery Symposium, and the 27th International Pump Users Symposium. *Chemical Engineering* and The TradeFair Group (both Access Intelligence companies; Rockville, Md.). Phone: 713-343-1891; Web: cpievent.com
Houston **September 13–15**

EUROPE

2nd International Conference on Efficient Carbon Capture for Coal Power Plants. Dechema e.v. (Frankfurt am Main, Germany). Phone: +49 69 7564 205; Web: icepe2011.de
Frankfurt am Main, Germany **June 20–22**

3rd European Process Intensification Conference. IChemE (Rugby, U.K.). Phone: +44 1788 578214; Web: icheme.org/EPIC2011/
Manchester, U.K. **June 20–23**

11th Annual Conference on Carbon Dioxide Utilization. Féderation Française pour les Sciences de la Chimie (FFC; Paris). Phone: +33 1 53 59 02 10 Web: ffc-asso.fr/ICCDU
Dijon, France **June 27–30**

25th National Chemistry Congress. Turkish Chemical Soc. and Atatürk University (Erzurum, Turkey). Phone: +90 442 231 44 26; Web: kimya2011.com
Erzurum, Turkey **June 27–30**

10th International Conference on Materials Chemistry. Royal Society of Chemistry (Cambridge, U.K.). Phone: +44 1223 432380; Web: rsc.org/MC10
Manchester, U.K. **July 4–7**

Nanopolymers. Smithers Rapra Technology Ltd. (Shropshire, U.K.). Phone: +44 1939 250383; Web: polymerconferences.com
Düsseldorf, Germany **September 13–14**

ELSEWHERE

43rd IUPAC World Chemistry Congress. IUPAC; Research Triangle Park, N.C.). Phone: 787-283-6104; Web: iupac2011.org
San Juan, Puerto Rico **July 30–August 7** ■

Suzanne Shelley

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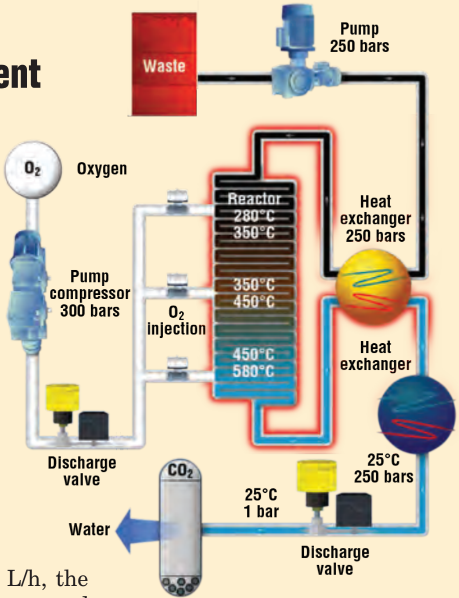
Supercritical water oxidation for organic waste treatment



Innoveox

A novel method for treating industrial liquid waste employs supercritical water infused with oxygen to destroy organic compounds. Developed by Innoveox (Paris; www.innoveox.com) and based on technology patented by the French government research organization CNRS (www.cnrs.fr), supercritical water oxidation (SCWO) offers a lower-cost, environmentally friendly alternative to traditional waste-treatment methods like incineration, landfilling or chemical treatment.

The Innoveox method works by subjecting virtually any "pumpable" organic industrial waste — including organic hazardous wastes, used oils, petroleum waste, solvents and others — to temperatures between 350 and 550°C and pressures of 221 bars with oxygen present (diagram). Under the reactor conditions, water becomes supercritical, and organic material becomes soluble in the fluid. The organic waste, with chemical oxygen demand (COD) values in the range of 25–250 g/L, rapidly breaks down via oxidation to yield purified water, carbon dioxide and energy. Inorganic material precipitates in the form of metal oxides and mineral salts.

The one-reactor method is cost-competitive with alternatives and can lead to significant cost savings depending on the nature of the waste and the location of the facility. Water and carbon dioxide can be re-used, and remaining inorganics can be harvested for valuable catalyst metals. "The only energy input is for preheating the waste," says Patrick Lemaitre, sales and marketing director, Innoveox.

Although Innoveox completed an industrial SCWO unit in Southwest France that is capable of treating 99.9% of industrial waste at a rate of 100 L/h, the company's business model revolves around custom-assembling SCWO units at a customer site, and providing waste treatment as a service, explains Lemaitre. The initial targets include petroleum refineries, chemical plants and pharmaceutical manufacturing facilities. In the shortterm, Innoveox plans to build four SCWO units, each with ten times the capacity of the prototype, at customer sites outside France.

Biodegradation system for VOCs poised for expansion

A system that utilizes existing biological wastewater-treatment facilities for destruction of biodegradable volatile organic compounds (VOCs) and other organic hazardous air pollutants (HAPs) has been demonstrated at three U.S. petroleum-refining and chemical facilities, and the developer has plans to extend the U.S. patent-pending treatment approach to eight additional facilities in coming months.

Environ International Corp. (Arlington, Va.; www.environcorp.com) developed the treatment method, known as VOC BioTreat, as an alternative to incineration or activated-carbon VOC treatment systems. The VOC BioTreat protocol has demonstrated the ability to meet VOC and HAP handling requirements in U.S. state and federal emissions regulations.

VOC BioTreat works by piping VOC off-gases into an existing wastewater treatment tank that contains activated sludge at depths of greater than 18 ft. Microbes in the tank break down VOCs as they bubble up through the tank. VOC BioTreat can be retrofitted into existing wastewater treatment facilities for somewhat lower capital costs as compared to installing thermal oxidizers or activated-carbon VOC treatment systems, but the annual operating costs are less than 10% of conventional systems.

In addition to the VOC BioTreat technology, Environ has developed a test method to confirm the performance of the proprietary technology within a plant setting. "The ability to reliably test for VOCs is critical for acceptance from the regulatory authorities," commented Carl Adams, lead researcher and Environ's global practice leader for industrial wastewater management. The VOC BioTreat technology recently received the grand prize for research excellence in the American Academy of Environmental Engineers' E3 competition.

Underground pipes

A hand-held device for locating buried pipe will be commercialized by Sensit Technologies (Valparaiso, Ind.; www.gasleaksensors.com) under license from Gas Technology Institute (GTI, Des Plaines, Ill.; gastechnology.org.). GTI says the technology is expected to save industry millions of dollars by helping to reduce the damage to buried pipes.

The device, which uses acoustic technology, can detect metallic and non-metallic pipes (including plastic) , says Kiran Kothari, program manager for GTI. In tests, it has located small-diameter pipe at depths up to 5 ft in various ground conditions, including concrete, tar and grassy soil.

'New' F-T technology

Three engineering contractors — CB&I Lummus UK Ltd., Jacobs Engineering Group Inc., and The Shaw Group — have been selected to promote the commercialization of a fixed-bed Fischer-Tropsch (F-T) process developed by BP (www.bp.com)

(*Continues on p. 12*)

Note: For more information, circle the 3-digit number on p. 62, or use the website designation.

A new way to grow functional MOFs

A team from CSIRO Materials Science and Engineering (Melbourne, Australia; www.csiro.au) has developed a new technique for growing smart materials known as metal-organic frameworks (MOFs), which can be used in pollution control, or as catalysts, or for transporting drugs in the human body. MOFs are well-ordered ultra-porous crystals that form multi-dimensional structures with huge surface areas. One gram of the material can have a surface area of thousands of square meters.

For MOF-based device fabrication, well-patterned MOF growth is required, and therefore conventional synthetic methods are not suitable. The team used a technique known as seeding. It discovered that the MOF crystals grow in a completely ordered way through the introduction of ceramic spherical microparticles — nanostructured poly-hydrate zinc phosphate (α-hopeite). It used a surfactant (Pluronic F127) to optimize a one-pot synthesis to grow MOFs.

Due to their similarity to the desert rose mineral, the team called those hopeite microparticles desert rose microparticles ("DRMs"). The DRMs are used as seeds for growing MOFs in solution on any flat surface and on complex 2D or 3D surface shapes. Also, the introduction of active species directly into the framework via the α-hopeite microparticles permits functionalization solely within the framework core, and not on its outer surface. The team's method allows unprecedented spatial control. It allows for the MOF shell to behave as a molecular sieve for the encapsulated functional species — for example, metal, polymer or semiconductor — within MOFs.

"The successful coupling of the sieving effect of the MOF matrix and the preserved functionality of the embedded species opens up a new route for the development of a future generation of microreactors for selective sensing and catalysis," the team says.

Also, the team says the DRMs enhance the growth rate of the framework by a factor of three compared with conventional solvothermal synthesis. "We have found that we can add nanoparticles to the seed that make MOFs magnetic, luminescent, catalytic or photochromic, all without compromising the quality of the MOF structure," the team says. CSIRO has applied for a patent on the technique.

Low-cost process for bioethanol fuel demonstrated in Japan

Mitsubishi Heavy Industries Ltd. (MHI; Tokyo, www.mhi.co.jp) says it has established technology to produce bioethanol for automobile use by using soft-cellulose, such as wheat straw and rice straw, as raw materials. MHI estimates the fuel cost for a full-scale production plant — accounting for the costs of feed material and its collection and transportation, as well as bioethanol production costs — to be less than ¥90/L ($0.90/L). This cost meets the specifications of the Society of Automotive Engineers of Japan (JASO). MHI plans to apply its achievement to realize bio-refinery technology producing chemicals using plant raw materials.

On this achievement, MHI collaborated with Hakutsuru Sake Brewing Co. (Kobe, www.hakutsuru.co.jp) and Kansai Chemical Engineering Co. (KCE; Amagasaki, both Japan; www.kce.co.jp). MHI developed a pretreatment process and a saccharification process, which uses a continuous hydrothermal treatment process to make the raw materials for sugar using only enzymes and hot water. MHI demonstrated the stability of the continuous operation, and optimization of the enzyme addition. In collaboration with Kobe University, Hakutsuru established the yeast-breeding technology to convert the wheat- and rice-straw-based sugars into ethanol in the fermentation process, without using genetic engineering. KCE developed and demonstrated the long-term, continuous operation of a new type of distillation column, and a liquid-phase adsorption-type dehydration unit that enables processing with less energy than existing gas-phase types.

After demonstrating the individual unit operations at the three companies, the entire process was combined at the MHI Futami Factory, which has been operating since December 2009. The Agricultural Association (Hyogo Prefecture, Japan) supplied straw of wheat and rice for this project, and also demonstrated the effective collection, transportation and storage technology of raw materials.

(*Continued from p. 11*)

and Davy Process Technology Ltd. (DPT; both London, U.K.; www.davyprotech.com). The BP/Davy process, which converts synthesis gas (syngas) into liquid hydrocarbons for producing diesel and jet fuel and naptha, has been demonstrated in a 300-bbl/d complex in Nikiski, Alaska (see *CE*, May 2004, pp. 23–27). The process is now available for license to third parties.

Meanwhile, GTL.F1 AG (Zurich, Switzerland) — a joint venture of Lurgi GmbH (Frankfurt, Germany; www.lurgi.com), PetroSA (Cape Town, South Africa; www.petrosa.co.za) and Statoil (Stavanger, Norway; www.statoil.com) — has started a new phase directed at licensing, engineering and commercial operations of its proprietary F-T technology. The process was developed in the laboratories of Statoil, then demonstrated in a 1,000-bbl/d semi-commercial plant at PetroSA's Mossel Bay Refinery, South Africa (*CE*, July 2002, p. 19). Having completed the development phase, Statoil has withdrawn from the GTL.F1 partnership.

Cellulosic biobutanol

Cobalt Technologies (Mountain View, Calif; www.cobalttech.com) and American Process Inc. (API; Atlanta, Ga.; www.americanprocess.com) have agreed to build the world's first industrial-scale cellulosic biorefinery to produce biobutanol. Under the agreement, the two companies will integrate Cobalt's patent-pending continuous fermentation and distillation technology into API's Alpena Biorefinery, currently under construction in Alpena, Mich. Slated to begin ethanol production in early 2012 with a switch to biobutanol in mid 2012, the API Alpena Biorefinery will produce 470,000 gal/yr of biobutanol, which will be pre-sold to chemical industry partners.

GreenPower+ is an API patent-pending proprietary process for extracting hemicelluloses sugars from woody biomass using steam or hot water and converting them to fermentable sugars. The ex-

(*Continues on p. 14*)

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Commercial production of 'Bio-cokes'

Last month, construction was completed on the world's first commercial plant to produce a next-generation solid fuel, called Bio-cokes, at Takatsuki, Japan. The renewable material is produced from forest residues and can be used as an alternative to coal-based coke in blast furnaces and as fuel for power-plant boilers and incinerators. It can also be produced from other biomass, such as waste tea leaves and algae.

The plant, owned by the Osaka Prefecture Forest Owners Assn. (OFA; Osaka, Japan; www.o-forest.org), is expected to start up this month and will produce 600–800 ton/yr in a demonstration reactor. OFA plans full-scale production of Bio-cokes (1,800 ton/yr) by April 2012. The OFA plant is the first commercial application of technology developed by Tamio Ida, an associate professor at Kinki University (East Osaka City, www.kindai.ac.jp). The conversion of forestry residues to coke takes place in cylindrical reactors at 180°C, with nearly 100% yield. The OFA plant is composed of 36 reactor vessels.

Lightweight diamond aerogel

Researchers at Lawrence Livermore National Laboratory (LLNL; Livermore, Calif.; www.llnl.gov) have created a nanocrystalline diamond aerogel. The new aerogel was produced by compressing a standard carbon-based aerogel precursor in a laser-heated diamond anvil cell, which consists of two opposing diamonds. LLNL has used this device to recreate the extreme pressures found deep inside planets.

The precursor was infused with neon to prevent the aerogel from collapsing on itself, then it was subjected to pressures above 200,000 atm at more than 2,240°F. This forced the carbon atoms to shift their arrangement and create crystalline diamonds that have a density of only about 40 mg/cm^3. LLNL says the diamond aerogel could have applications in antireflective coatings for lenses and other optical devices.

Improved solvent extraction for nuclear-waste-contaminated water

Japan Atomic Energy Agency (JAEA; Ibaraki, www.jaea.go.jp) has enhanced the efficiency of a solvent-extraction process to separate organic solvents from water contaminated by radioactive waste. JAEA was able to reduce the toluene concentration from 5,000 parts per million (ppm) to below 10 ppm, which is below the regulation limit of 20 ppm, and better than the 50 ppm achieved by conventional solvent extraction methods. In a demonstration unit processing 200 L/h, the extraction process achieves a 70% recovery of radioactive uranium from wastewater generated at the centrifugal machine for uranium enrichment at Ningyo-toge Environmental Engineering Center of JAEA.

JAEA has not tested the process on radiation-contaminated water because permission to do so requires permission of and authorization by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). However, JAEA believes the technology could be applied to the low-level, radiation-contaminated water that is being generated at Fukushima 1st Atomic Power Plant, and plans to demonstrate industrial applications within two years.

Rubber manufacturing process allows in-mold curing

Along with an innovative elastomeric compound, scientists at Federal Mogul Corp. (Southfield, Mich; www.federalmogul.com) have developed a rubber manufacturing process that eliminates the need for curing in a batch oven after molding. The proprietary compound, known as K16, is intended for use in dynamic sealing applications, especially in automotive transmissions. Following a series of studies aimed at establishing a detailed understanding of the compound's cure chemistry, Federal Mogul developed a process-control strategy that manages variations in polymer cross-linking that would normally take place in a batch oven. The polymer chemistry and molding conditions allow full curing of the rubber while in the mold and produce the correct elastic properties. The streamlined manufacturing process reduces energy consumption and production time, and eliminates the need to transport material to the oven.

(*Continued from p. 12*)

tracted biomass is returned to the biomass boiler for the production of steam or electricity (or both), while sugars are converted to final bio-products.

In Cobalt's process, sugars are converted to *n*-butanol in a continuous fermentation process, whereby bacteria in biofilms are used (instead of engineered yeasts) in a bioreactor similar to that used for wastewater treatment. A process involving both distillation and phase separation is used to purify the *n*-butanol (*CE*, May 2010, pp. 25–29).

Diamond electrodes

Advanced Diamond Technologies, Inc. (ADT; Romeoville, Ill.; www.thindiamond.com) has commercialized electrodes that have the potential to reduce electrochemical-based water-treatment costs by a factor of ten. ADT has entered into a distribution agreement with Klaris Corp. (Calgary, Alta, Canada; www.klaris.ca) to promote and support the implementation of the technology worldwide.

The so-called UNCD Electrodes are based on boron-doped ultrananocrystalline diamond (UNCD) thin films deposited on niobium and tantalum substrates. The electrodes take advantage of the properties of diamond to improve lifetimes and enable high current densities for generation of strong oxidizers, such as ozone, as well as imparting high chemical stability and resistance to fouling and scaling.

Nano IR spectroscopy

Researchers from the Basque nanoscience research Center CIC nanoGune (San Sebastián, Spain; www.nanogune.eu) and Neaspec GmbH (Martinsried, Germany; www.neaspec.com) have developed an instrument for recording infrared (IR) spectra at a spatial resolution that is 100 times better than that in conventional IR spectroscopy. The technique could be applied to analyze the local chemical composition and structure of nanoscale materials.

The technique is based

(*Continues on p. 16*)

CO_2-capture technologies move ahead

Scaleup is set for two technologies that facilitate the capture of carbon dioxide from fluegas by substituting oxygen for combustion air. Oxycombustion, as it is called, results in a much smaller fluegas stream, containing up to 90% CO_2; part of that is recycled to dilute the O_2 and control the combustion temperature. The O_2 is entrained in the CO_2 stream for injection into the furnace. The companies developing the two technologies are Air Liquide (Paris; www.airliquide.com) and Air Products (Allentown, Pa.; www.airproducts.com).

In the case of Air Liquide, a pilot plant is scheduled to start up at year-end in partnership with Australia's Callide Oxyfuel Services, an electricity producer. The pilot unit will produce about 75 ton/d of CO_2 from a slipstream in Callide's 100-MW_{th} coal-fired power plant near Biloela, Queensland, says Dennis Vauk, a senior international expert for the energy market with Air Liquide in Houston, Tex. The CO_2 will be purified and compressed onsite and the liquid CO_2 will be shipped for sequestration. Vauk notes that Air Liquide is also working on what is expected to be the world's first full-scale oxycombustion demonstration plant as part of the FutureGen 2.0 project of the U.S. Dept. of Energy (Washington, D.C.; www.energy.gov).

A three-year demonstration of Air Products' oxycombustion technology was inaugurated in May at Vattenfall AB's R&D facility in Schwarze Pumpe, Germany. Air Products will take fluegas directly from Vattenfall's 30-MW wall-fired boiler and purify and compress it, using a proprietary staged-compression process that is said to allow cost savings in the combustion process and minimize the concentration of acidic components. Vattenfall started up the pilot plant for CO_2-capture in 1968. It was initially used for a three-year trial of an oxycombustion process developed by Alstom (Paris; www.alstom.com).

Meanwhile, Metso Corp. (Helsinki; www.metso.com) and Fortum Corp. (Espoo, Finland; www.fortum.com) have completed an oxyfuel combustion test of approximately one year on a 4-MW circulating fluidized bed (CFB) boiler at Metso's test plant in Tampere, Finland. The technology was developed jointly by the two companies and represents the world's biggest known oxycombustion process based on CFB technology, according to Metso.

Modifying the plant for oxyfuel combustion "has been challenging, and we are pleased with what we have achieved," says Jussi Mantyhniemi, general manager, technology for Metso's power business line. An advantage of CFB technology, he adds, is that "coal and biomass can be co-fired, thereby turning the power plant into a carbon sink," (For more details on CO_2 capture, including oxycombustion, see *CE,* December 2008, pp 16–20, and October 2008, p. 14).

A platinum-free fuel-cell catalyst

A research team from Los Alamos National Laboratory (Los Alamos, N.M.; www.lanl.gov) has developed a novel catalyst for the cathode of a fuel cell that avoids using expensive ($1,800/oz.) platinum metal. The cathode catalyst is on based carbon, partially derived from polyaniline, and uses iron and cobalt metal instead of relying on platinum. The researchers found that fuel cells containing the catalyst generated currents comparable to those in a Pt-containing fuel cell, and held up to repeated on-off cycles. The catalyst also demonstrated efficient conversion of fuel to water, and represents a potential route around one of the major cost barriers to widespread use of H_2 fuel cells. The catalyst is described in a recent issue of the journal *Science*.

A comprehensive zeolite database

A team led by Rice University (Houston; www.rice.edu) researcher Michael Deem has assembled a database of 2.6 million possible unique zeolites — porous silicate minerals often used as catalysts or molecular sieves. The database of potential structures could inform efforts to synthesize new zeolites. Although there are about 50 naturally occurring zeolites and well over a hundred human-made varieties, the database — which contains structural data for all physically possible zeolites — expands the untapped diversity of artificial zeolite varieties.

Over the past four years, Deem and colleagues have used computational methods to calculate every conceivable atomic arrangement for the structures, and have developed tools to examine and compare the would-be chemical and physical properties of each variety. The publicly available database contains information such as x-ray diffraction patterns, dielectric constants and ring-size distributions (for more on databases, see p. 17). ■

(*Continued from p. 14*)

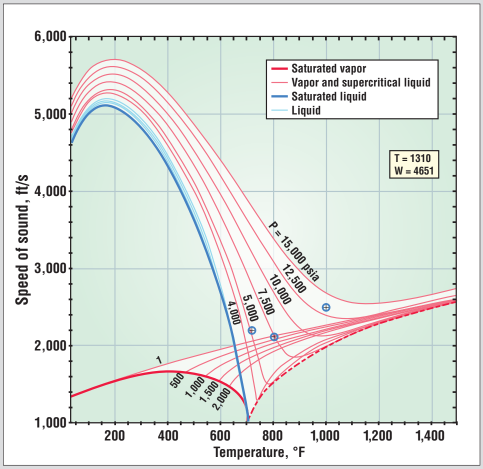
on a scattering-type, near-field microscope that uses a sharp metallic tip to scan the topography of a sample surface. A thermal source illuminates the tip with IR radiation, which is then scattered from a very small spot on the surface. The scattered IR light is then analyzed by a Fourier-transform IR spectrometer, which gives spectral information of the nano-scale sample volume.

Bio-jet fuel

Last month, Gevo, Inc. (Englewood, Col.; www.gevo.com) signed an engineering and consulting agreement with Mustang Engineering, LP (Houston, Tex.; www.mustangeng.com) to convert Gevo's renewable isobutanol to bio-jet fuel. The effort will focus on the downstream processing of isobutanol to paraffinic kerosene for jet-engine testing, airline-suitability flights and advancing commercialization. ❐

INFORMATION GETS DYNAMIC

Enhanced chemical information tools help CPI engineers manage ever-increasing volume and tightening work demands



Source: Knovel

FIGURE 1. Information resources, such as Knovel, allow users to manipulate data of the kind that at one time were static, and adapt that data to their own engineering problem

As engineers in the chemical process industries (CPI) are pressed harder to meet deadlines in the workplace, the amount of information available to them in their field is growing at an exponential pace. To address the situation, chemistry- and engineering-oriented information resources are developing tools and systems that offer opportunities to process information more efficiently and interact with available information more effectively.

Among the tools becoming available and becoming more widely used are those for enhanced search capabilities, those for refining search results, and those enabling direct interaction with, and sharing of, data. To a greater extent than ever before, the capabilities of information resources for CPI workers emphasize how the information is used once it is located. Tools now make it easier to adapt data directly to apply it to a specific problem relevant to the searcher, as well as make it easier to share information with coworkers.

As information resource platforms evolve, changes in the way engineers in the CPI work are occurring in parallel, and the changing needs of engineers are having a significant influence on what capabilities are offered by information resources. Added into an already complex interplay is the maturation of wider technological trends, such as social networking, community forums and web-enabled mobile devices. The result of the convergence seems to be an ever-richer environment for chemical engineers to access and use available chemistry-related information. The improved set of tools can help address the increased pressure felt by CPI professionals to conduct comprehensive information-based research in a timely fashion.

Many factors drive demand

Because of its global nature and strict time demands, modern engineering work places a heavier burden on information resources. To a large extent, today's CPI is characterized by geographically dispersed corporate structures and leaner, less specialized engineering teams. The result is that interdisciplinary know-how becomes a premium, and training and knowledge transfer become more important. In addition, the ability to effectively communicate, collaborate and share information across continents and time zones becomes critical to success. Meanwhile, engineering teams are under greater time constraints than ever before, and the pressure to rapidly find correct answers on project-related questions is equally high.

The situation is rendering information resources indispensable, and the developers and curators of such products are answering with a fundamental focus on quality. Although centralized databases of computerized chemical information are important, and the ability to parse a torrent of available information is equally so, access to them means little without quality.

"The integrity of the data contained in a database is of utmost importance to engineers," says Shandon Quinn, director of market development for chemicals at global scientific publisher Elsevier Inc. (Amsterdam; www.elsevierchem.com), owner of the information platform Engineering Village (EV; www.engineeringvillage2.com). The subscription-based service hosts a number databases, including bibliographic databases, European and U.S. patent databases, news and others, making it a "one-stop shop" for several different types of useful content. One key area of emphasis for EV has been information quality. The EV team operates a content management system in which information sources are continually scrutinized to ensure that the highest-quality information is included, Quinn comments.

Organizers of other resources place information quality as a high priority as well, and have set up systems of their own to select the highest quality data. For example, Knovel (New York; www.knovel.com), operator of a Web-based application of the same name that integrates technical information with analytical and search tools to aid in problem solving, maintains an editorial advisory board to pre-validate information for its customers, and to guide content additions. The subscription-based content aggregator and search engine allows users to gain access to engineering reference content sourced from professional societies, publishers and authors. Knovel offers access to a mosaic of different types of information, from material data sheets and technical references to interactive

MAKING CHEMISTRY-SPECIFIC USE OF THE SEMANTIC WEB

In coming years, it is likely that the volume of information available through the Internet will continue to grow unabated. Because of this, more powerful tools will be required for processing this information and extracting useful items for a given searcher. Future Internet-based searching will increasingly have access to artificial intelligence systems that are capable of absorbing the meaning from textual language, rather than just identifying keywords.

The Semantic Web is a term that describes what many see as a part of the Internet's next evolutionary step. The term refers to a virtual data network that enables machines to understand the meanings of language in Web-based information. The Semantic Web extends the network of human-readable Web pages by adding machine-readable metadata (descriptors of the content and context of data files) about Web pages and how they are related to each other. This enables automated agents to access the Web more intelligently and perform tasks on behalf of human users.

Much effort is being devoted to emerging tools across many fronts, and chemistry is among them. Peter Murray-Rust, professor at the University of Cambridge (Cambridge, U.K.; www.ch.cam.ac.uk) is one of a cadre of researchers interested in the future of chemical informatics. Murray-Rust has developed Oscar (Open-Source Chemistry Analysis Routines), a software tool that is designed for the semantic annotation of chemistry documents and papers. The software package allows chemistry-specific parsing of documents — identifying chemical names, formulas, acronyms, as well as ontology terms and chemical data, such as spectra, and other experimental data.

Murray-Rust treats chemistry as a language that is communicated not only through natural language, but through formulas, equations and graphics. Oscar can recognize names in text and is able to link them to their meaning through their ontological relationships. Key to the software is its ability to process natural language and discern the context in which chemistry-related words are used. The tool, which can be downloaded and tested for free, could save time and effort in research and data gathering by better filtering out only the most relevant hits, while ensuring that nothing with an equivalent, but different name, gets missed

The idea is to automate the extraction of knowledge from text for later use by machines, or to give human searchers additional information about the text, such as whether the author of a given paper agrees with a previous publication, or is criticizing it. Murray-Rust and colleagues are trying to combine "shallow," fast-processing approaches that can identify parts of speech (deciding that a word is used as a verb or a noun in a sentence), with "deeper" systems that require more processing time, but that can decipher more meaning, such as using context to decide whether a phrase is meant literally or idiomatically. The combination would allow the processing-heavy system to be used only on text that has been identified as interesting by a faster-running shallow system. Murray-Rust is working on trying to incorporate a method to automatically discover information about the meaning of chemistry terms into his chemistry search tool. ❏

tables and conference proceedings.

Chemical Abstracts Service (CAS; Columbus, Ohio; www.cas.org), a division of the American Chemical Society (ACS; Washington, D.C.; www.acs.org), also devotes considerable attention to information quality. The world's largest collection of chemical information, CAS employs a dedicated editorial staff to curate the content found in CAS databases to ensure its reliability and quality. "The volume of available information is huge, and part of that is of poor quality," says Kirk Schwall, CAS director of SciFinder product development. "Our challenge is to make sure that we are offering the most reliable peer-reviewed information, and nothing else."

Aside from ensuring data quality, providers of information resources are also focused on several other capabilities in the tools that they offer. One of these capabilities is rendering data and information interactive, to enhance their value for users. Another capability is optimizing searching specifically for engineers to make research more efficient and productive. Other aspects of providing content that information resources view as important are extending a tool's reach to mobile data platforms, such as Web-enabled mobile devices, and continuing to make additional content available in areas of current interest to chemical engineers. Knovel founder and chemical engineer Sasha Gurke notes that to meet demand from users, his company has made additional content available in areas such as nanotechnology, process automation and control, alternative energy and sustainability.

Optimizing search for engineers

A major push to improve information tools in chemistry-related fields has been to optimize search capabilities specifically for the needs of chemical engineers and research and development personnel. "Google only retrieves publicly available information, so it misses some premium providers of information" such as professional groups, publishers and authors, explains Knovel's Gurke. Also, chemical engineers require databases with chemistry-specific search capabilities.

"Considering the time constraints experienced by most working engineers, the precision of search is critical," adds Elsevier's Quinn, "but there remains a pressing need to produce comprehensive results at the same time, so that engineers are confident that they are not missing anything important to their project."

Elsevier's Engineering Village is an example of an information resource that has adopted this approach. The Web-based information services platform hosts a number of interoperable databases specifically targeted toward engineering disciplines. EV concentrates considerable effort on establishing and maintaining "controlled vocabularies" that standardize engineering terminology so that indexing is more efficient, and information is better organized for users. For example, some sources might use the term "biopolymers," while others, meaning the same thing, might use "bioplastics." EV's controlled vocabularies index positions the terms in a way that allows searches return as many relevant records as possible.

"Today's engineering work is more interdisciplinary than it has been in the past," comments Elsevier's Quinn. "So there is a greater need to understand terminology across a number of fields, and that's a big reason why the standardized indexing is so useful."

Other features aimed at improving searches for chemistry provide alter-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the Italian Design
in the world
Pompetravaini,
with the new liquid ring,
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TRVX series, sets new limits:
Halved overall dimension,
30% less weight and plus
10% performance.
Who can offer You more?
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Our commitment is always to stay ahead
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Chemvac Pumps
pompetravaini spa
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Ph. +39.0331.889000 • Fax +39.0331.889057
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natives to keyword searching, which may not always be the most useful method for searching in chemical engineering and other chemistry-heavy disciplines. In many cases, it may be more successful to search by chemical structure, or by reaction pathway, for example. On Knovel's platform, users can search numerically, and will soon have the ability to search for mathematical equations. CAS has introduced functionality to its platform that allows users to search for Markush structures (generalized formulas for a set of related compounds). It will allow searchers to identify a family of chemical compounds that share a common chemical backbone, for example, but may differ by a side chain. EV also has a search function that goes beyond keywords, allowing chemical structures and reactions to be search subjects.

Faceting of search results is another key consideration. Faceting refers to the dynamic clustering of search results into categories that allow users to drill into specific areas of interest while easily excluding those areas that are not relevant to a particular search. This month, Knovel will launch a newly revised platform with faceted search results as a major feature. It will allow users to view and filter search results by content type. EV also focuses on faceting as a quick and useful way to refine search results into a manageable set of highly relevant results.

Allowing interactivity

Aside from making it easier to locate and organize items of interest, information resource-tool suppliers are trying hard to give the search results more value by introducing the ability to interact directly with the data and information. Summarizing the philosophy, Knovel director of marketing Diana Bittern says, "We give Knovel users the ability to connect to information in a way that's most meaningful to them, and then interact with it to create additional value for them."

Knovel enlivens reference data by introducing interactivity and allowing engineers to manipulate data — such as graphs, equations and tables — and incorporate them into their work though programs like Microsoft Excel or PTC's Mathcad. For example, users can interpolate a plot, or adapt an equation for use in their own situation.

Knovel's Gurke says that recently there has been a need to combine data with calculations software. For example, after finding a useful calculation example, Knovel users can design directly on the platform with Knovel Math software, allowing them to obtain a validated solution right away.

Further, Knovel gives users personalized access to a shared workplace, where they can work interactively and dynamically with content that, in the past, would have been static in a book or other printed publication, explains Bittern.

CAS recently launched a new tool that also facilitates interactive work. Since 1995, CAS has offered chemical researchers and industry professionals SciFinder, a single-source platform for a wide range of chemistry-related databases. Now, a newly launched feature, called SciPlanner, has been added. SciPlanner is an interactive workspace that represents a new way for scientists and engineers to more quickly identify synthesis options for designing reaction pathways and approaches. The feature also helps to organize results and manage data. SciPlanner's interactivity is a key feature, with a live, virtual whiteboard — a kind of "smartboard" system — that enables work to be subsequently shared with colleagues.

Among SciFinder's features are the ability to sort reference search results by citation count, to identify influential authors by the level of citation, and the ability to copy and paste drawn chemical structures directly into the SciFinder structure-drawing editor to save time. A version of SciFinder that is compatible with Web-enabled mobile devices is also available.

Peer connections

Mobile applications are only one of a host of developments that are poised to become more widely used in the CPI space, as they are in other sectors. Examples are crowd-sourcing, social networking and community-editable Web pages (wikis), which are the types of elements supported by community forums. A prominent one for the chemical engineering community is CheResources.com. The platform offers tools of a more organic kind, such as those for when chemical engineers look for direct interaction with peers, rather than with databases. CheResources.com has built a strong following with a core group of experienced engineers who relate experiences and advice.

"We offer high-quality advice from experienced engineers on real problems," says Chris Haslego, founder and community manager of the site. The Website has been transitioning from a more static, article-driven site in the past to a more community-driven format, where blogs, question-and-answers, and postings make up most of the new activity. "We're moving to a Website that is much more dynamic," says Haslego.

"Our next challenge revolves around downloads and mobile applications," he adds. The site has recently introduced a download section, where members can download and use spreadsheets that have been developed by others, saving time for engineers, Haslego explains further. Interactivity is the key, because they can adapt the spreadsheets to their own problems. ■

Scott Jenkins

COLUMN INTERNALS: THE NEXT BIG THING

New technologies boost capacity and efficiency of distillation trays and packings

When it comes to distillation trays and packing, chemical processors require the same criteria they seek from all equipment in this tight economy — technology that will reduce energy use and boost throughput without costly facility expansion. In an effort to meet these needs, tray and packing specialists are improving existing technologies and launching a whole new generation of trays designed to double existing capacity.

"A main concern for processors is the energy efficiency of their plants. Because distillation represents a substantial amount of the total energy consumed, reducing energy use is a key issue," says Christoph Ender, vice president sales for U.S. and Latin America and the global marketing and business development leader with Koch-Glitsch, LP (Wichita, Kan.). "This is also important from an environmental point of view in that CO_2 taxes are going to be applied in many areas around the world, so any reduction of fossil fuel consumption also reduces the tax liability of the plant."

Mark Pilling, manager of technology with Sulzer Chemtech (Tulsa, Okla.), agrees. "Our customers are very cost conscious, so pressure drop is a big driving force because it affects the energy use and operating costs of system components. Developing devices with lower pressure drop is important because distillation towers are massive, so small savings in pressure drop can result in millions of dollars saved over the life of a project."

In addition to reducing energy, today's competitive environment has processors on a quest to get more capacity out of existing towers. "Increasing throughput is a factor in many industries where it is desired to increase the economics of the plant with minimal investment," notes Koch-Glitsch's Ender. He says this is especially true in the U.S. and Western Europe, which have to compete with modern, large-scale plants in the Middle East and Far East. "These plants must stay competitive, so increased throughput at minimal cost plays an important role."

Increased capacity is especially important in the natural gas processing industry and in petroleum refineries. As the price of oil hits record highs, the U.S. natural gas processing industry, which provides a less expensive and cleaner energy source, is currently booming. "The U.S. natural gas industry is investing heavily in new plants, but many are also upgrading existing plants, including investing in new distillation technologies that can provide cost-effective capacity increases," says Neil A. Sandford, tray product manager with Koch-Glitsch.

U.S. petroleum refineries, too, find themselves scrambling to add capacity to existing facilities. "Refineries desperately need more throughput from their processes," says Mike Resetarits, technical director with Fractionation Research, Inc. (FRI; Stillwater, Okla.), a non-profit research consortium supported by memberships, which include the largest petroleum and petrochemical companies in the world. "Environmental regulations have forbid the building of any new refineries in the U.S. However, the population has grown and everyone is still driving, so the gasoline consumption in the U.S. has doubled. This means refineries have to squeeze more and more out of the existing processes, so they desperately seek new technologies to help them do this."

Sulzer Chemtech.

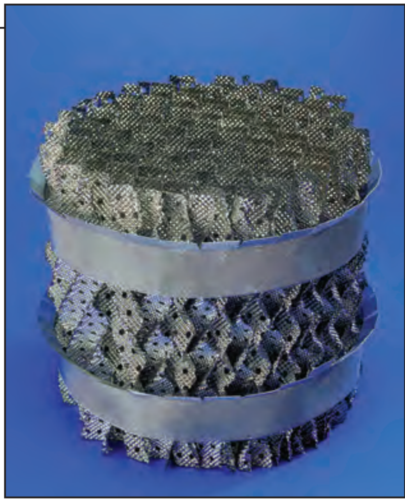


FIGURE 1. This high-capacity, enhanced structured packing offers new geometric features that reduce the likelihood of premature flooding at the interface

Improved packing designs

While the technology behind today's trays and packings has been around for quite a while, vendors are making design changes that help processors reduce energy consumption while increasing throughput.

Sulzer Chemtech has been working to optimize its structured packing designs. What they have developed is a device that can provide the same efficiency at a lower pressure drop. "With our new devices, we can save as much as 40% on pressure drop across the tower and, over the course of a lifetime in a big plant, that can add up to millions of dollars saved," says Pilling.

Sulzer's MellapakPlus, touted as a new generation of structured packing, is a capacity-enhanced structured packing that combines metal sheet packing with new geometrical features. The S-shaped design allows vapor flow to smoothly change direction at the interface between two packing elements. At the interface, vapor flow is nearly parallel to the vertical axis of the column. The gas velocity is therefore reduced by about 25% compared to the velocity inside the packing element. Both factors combine to reduce the pressure drop and the shear forces, which are especially critical at the interface due to the presence of thicker and less-stable liquid films. As a result, premature flooding at the interface is not a concern.

Shell Global Solutions.

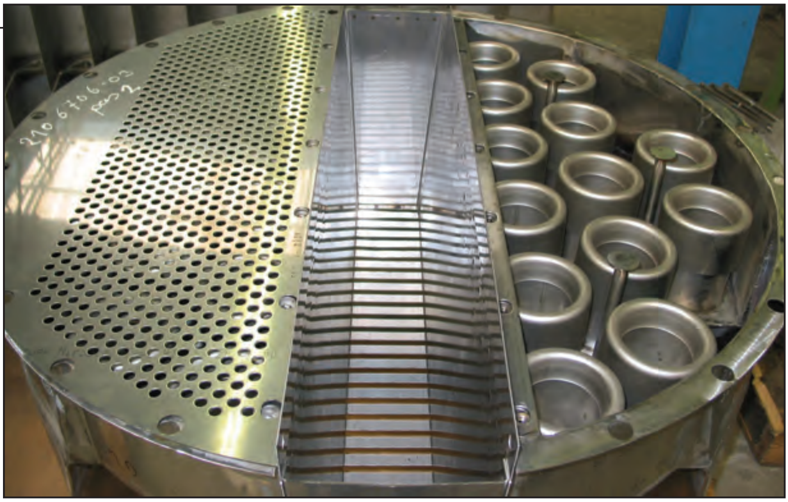


FIGURE 2. Shell's ConSep tray layout was tested at FRI. The sieve deck has been removed on the right hand side of the center downcomer to reveal the separation deck of the tray below. The contacting tray layout is two-pass, using truncated downcomers

In the interior part of the packing element, the geometrical features of MellapakPlus and the previous version of Mellapak are identical. So, separation efficiency is similar, but MellapakPlus boasts a significant increase in capacity and a reduction in pressure drop.

For refineries that are extracting more fuel out of oil, the internals in the columns that handle the "bottom of the barrel" are subject to severe fouling. For these applications, a new grid-type product with increased fouling resistance has been introduced by Koch-Glitsch. The company's high-performance severe-service grid packing combines the efficiency of structured packing with the robustness and fouling resistance of grid packing. This packing is a rugged assembly of rods welded to sturdy corrugated sheets. This combination provides a robust design that resists damage that would otherwise result from tower upset or erosion. The gaps between the sheets provide improved fouling resistance.

For other heavy service industries, Jaeger (Houston) is offering the Raschig Super-Ring heavy-duty random packing. The alternating wave structure has produced a shape that is open on all sides and provides a large number of contact points for homogeneous distribution of liquid and gas. The Raschig Super-Ring has more than 30% greater load capacity, an almost 70% lower pressure drop and a mass-transfer efficiency exceeding that of conventional metal packing by over 10%.

Amistco (Alvin, Tex.) also offers a high performance packing that combines the performance of saddle and ring styles. The unique shape permits low liquid holdup and low pressure drop, while the external geometry prevents interlocking or entangling, ensuring randomness and optimum surface area within the packed bed. Internal fingers, arches and vanes promote optimum interfacial gas-liquid contact with minimal drag or holdup.

DISTILLATION TRAY AND PACKING PROVIDERS:

Amistco	www.amistco.com
Jaeger	www.jaeger.com
Koch-Glitsch	www.koch-glitsch.com
Shell Global Solutions	www.shell.com/globalsolutions
Sulzer Chemtech	www.sulzerchemtech.com
UOP	www.uop.com

Next generation trays

Likewise, trays are becoming more energy efficient and providing higher capacities. New high efficiency tray designs are allowing better management of liquid and vapor flow across the tray to extract the maximum efficiency.

For instance, Koch-Glitsch's SuperFrac high-performance trays offer capacity expansion capabilities for existing vessels. SuperFrac tray is a crossflow device that can be used in new construction or revamps to achieve higher capacities and improve efficiency. They are especially suitable

Koch-Glitsch

FIGURE 3. Intalox Ultra random packing provides low pressure drop, high capacity and increased efficiency in applications such as acid gas removal, demethanizer/deethanizer, ethylene water quench, sour water strippers and atmospheric- and high-pressure distillation

for applications requiring a large number of mass transfer stages or where mass transfer efficiency is critical to the economics of operation.

But in situations where even the highest performing trays aren't providing enough capacity, several tray vendors have developed what is being called the next generation in tray technology. The newest innovation, the co-current tray, allows vapor and liquid to flow upward together for a short period of time versus "fighting each other," according to FRI's Resetarits. Currently only three U.S. providers offer the technology, including Shell, UOP and Koch-Glitsch. There is one provider in China and one in Japan, says Resetarits.

"While each technology operates on a slightly different principle, they all basically do the same thing, which is to take gravity out of the equation," says Brian Miller, senior account team leader with UOP LLC (Des Plaines, Ill.). "They find a way to get the liquid onto a contacting device and have the liquid and vapor together, flowing up the tower, then separate it so the liquid can drop down to the next device while the vapor continues to flow up the tower."

Waldo de Villiers, distillation specialist with Shell Global Solutions (Houston), which offers ConSep cocurrent trays, explains it like this: "Con-

CAPTURING CARBON WITH TECHNOLOGY

Carbon dioxide absorption is a relatively old technology, but it's getting renewed interest globally as processors attempt to capture more and more CO_2 before it gets into the atmosphere, especially in fluegases, says Mike Resetarits, technical director with Fractionation Research, Inc. "There are new technologies such as absorption solvents that are gaining interest, including ionic fluids that can not only capture CO_2, but also reduce the energy consumed by the regeneration process," he says. "The reason being is that if you have an absorber where you remove CO_2, right next to it you have a regenerator where you regenerate your solvent. The new, superior solvents require less energy from regeneration."

In addition, packing providers are working on technologies that also will help in the environmental effort. One of the first advances is from Sulzer Chemtech. The company has developed a new structured packing for absorbing CO_2 more efficiently from the fluegas stream of fossil-fueled power plants. The Mellapak CC significantly reduces the column size and the pressure drop across the CO_2 absorber, thus reducing capital and operational expenses for the customer. Compared with conventional structured packing, Mellapak CC provides 20% higher efficiency and 20% lower pressure drop, says Dr. Abhilash Menon, global application manager of CO_2 capture with Sulzer Chemtech (Winterthur, Switzerland).

In addition, the company is offering AYPlus DC structured packing for emission avoidance at the top of the CO_2 absorber. "Recently, solvent emissions to the atmosphere from the top of the CO_2 absorber in post-combustion capture has become an important issue. Due to the low vapor pressure of most amine solvents, these emissions are in the low ppm range, which is considered to be too high to meet environmental regulations in Europe," says Menon. "The required make-up water to reduce the solvent emissions substantially is very low. Conventional structured packing shows significantly reduced efficiency under such conditions," he continues. "So Sulzer has developed AYPlus CD, which shows extraordinary wetting characteristics with aqueous media. To handle such low liquids, a special liquid distributor was also developed. This combination drastically increases the separation performance, making it possible to realize 'close to zero' solvent emissions on top of the CO_2 absorber." ❑

Shell Global Solutions.

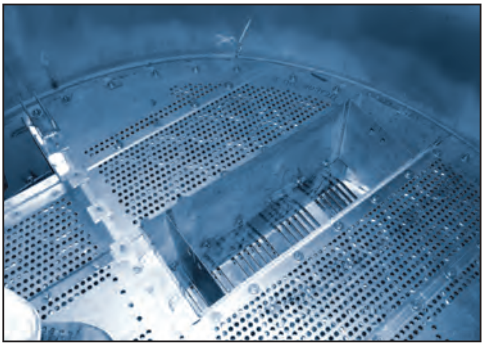


FIGURE 4. A picture taken during the installation of ConSep trays in a Depropanizer. The swirl tubes are visible through the perforations in the sieve deck. ConSep trays are fabricated by Sulzer Chemtech

ventional or high-capacity distillation trays use gravity to separate liquid from vapor. The system limit or ultimate capacity of a column is defined as the vapor load at which a given liquid load would be entrained upwards independent of the column hardware. It therefore represents the maximum capacity of counter flow devices using gravity for separation. Shell ConSep trays are designed to operate beyond the system limit."

Shell's trays combine a conventional contacting deck with a separation deck equipped with swirl tubes. The contacting deck is operated in a flooded mode. The swirl tubes use centrifugal force to separate entrained liquid from vapor. De-entrained liquid is returned to the downcomer of the tray below, thus preserving the overall counter-current operation even though cocurrent flow may exist on the contacting deck.

For traditional trays, flooding can be caused by entrainment or jet-flood limitations, downcomer capacity limitations (choking) or downcomer back-up limitations. In Shell's technology, jet flood limitation is removed as entrained liquid is efficiently separated from vapor and returned as degassed liquid to the downcomer of the contacting tray below. This results in enhanced downcomer capacity compared to downcomers handling aerated froth. Downcomer backup is managed by designing for relatively high open area and the use of low-pressure-drop swirl tubes.

UOP's Simulflow device, developed to alleviate distillation column bottlenecks or to double the capacity of a column containing conventional trays, achieves its capacity increase via simultaneous liquid and vapor

Newsfront

Koch-Glitsch.

FIGURE 5. SuperFrac trays can be used in new construction and revamp opportunities and are beneficial in applications requiring a large number of mass transfer stages or where mass transfer efficiency is critical to the economics of the operation

flow against gravity within a contacting channel and efficient vapor-liquid phase separators. Each stage is comprised of individual linear modules of varying horizontal length to accommodate a circular column area. Each successive stage is rotated by 90 deg in order to ensure uniform fluid distribution throughout the column. These features form a unit cell structure, allowing predictable results at various column diameters (and high confidence).

Similarly, installing Koch-Glitsch's Ultra-Frac trays into existing columns also can provide substantial capacity increases without major capital investment. Functioning as a de-entrainer, the trays provide significantly higher vapor rates without degrading efficiency. And, at low-to-medium liquid rates, the trays exhibit foam suppression capability.

"In general, the capacity advantage we're seeing over conventional high capacity trays is in the neighborhood of 40 to 60% and you can expect to double the capacity you can get if you're using traditional trays," says Miller.

While many facilities are looking hard at the technology because of the significant capacity expansion, it is not yet taking off like wildfire. "Cocurrent technology is something you'd only use in specific circumstances," says Miller. "These devices are not cheap and they can be complicated. Right now, they are typically used as a last resort when the only other option would be to build a new tower and that is either cost or space prohibitive." ■

Joy LePree

Fractionation Column

Hire happy people

So I called my son, Steve, and I asked him, "Which course sounds better to you, 'Dealing with Difficult People' or 'Unacceptable Employee Behavior'?" Steve is a human resources specialist at a 2,000-employee company. He is not a member of the AIChE, but is instead a member of the ACHE, the American College of Healthcare Executives. Proof that the apple does not fall far from the tree? Steve knew that my question to him was mostly a rhetorical one.

FRI technicians in front of test column. From left to right: Kenny Martin, Brad Murphy, Fred Smith, Chad Kindred, Allen Bowers, Kenny Grimes, Terry Thurber, and Joe Rains

Since collecting its first distillation data point in 1954, Fractionation Research, Inc. (FRI; Stillwater, Okla.; www.fri.org) has collected over 25,000 data points — roughly 450 data points per year. FRI started detailed tracking of day-by-day productivity in 2000. In 2010, FRI set a productivity record with 699 data points, and we weren't really trying to set any record. In fact, two years ago, we stopped using "data points per year" as the primary variable whereby we measure ourselves. Instead, we switched to "adherence to annual plan" as the primary productivity measure.

So what happened in 2010? Was FRI blessed by great weather? Absolutely not, the winter of 2010 was the worst in recent memory. So what went well?

Answer No. 1: Better adherence to plans. We focused almost every day on our Annual Plan, as a team — engineers, technicians and administrators all pulling and pushing in the same direction. FRI's 2010 Annual Plan showed five major projects being started and completed, and that is what was done. Additionally, individual projects were better planned. Difficulties were anticipated. Parts were fabricated and equipment pieces were purchased, in advance of project executions, not during project executions.

Answer No. 2: We purposely hired happy people to fill some voids. In fact, our present technician staff is probably the least experienced that FRI has had in many years, but, every day and all day, they smile, work together, communicate completely and enjoy their colleagues and their jobs. That is possibly the way they were born. FRI's management does not need to deal with any so-called "counter-culture" or "difficult people" or "unacceptable employee behavior."

I told Steve that I coined a phrase for myself in 1999: "hire happy people". He told me that many articles and books have been written about the extreme company benefits brought by a satisfied workforce, including doubled productivity, and about making dissatisfied subordinates happier. Less has been written, he said, about starting the process by hiring happy people. He himself, however, has had a sign on his desk for a few years. It reads, "Hire for attitude and train for skills."

That said, I leave you with one more rhetorical question: How would *you* like to have *you* working for *you*? ■

Mike Resetarits
resetarits@fri.org

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

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Flow Profile for Reciprocating Pumps

Reciprocating pumps are often used in the chemical process industries (CPI) because of their ability to generate high pressures at low velocities. A subcategory of positive-displacement pumps, reciprocating pumps act through the reciprocating motion of a piston, plunger or diaphragm. Such pumps work by way of a connecting-rod-and-crank mechanism with a piston.

By nature, reciprocating pumps generate pulsing flow, which, when plotted as a function of time, or of crank angle, produces a curve that resembles a sine wave to a first approximation. For example, manufacturers of pulsation dampeners and surge suppressors often use sinusoidal curves for piston pumps and compressors in their product literature and sizing formulas. However, a closer examination of the flow profile for a piston-and-crank pump or compressor reveals the curve to be a significantly distorted sine wave because of the interaction between the crank and the connecting rod.

Calculating flowrate

In graphical form, the crank and crankshaft of a reciprocating pump can be visualized by placing the crankshaft center at the 90-deg mark of a 180-deg *x*-axis, and placing the crank bearing at the origin (see figure). A connecting rod links the crank to the piston.

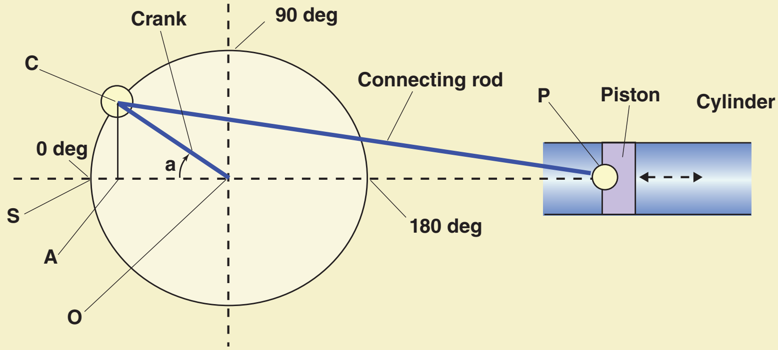
Determining the position of the piston at any crank angle can be accomplished by measuring on a piston pump, compressor, or piston engine, or it can be calculated using trigonometric relationships.

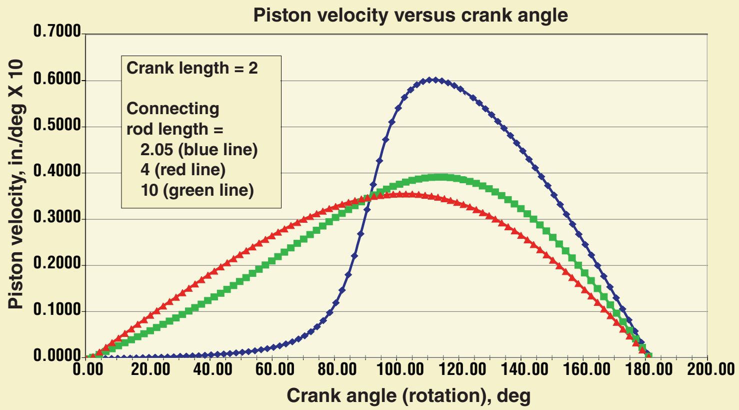
The degree to which the actual flow profile curve deviates from the sinusoidal curve is determined by the ratio of the connecting rod length to the crankshaft length. Smaller values of the ratio translate into greater levels of distortion. As the connecting rod becomes very long, the flow profile would approach the sine curve**.**

To calculate the flowrate at a given crank angle, use the following procedure and definitions:

Crank length = OC
Piston rod length = CP
For any angle a, Line $AC = OC \sin(a)$
Line $SA = OC - OC \cos(a)$
Line $AP = (CP^2 - AC^2)^{0.5}$
Line $SP = AP + SA$

1. Calculate the piston position for two crank angles, perhaps 2 deg apart.
2. The difference in piston positions equals piston displacement over the time interval between the two crank angles. The value is an average over the span of the two readings, not an instantaneous reading. As the step size approaches zero, displacement nears the true velocity.
3. This value can be converted into flowrates (gal/min or other units) if the piston diameter and speed (revolutions per minute, rpm) are known.





Observations of the plot

In an illustrative example, plots of piston velocity versus crank angle are shown (see graph). The ratios of the connecting rod length to crank shaft length are 1.05 to 1 (blue line), 2 to 1 (red line) and 5 to 1 (green line). The following observations can be made:

1. At the beginning of the discharge stroke, flowrate approaches zero asympotically, rather than as a sinusoidal curve
2. Peak flowrates do not occur at the 90-deg point, but rather at 95–120 deg, depending on the ratio of rod length to crank length
3. Peak flowrates are higher than would be predicted with a pure sine curve
4. From 180 to 360 deg (the suction portion of the pump cycle), the curve mirrors the 0-to-180-deg portion
5. Flowrates during the suction portion of the curve are also higher and occur earlier than the 270-deg point

Effects of distorted sine curve

Within the areas of fluid flow and mechanical pump design, there are a number of aspects that are affected by the deviation of flow profile from a perfect sine curve for pumps and compressors. The effects include the following:

- Check valves and passages will have higher-than-predicted peak flowrates and pressure drop will be higher, by the square of flowrate
- The higher flowrates and pressure drops will affect net positive suction head (NPSH) and possibly induce vaporization
- Maximum crank revolutions per minute will be lower than what would be allowed by the pure (non-distorted) sinusoidal curve
- Loads experienced by bearings will increase somewhat, especially in high-speed compressors
- Stress analysis of the connecting rods will be affected
- Surge dampeners must handle the sharper peak of a bell curve, rather than a smoother sine curve
- Multi-piston pumps and compressors would have less "smoothing" effect than would be predicted because the bell-shaped curve has a sharper peak

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Note. Material for this edition of "Facts at Your Fingertips" was contributed by Arthur Krugler, P.E., Krugler Engineering Group Inc., Whittier, Calif. (www.kruglerengineeringgroup.com).

People


Curley


Fenerty


Valore


Roberts


Macklin

Mark Larsen becomes senior vice president of the Hygienic Div. of **Alfa Laval, Inc.** (Kenosha, Wisc.).

Sandmeyer Steel (Philadelphia) names *John Curley III* vice president of international sales and global marketing, and *Shawn Fenerty* vice president of national sales.

Chris Barber becomes vice president of southern operations, distribution & fulfillment for **Intelligrated** (Cincinnati, Ohio), a provider of automated materials-handling systems.

David Jukes becomes president of **Univar Europe** (Brussels).

Kroff Chemical Co. (Pittsburgh), a maker of water- and wastewater-treatment products, names *Timothy Laube* general manager.

Rodney Walker becomes technical director of oil re-refining for **Safety-Kleen** (Plano, Tex.).

Cleveland Vibrator Co. (Cleveland, Ohio) names *Michael Valore* CEO, *Glen Roberts* president, and *Craig Macklin* vice president of strategic development.

AgriLabs (St. Joseph, Mo.), a maker of products for the animal health industry, names *Jim Glassford* vice president of marketing.

Jacques Beaudry-Losique is named vice president of corporate development and strategy for **Codexis, Inc.** (Redwood City, Calif.), a developer of biocatalysts for pharmaceutical, biofuels and other applications. ■

Suzanne Shelley

Measuring Flow

Understanding how flowmeters work and the pros and cons of each type of device can help in selecting the right one

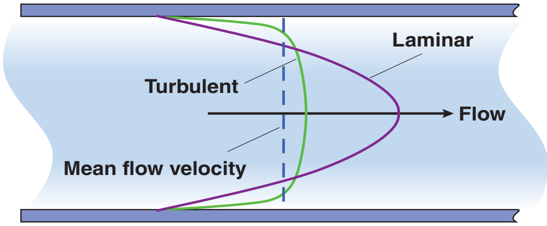


FIGURE 1. In specifying velocity meters, it is important to know if the flow profile of velocities is turbulent or laminar

Ron DiGiacomo
ABB Measurement Products

One of the most important measurements in the chemical process industries (CPI) is rate of flow. Flowrates can be important to measure, and in fact can be critical to measure, throughout a process — from dosing components into a reactor to material transfers in-between process steps, to discharging products at the end. Flow metering technologies fall into four classifications: velocity, inferential, positive displacement and mass. This article summarizes the considerations in selecting and applying these different types of flowmeters, and provides examples of flowmeters in each category.

Velocity meters

Many kinds of flowmeters on the market sense a fluid's average velocity through a pipe. Multiplying the measured average velocity by the cross-sectional area of the meter or pipe results in volumetric flowrates. For example, if the average fluid velocity is 2.5 ft/sec and the inside diameter of the pipe or flowmeter is 12 in. (0.79 ft^2 area), the volumetric flowrate equals 1.98 ft^3/s (2.5 × 0.79) or about 14.8 gal/s.

Laminar and turbulent flow profiles. When specifying velocity meters, chemical engineers must be concerned with the fluid's velocity profile in the pipe, and this profile depends on piping geometry and Reynolds number. Assuming there are sufficient straight-piping runs, the cross-sectional view shown in Figure 1 illustrates two flow-profile situations: turbulent and laminar.

In cases of relatively little piping-friction loss and low fluid viscosity, the flow profile of velocities is uniform across the entire cross-section of the pipe — this is called fully developed turbulent flow. In this case, the fluid velocity at the pipe walls closely matches the fluid velocity at the center and at all points in-between. The velocity at any point is the average velocity. This condition results when the Reynolds number is 10,000 or above. Calculating volumetric flowrates in this flow regime is relatively easy, as noted above.

But, depending on the pipe diameter and the fluid's density, viscosity, and momentum (variables affecting the Reynolds number), the flow velocity within a pipe can vary significantly between the pipe wall and its center. The average velocity through a pipe becomes increasingly difficult to measure precisely when Reynolds numbers are low. For long, straight pipe runs and low Reynolds numbers, the flow velocity would be highest at the pipe's center, and trail off in symmetrical fashion toward the pipe wall. Such conditions are typical of laminar flow profiles.

With an insertion probe flowmeter, engineers can establish the fluid velocities across the diameter of a pipe at multiple cross-sectional locations. By determining the pipe's actual flow profile, and integrating the data to determine the mean flow velocity, they can check on how accurately a flowmeter measures the true flowrate.

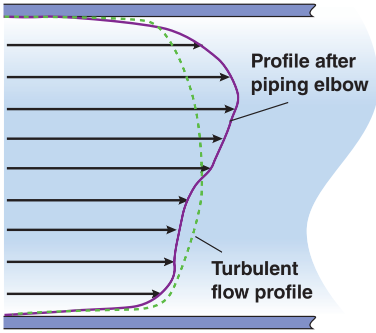
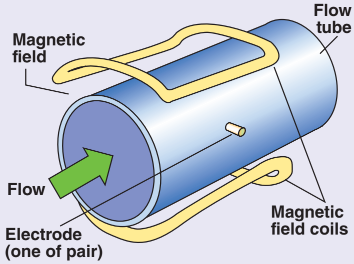


FIGURE 2. Pipe fittings such as elbows, tees and valves will distort the flow profile within a pipe

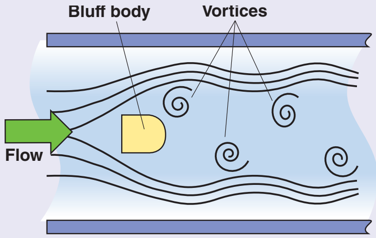
Pipe geometry plays a role. Manufacturers will specify the length of straight pipe upstream and downstream of a velocity flowmeter for achieving high accuracies. But often plant piping geometries in a chemical plant will be such that sufficiently long straight pipe runs are not feasible. The flowmeter may have to be located near an elbow, tee, valve, or change in pipe diameter. In this case the flow will not be fully developed and result in a distorted profile, such as in the example shown in Figure 2. Various flow straightening devices installed upstream of the flowmeter can help correct these distortions by

A SAMPLING OF VELOCITY FLOWMETERS AND THEIR PRINCIPLE OF OPERATION

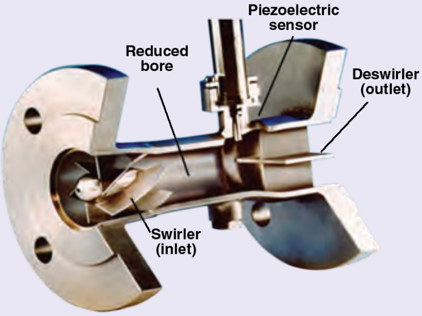
Electromagnetic flowmeters subject conductive liquids to alternating or pulsating direct-current magnetic fields. Electrodes on either side of the pipe wall pick up the induced voltage following Faraday's law, which is proportional to fluid velocity.



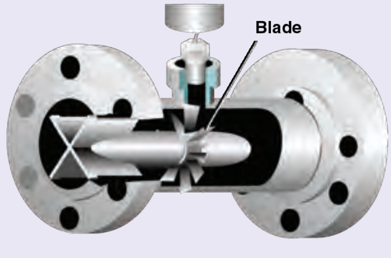
Vortex meters place a bluff obstacle in the flow stream, which creates vortices or eddies whose frequency is proportional to flow velocity. Sensors detect and count the pressure variations produced over a fixed time.



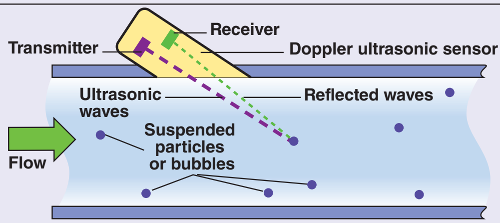
Swirl meters are similar to vortex meters, except vanes at the inlet swirl the flow, creating the pressure variations. Straightening vanes at the outlet de-swirl the flow.



Turbine meters contain a turbine. The flow against the turbine's vanes causes the turbine to rotate at a rate proportional to flow velocity. A sensor detects the rotational rate.



Ultrasonic meters come in two types. The Doppler flowmeter sends an ultrasonic beam into the flow and measures the frequency shift of reflections from discontinuities in the flow. Transit-time flowmeters have an ultrasonic transmitter and receiver separated by a known distance. The difference in transit time for a signal aided by the flow versus the signal moving against the flow is a function of fluid velocity.



creating uniform flow profiles, and thereby permitting average velocity to be inferred. (Straightening vanes are engineered, bundled tubes that are installed upstream of a meter in order to ensure a more uniform flow profile.)

The most practical, liquid pipeline flowrates in the CPI range from 0.5 to 12 ft/s, providing a range (turndown) of 24:1. Lower rates can be difficult to measure accurately and higher rates result in higher pressure drops, pumping energy costs and erosion (if abrasive solids are present). In the case of pipelines carrying gases, the practical flow velocities range from 15 to 200 ft/s, a turndown range of about 13:1. Many actual applications have flowrate ranges well within these extremes.

A sampling of velocity flowmeters and their principles of operation are given in the box above.

Inferential flowmeters

An inferential flowmeter calculates flowrates based on a non-flow measurement that has widely accepted correlations to rate of flow.

Differential pressure. Most of these flow measurement devices depend on three principles. First, with or without the restriction in a pipe, the overall flowrate remains the same, which pertains to the continuity equation. Second, Bernoulli's law says the fluid flow velocity (kinetic energy) through the restriction must increase. Third, the law of conservation of energy says the increased kinetic energy comes at the expense of fluid pressure (potential energy). The pressure drop across the restriction is a function of the fluid velocity, which can be calculated. Variables in the calculation of flowrate for differential flowmeters include the following:

- The square root of the measured differential pressure
- Fluid density
- Pipe cross-sectional area
- Area through the restriction
- A coefficient specific to the application, which includes the device

When a fluid passes through a restriction in a pipe, it does not follow the contour of restriction perfectly. It produces a "jet" stream that's narrower than the restrictive bore. The smaller jet diameter results in a faster stream velocity through the restriction, resulting in higher pressure loss than if the fluid perfectly followed the contour of the bore. Consequently, calculated flowrates from measured pressure drop and a known restriction bore diameter would tend to overstate the fluid flowrate. Therefore the rate must be corrected downward from the ideal discharge coefficient, which is equal to one. The overall flow coefficient applied to the basic equation is often specific to both the device and the application, and depends on additional factors involving gas expansion and velocity of approach. This coefficient (*K* factor) can range from 0.6 to 0.98 for differential pressure flowmeters.

Flowmeters based on differential pressure represent a popular choice in the CPI, constituting nearly 30% of installations. They have good application flexibility since they can measure liquid, gas and steam flows, and are suitable for extreme temperatures and pressures with moderate pressure losses. These losses depend on restriction size and type (orifice, wedge, pitot, Venturi and so on) and can be quite high and permanent given a low enough Beta ratio. (Beta ratio is the diameter of the restrictive orifice divided by the pipe diameter.) Accuracy ranges from 1 to 5%. Compensation techniques can improve accuracy to 0.5–1.5 %.

On the other hand, restrictive flowmeter piping elements are relatively expensive to install. Their dependence on the square root of differential pressure can severely diminish rangeability. Additionally, they require an instrument to measure differential pressure and compute a standard flow signal. Changes in temperature, pressure, and viscosity can significantly affect accuracy of differential pressure flowmeters. And while they have no moving parts, maintenance can be intensive.

A sampling of differential pressure flowmeters is shown in the box on p. 33.

Variable area meters. Often called rotameters, variable area meters (Figure 3) are another kind of inferential flowmeter. Simple and inexpensive, these devices provide practical flow measurement solutions for many applications. They basically consist of two components: a tapered metering tube and a float that rides within the tube. The float position — a balance of upward flow and float weight — is a linear function of flowrate. Operators can take direct readings based on the float position with transparent glass and plastic tubes. Rotameters with metal tubes include a magnetically coupled pointer to indicate float position.

Rotameters are easy to install and maintain, but must be mounted perfectly vertical. Accuracy (±2% of full scale) is relatively low and depends on precise knowledge of the fluid and process. They're also susceptible to vibration and plugging by solids. They apply primarily to flowrates below 200 gal/min and pipe sizes less than 3 in.

Target meters. These flowmeters insert a physical target within the fluid flow. The moving fluid deflects a force bar attached to the target. The deflection depends on the target area, as well as the fluid density and velocity. Target meters measure flows in line sizes above 0.5 in. By changing the target size and material, engineers can adapt them to different fluids and flowrate ranges. In most cases, their calibration must be verified in the field. Target meters are relatively uncommon and are found primarily in water and steam applications, as well as on wet gases.

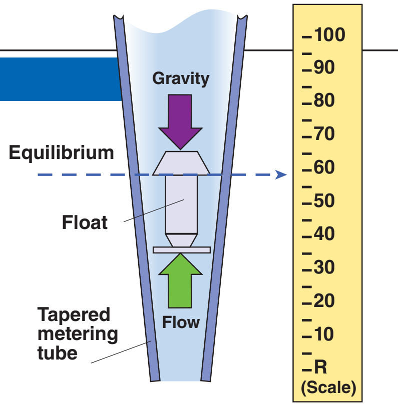


FIGURE 3. Variable area meters, or rotameters, are a practical way to measure flow in many applications. They are, however, susceptible to vibration and plugging

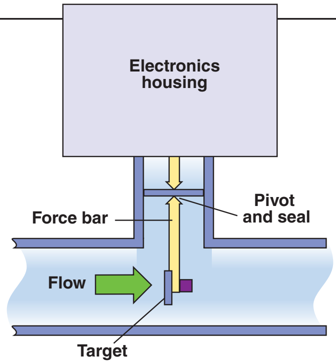


FIGURE 4. Target meters insert a physical target within the fluid flow. They are found primarily in water and steam applications, as well as on wet gases

Positive displacement meters

Positive displacement flowmeters are true volumetric-flow devices, measuring the actual fluid volume that passes through a meter body with no concern for velocity. Accordingly, fluid velocity, pipe internal diameters and flow profiles are not a concern. Volume flowrate is not calculated, but rather measured directly. These flowmeters capture a specific volume of fluid and pass it to the outlet. The fluid pressure moves the mechanism that empties one chamber as another fills. Residential gas meters are a common example.

Counting the cycles of rotational or linear motion provides a measure of the displaced fluid. A transmitter converts the counts to true volumetric flowrate. Some examples include the following:

- Single or multiple reciprocating piston meters
- Oval-gear meters with synchronized, close fitting teeth
- Movable nutating disks mounted on a concentric sphere located in spherical side-walled chambers
- Rotary vanes creating two or more compartments and sealed against the meter's housing

Engineers can apply these flowmeters to a wide range of non-abrasive fluids, including high-viscosity fluids. Examples include heating oils, lubrication oils, polymer additives and ink. Accuracy may be up to ±0.1% of full scale with a rangeability of 70:1 or better. They require no power and can handle high pressures.

Positive displacement flowmeters are not suitable for applications that include solids, entrapped air in liquids or entrained liquids in gases. They are expensive to install and maintain, having many moving parts. The pressure drop across these meters is high.

Direct mass flow measurement

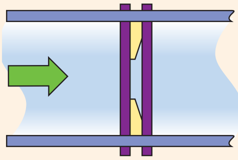
In the CPI, two kinds of flowmeters directly measure mass rates of fluid flow: Coriolis flowmeters for liquids and gases; and thermal flowmeters for gases. Chemical processes are generally concerned more with rates of mass flow because reactions within the plant depend on mass rather than volume ratios.

Coriolis flowmeters. In the early 1800s Gustave-Gaspard Coriolis, a French engineer and mathematician, discovered and described Coriolis forces. These forces come into play on rotating (or oscillating) bodies. Since the earth is a rotating body, Coriolis forces affect the weather, ballistics and oceanography.

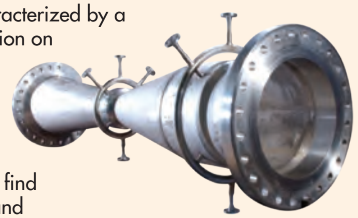
To get an understanding of this principle, suppose you stood very near the north pole of the earth. The rotational distance you would travel over 24 hours would be relatively small. But as you walked toward the equator, you would gain rotational speed. At the equator your rotational distance traveled in 24 hours would be about 25,000 miles, amounting to a rotational speed of more than 1,000 miles per hour. Obviously, while walking away from the rotational axis, you would be experiencing acceleration. Any acceleration requires a force — in this case the Coriolis force. Physics

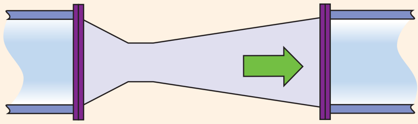
FLOWMETER ELEMENTS BASED ON DIFFERENTIAL PRESSURE MEASUREMENTS

Orifice plates are the most common differential pressure (DP) elements in the CPI. Their flow characteristics are well documented in the literature. They're inexpensive and available in a variety of materials. The rangeability, however, is less than 5:1, and accuracy is moderate at 2–4% of full scale. Maintenance of good accuracy requires a sharp edge to the upstream side, which degrades with wear. Pressure loss is high, relative to other DP elements.

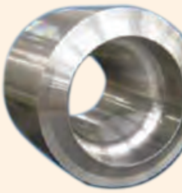


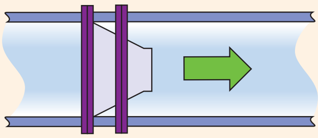
Venturi meters are characterized by a gradual tapered restriction on the inlet and outlet. This element has high discharge coefficients near the ideal value of one. Pressure loss is minimal. Venturi meters find use primarily in water and wastewater applications and have limited acceptance elsewhere in the CPI. The rangeability of about 6:1 is better than orifice plates. Performance characteristics are well documented.



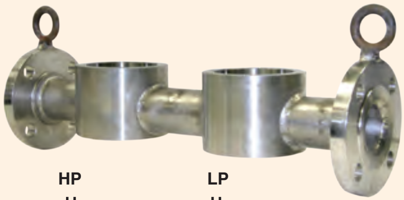


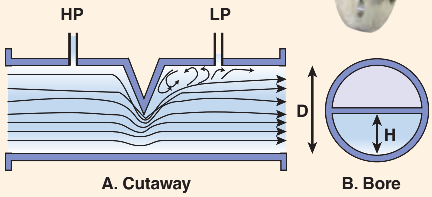
Nozzle elements mimic the properties of the Venturi meter. They come in three standard, documented types: ISA 1932 nozzle, common outside of the U.S.; the long radius nozzle; and Venturi nozzle, which combines aspects of the other two.



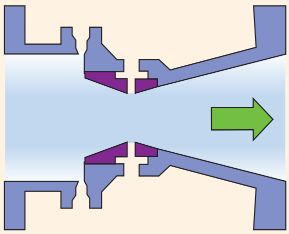


Wedge elements consist of a V-shaped restriction molded into the top of the meter body. This basic meter has been on the market for more than 40 years, demonstrating its ability to handle tough, dirty fluids. The slanted faces of the wedge provide self-scouring action and minimize damage from impact with secondary phases. Wedge meter rangeability of 8:1 is relatively high for a DP element. Accuracies are possible to ±0.5% of full scale.

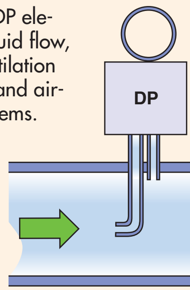


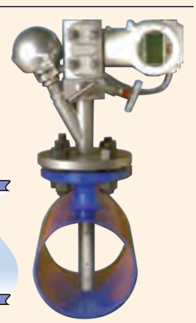


Flow tubes are defined by the American Society of Mechanical Engineers (ASME) as any DP element whose design differs from the classic Venturi, which includes short-form Venturies, nozzles and wedges. Flow tubes come in several proprietary shapes, but all tend to be more compact than the classic and short-form Venturies. With proprietary designs, flow tubes vary in configuration, tap locations, differential pressure and pressure loss for a given flow. Manufacturers must supply test data for flow tubes.



Pitot tubes are low-cost DP elements used to measure fluid flow, especially air flow in ventilation and heating, ventilating and air-conditioning (HVAC) systems. They work by converting the kinetic energy of the flow velocity into potential energy (pressure). Engineers can easily insert pitot tubes into existing piping, minimizing installation costs. One type makes a measurement at a point within the pipeline or ductwork, requiring knowledge of the flow profile. Another, as shown in the photo, contains multiple orifices, providing an averaging effect.





tells us that force equals mass times acceleration. So the force developed is proportional to mass.

Commercial Coriolis flowmeters (Figures 5 and 6) are a relatively recent innovation, having emerged in the mid to late 1970s. Steady technical improvements since then have greatly increased their acceptance in the CPI. No other flow device is more versatile and capable. Aside from measuring mass flowrates, Coriolis flowmeters can provide simultaneous outputs for volumetric flowrate, total flow, density, temperature and percent concentration. These meters are unaffected by flow profiles and viscosity, so they don't require long runs of straight pipe upstream and downstream. The fluid flow can be turbulent, laminar or anything in-between. The fluid can be viscous or free flowing. Additionally, mass is not affected by changes in temperature or pressure. Accuracies can be as high as ±0.05% of rate.

Purchase prices for Coriolis meters are relatively high, but they are decreasing as these meters become more popular. Pressure drop through these

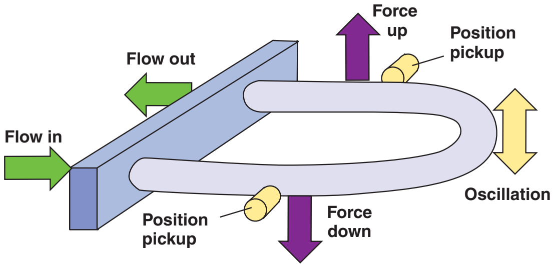


FIGURE 5. With flow, Coriolis forces twist the oscillating tube. The amount of twist is proportional to the mass flowrate

FIGURE 6. Coriolis flow tubes come in a variety of shapes, depending on the manufacturer. Above is an S-shape Coriolis flowmeter

FIGURE 7. Thermal mass flowmeters introduce heat into the flow and measure its dissipation. They measure at a point within the gas stream

meters is relatively high because of circuitous tube geometries, and typically, the separation into two tubes. Sizes up to 12 in. are available. Entrained gases can be problematical, so control valves should be downstream to keep pressure on the meter to prevent emergence of gas bubbles. Coriolis flowmeters are somewhat sensitive to vibration, but this can often be overcome by harmonic studies and sophisticated signal processing.

Since rotating flow tubes are impractical, Coriolis flowmeters resort to oscillation. Usually a single tube or dual tubes oscillating 180 deg. out of phase take the fluid away from the axis of oscillation and back again. The Coriolis forces developed within the fluid push against the elastic tubes, twisting them. Strategically mounted magnetic pickup coils measure the degree of tube twist or distortion, which corresponds to the mass flowrate. At zero flowrate, no Coriolis forces are developed, therefore the tubes retain their normal shape. With flow, signals from the pickoff coils experience a difference in phase that's proportional to the mass flowrate. In short, a Coriolis flowmeter comprises the following parts:

- Flow tube or tubes that take the fluid away from and back toward the axis of oscillation
- A flow splitter to divert the fluid into two flow tubes
- A drive coil to oscillate the flow tubes at their natural (resonant) frequency
- Pickoff coils that measure the distortion of the tubes
- A resistance temperature detector (RTD) to measure tube temperature, which can affect the elasticity of the tubes and thus their degree of twisting

The resonant frequency developed by the drive coil depends on the mass that is oscillating. Since the tube mass and volume are constant, this frequency is also a measure of the fluid's density. Measurement of fluid density is a bonus provided by Coriolis flowmeters.

Applications in the CPI for Coriolis flowmeters include the following:

- Custody transfer
- Critical process control
- Filling and dosing
- Reactor charging
- Blending
- Loading and unloading

Their accuracy makes Coriolis flowmeters obvious candidates for custody transfer. The capability for a single flowmeter to measure a variety of different fluids suggests applications such as batch operations and tanker-truck loading and unloading. For anything sold by weight, they can replace load cells for filling and dosing. They're also good candidates for material balances and blending by weight.

Thermal mass flowmeters. Introducing heat into fluids (mostly gases) offers a way to measure their mass flowrates. The heat dissipated by the flow stream — measured by temperature sensors — is a measure of the mass flowrate. Thermal mass flowmeters (Figure 7) have no moving parts, are easy to install, and provide a relatively unobstructed flow path. Since they are measuring mass, corrections for temperature and pressure are unnecessary. They are accurate over a wide range of gaseous flowrates. But because they essentially measure flow at a point within the gas stream, they require some flow conditioning or knowledge of the flow profile.

Manufacturers of thermal mass flowmeters use two different methods to measure heat dissipation. Both depend on the principle that higher mass flowrates have a greater cooling effect on the sensors:

1. *Constant temperature differential*: This technique uses a heated sensor (generally an RTD) upstream from another RTD that measures gas temperature. The electrical power needed to maintain the same temperature difference between the heated and unheated sensor is a function of the mass flow.
2. *Constant current*: Here the electrical current to heat the upstream sensor is kept constant. The downstream sensor measures the process temperature. In this case mass flow is a function of the temperature difference between the two sensors.

Applications for thermal mass flowmeters include boiler control, biogas measurements, compressed air accounting, pharmaceuticals, pneumatics, and applications in the food-and-beverage industries. ■

Edited by Dorothy Lozowski

Author

Ronald W. DiGiacomo manages business development for flow technologies in North America for ABB Inc. (125 E. County Line Rd., Warminster, PA 18974; Phone: 215-589-4350; Email: ron.w.digiacomo@us.abb.com). He has 25 years of experience in process instrumentation and control, primarily in flow measurement. Previously, he spent 15 years with two Emerson divisions and five years with Invensys companies.

COMPACT, HIGH-EFFICIENCY HEAT EXCHANGERS: Understanding Fouling

Engineers should plan to avoid fouling of heat exchangers instead of reacting to it

Jeff Kerner
Jennings Alberts Inc.

The topic of fouling in heat exchangers has been of increasing interest in recent years, since it is so closely linked to the cost of building and running a chemical plant. It has been reported that fouling costs are about 0.25% of the gross national product (GNP) of highly industrialized countries, which, based on current estimates of GNP for the U.S. of $15 trillion, makes the staggering cost of fouling $37 billion a year. One can easily envision that the cost for the chemical process industries (CPI), both U.S. and worldwide, are unthinkably high.

When considering fouling and its associated costs due to downtime, labor and cleaning, the first issue that comes to mind is maintenance expense. However, fouling also directly impacts capital expense (Capex) and operating expense (Opex). Capex is affected because larger heat exchangers are required to compensate for fouling. In addition, greater floor space and beefier foundations are needed for these larger heat exchangers. Increased diameter piping is an additional cost, since a higher flowrate of coolant will generally be required to achieve the desired heat transfer in a fouled heat exchanger. There are also the costs of both online and offline cleaning equipment. While maintenance costs are usually factored into Opex, operating expenses are also affected by the reduced production rate of the fouled heat exchanger as well as increased fuel or electrical costs in those applications where additional steam or electricity is needed to overcome the effects of a fouled heat exchanger.

This article summarizes the fouling mechanisms in high-efficiency compact heat exchangers (CHEs) and also describes fouling mitigation and monitoring methods that can be used when designing or using CHEs.

TABLE I. RECOMMENDED FOULING RESISTANCES FOR PHES VS. TEMA VALUES

Process Fluid	R_f-PHE	R_f-TEMA
	m^2/K-kW	m^2/K-kW
Soft water	0.018	0.18–0.35
Cooling tower water	0.044	0.18–0.35
Sea water	0.026	0.18–0.35
River water	0.044	0.35–0.53
Lube oil	0.053	0.36
Organic solvents	0.018–0.053	0.36
Steam (oil bearing)	0.009	0.18

PHE = plate heat exchanger

Compact heat exchangers

Compact heat exchangers, in general, are characterized by a large heat-transfer surface area per unit volume of the exchanger, (characterized by the term β) where $\beta > 700\ m^2/m^3$ for heat exchangers handling gases and $\beta > 400\ m^2/m^3$ for those handling liquids. Compact heat exchangers that are commercially available are the plate-and-frame, fluted-plate-block (also known as the welded-plate-fin), spiral, enhanced-tube and printed-circuit heat exchangers. For the scope of this article, only the three compact heat exchangers commonly used for liquid-to-liquid services in the CPI will be discussed (plate-and-frame heat exchangers, fluted-plate-block heat exchangers and spiral heat exchangers; see box on p. 36). These three types are chosen for this article since, in the author's experience, liquid-to-liquid services represent the bulk of heat exchanger applications that the chemical engineer will encounter in CPI operating plants as well as those applications in which fouling is most often seen.

General overview of fouling

Except in the cleanest of applications (deionized [DI] or purified water, refrigerants and well-treated closed-loop systems), deposits that tend to form on heat transfer surfaces reduce the heat transfer efficiency of the exchanger. The five recognized mechanisms of fouling were first described by Epstein in 1983 and are listed in [*1*] as the following:

1. Particulate matter (sedimentation of fine, suspended particles or flow blockage by large particles)
2. Crystallization (precipitation followed by deposition of dissolved salts)
3. Chemical reaction (deposit formation on the heat transfer surface by a chemical reaction in which the surface itself is not a reactant)
4. Corrosion (fouling of the heat transfer surface)
5. Bio-fouling (microbial fouling due to growth and deposition of biological films or slimes)

In addition to the fouling tendency of the fluid, the physical parameters that affect fouling have been well-documented [*2, 3*]. These include the following:

- Metal wall temperature
- Fluid temperature
- Wall shear stress
- Fluid velocity
- Surface material or finish
- Chemical treatment

Fouling factors

Most heat-exchanger designs include a resistance term known as the fouling factor, R_f. The selection of too high a fouling factor can actually result in increased fouling for any heat exchanger. This is due to the fact that as more surface area is introduced into the design, the cross-sectional area for flow typically increases, reducing the velocities for that fluid. As a result of these lower velocities, heat exchangers designed with too high a fouling factor can foul more quickly than those designed with a more realistic, lower fouling factor, leading to more frequent cleaning of the high fouling-factor design.

In the author's experience, for most applications where a CHE is to be used, fouling factors should not add more than 25% excess surface area to its design, and often less. This comes about because high efficiency CHEs typically have higher film coefficients than conventional shell-and-tube heat exchangers causing the fouling factor selected for a CHE to have a much greater effect on the calculated surface area needed. This is evident in the equation for the overall heat transfer coefficient, U_o:

$$U_0 = \left(\frac{1}{h_H} + \frac{1}{h_C} + \frac{x}{k} + R_f\right)^{-1} \quad (1)$$

Where:

U = overall heat transfer coefficient
h_H = hot fluid film coefficient
h_C = cold fluid film coefficient
x = thickness of wall separating the two fluids
k = thermal conductivity of wall
R_f = fouling factor

In the above equation, the higher the value of the film coefficients, h_H and h_C, the smaller the value of the first two terms in the denominator. Since the wall resistance term, x/k, is small relative to the other values in the denominator, it can be neglected. This allows the fouling resistance, R_f, to strongly weigh on the value of U_o and to do so in an inverse manner. That is, the use of too high an R_f, in high efficiency heat exchangers can significantly reduce the overall heat transfer coefficient, U_o, making the size of the CHE excessively large (and, as pointed out above for all heat exchangers), accelerating fouling. For this reason, TEMA (Tubular Exchanger Manufacturers Assn.) fouling factors for shell-and-tube heat exchangers should not be used to design plate heat exchangers [*1–3*].

As an example, the author points to Table I from a paper by Panchal and Rabas [*3*], comparing TEMA fouling factors for shell and tubes with fouling factors measured and generally accepted for one type of CHE, the plate heat exchanger. Using the table, and using a modest clean U value for a coastal sea water in a plate heat exchanger of 3,500 W/m^{2}K (approximately 600 Btu/ft^2-h-°F), then if a typical TEMA fouling factor of 0.00035 m^2-K/W (approximately 0.002 ft^2-h-°F/Btu) used for shell and tubes operating in the same water were used to design a plate heat exchanger, the plate heat exchanger would be 120% overdesigned.

Even with a realistic fouling factor used for the design of high efficiency heat exchangers, the author has witnessed many situations where shortly after placing a heat exchanger into service that has been designed for the worst-case summer coolant temperature, it is not at all unusual for plant

HIGH EFFICIENCY CHES

Within the class of compact heat exchangers described and defined in the main text, the sub-class of high efficiency CHEs is generally characterized by high film coefficients and low fouling factors that both contribute to higher overall *U* values. While these attributes alone tend to make the CHEs smaller in size than conventional shell-and-tube and other "longitudinal" heat exchangers, the use of close channel spacings also allows this sub-class to get more heat transfer area into a given footprint and a given volume.

Corrugated plate technology

Corrugated plate technology is the concept behind two of the three types of CHEs covered in this article.

Plate heat exchangers. The first type is best known as the plate-type heat exchanger (also called a plate-and-frame heat exchanger) as shown in Figure 1. Flow paths in plate heat exchangers are almost always truly countercurrent, maximizing the thermal driving force between hot and cold fluids. The fluids are contained in their flow path by elastomeric gaskets or, in the case of higher design-pressure plate heat exchangers, by brazing or fusion bonding instead of gaskets.

The corrugated surfaces of the plates create a large number of contact points, allowing the units to be built with rather thin heat transfer surfaces (0.4–0.8-mm thick), yet able to withstand high design pressures in excess of 20 barg for gasketed plate heat exchangers and up to 54 barg for brazed and for fused plate heat exchangers. The corrugated plates have rather shallow pressing depths (2–4 mm and, in special designs, up to 16 mm) that create a turbulent path for fluid flow (Figure 2), generating high wall-shear stress, often at relatively low channel velocities. Wall shear stress is an important factor in mitigating fouling (see "Fouling mitigation" section in main text). The plate and frame heat exchanger has been shown to demonstrate much higher heat transfer coefficients than conventional shell and tube exchangers and has been discussed before (see "Plate Heat Exchangers: Avoiding Common Misconceptions and Improving Heat Revovery," *Chem. Eng.*, February 2009, pp. 40–47).

Fluted-plate block heat exchangers. Another type of heat exchanger based on corrugated plate technology is known as the fluted-plate block heat exchanger. This design is similar to the plate-and-frame type discussed earlier in that each consists of stamped, corrugated

Diagrams: Alfa Laval (Figures 1–5)

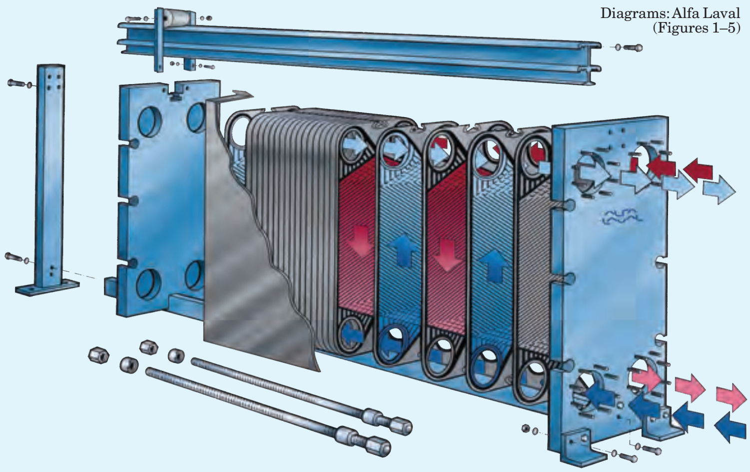


FIGURE 1. **In the plate-and-frame heat exchanger, flow paths are countercurrent**

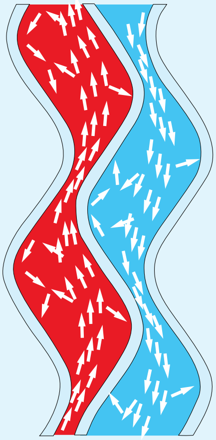
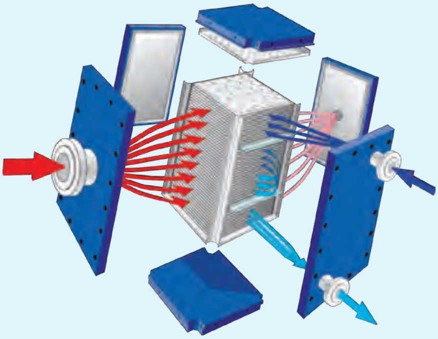


FIGURE 2. The corrugated plates have shallow depths, which create a turbulent path for fluid flow



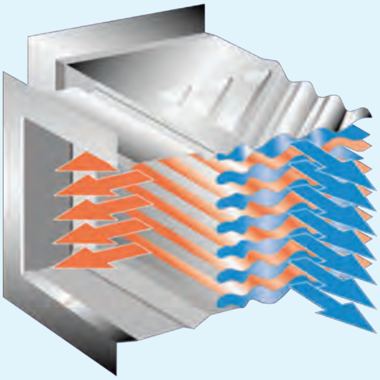


FIGURE 3. In fluted-plate block heat exchangers (top), the overall flow between hot and cold is countercurrent (bottom)

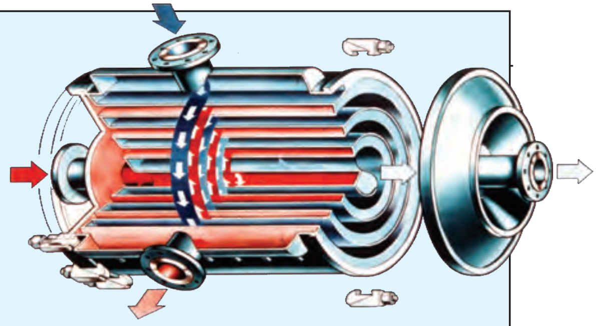


FIGURE 4. Spiral heat exchangers incorporate metal sheets wound around a center tube

plates. However, in the fluted-plate block heat exchanger, the two media flow in alternately-welded (not gasketed) channels between the plates. The flow pattern is cross-flow within each pass. Due to the shorter length of each plate than found in a plate heat exchanger, the fluted-plate block heat exchanger may require multiple passes, although the resulting, overall flow arrangement between hot and cold media is almost always countercurrent (Figure 3).

Four heavy steel panels surround the plate pack. Each pass is separated from the adjacent passes by a baffle, which forces the fluid to turn between the plate pack and the panel. As in the plate-type heat exchanger discussed previously, the corrugated plates in the fluted-plate block heat exchanger create narrow channels for each fluid. These narrow channels generate turbulence, resulting in high film coefficients and high wall-shear stress, typical of corrugated plates with narrow channel spacings. Both the plate type and the fluted-plate block heat exchanger are characterized by small residence times due to their relatively low holdup volumes.

Spiral heat exchangers

The third type of heat exchanger in the class of CHEs to be discussed is the spiral heat exchanger. Unlike the plate-type heat exchanger and the fluted-plate block heat exchanger, the heat transfer surfaces of the spiral heat exchanger are not corrugated plates. Instead, the surfaces are sheets of steel (or any alloy that can be cold-worked and welded) wound around a center tube, which is then wound so that two separate, concentric channels are formed (Figure 4). Uniform spacing between the wound passages is maintained along the length of the spiral winding by spacer studs that are welded to one of the sheets. Most manufacturers offer spacings of 6–25 mm. Both of the fluid flow channels are closed by alternate channels welded at each side of the spiral sheet.

While the spiral can be configured into a number of flow patterns that result in spiral flow on both sides, spiral flow on one side and cross-flow on the other side, or a combination of spiral flow and cross flow (for condensing and subsequent sub-cooling), this article discusses those spiral configurations where one or both fluids are in spiral flow, since this is the design most often used in liquid-liquid applications.

The spiral heat exchanger does not contain the parallel flow passages found in the corrugated plate types discussed above nor in the tube channels of a shell and tube. Instead, the spiral has a unique self-scrubbing feature due to the fact that the fluid (or both fluids) are in a single flow passage. That is, the fluid, upon entering the spiral heat exchanger, does not have the possibility of dividing up into a number of parallel flow paths as it can in the plate heat exchanger, fluted-plate block heat exchanger or tube bundle of a shell-and-tube heat exchanger. Once the fluid enters the spiral channel, it must continue through that same cross-sectional area for flow until it exits the heat exchanger. As a result of this continuous, curving passage for flow, any solids that build up in the channel constrict the cross-sectional area for flow at that point, and as long as there is enough dead head in the pump feeding the fluid through that channel, the local velocity at the point of build-up increases as the local cross-sectional area decreases.

The self-scrubbing feature is most effective, especially due to sedimentation of particulate matter, when the axis of the spiral channel is horizontal. In this configuration, the spiral is especially effective for handling fluids with high concentrations of suspended solids.

In a spiral heat exchanger, both fluids are usually considered to be in nearly pure countercurrent flow. ❑

personnel to have to throttle back significantly on the coolant to prevent overcooling in the non-summer months. It should be noted that installing a bypass line around the heat exchanger for the hot process fluid in order to control its exit temperature, while allowing the coolant flow to remain sufficiently high all year round, may be a better idea. Without such a bypass line, it is this lower coolant flowrate in a heat exchanger that is already overdesigned, along with its concomitant lower velocity (and lower wall shear stresses between the flowing fluid and the heat transfer surface, to be discussed below) that can accelerate fouling. In general, the engineer must adopt a sensible approach to protect against fouling by selecting a reasonable fouling factor while providing enough surface area to operate under worst-case cooling conditions during the summer months.

It is important to point out that the fouling factor is only one component of what is often called the "design margin" [*4*]. The design margin is defined as the heat transfer area over and above the clean heat transfer area. However, in the design of heat exchangers, margins or "safety factors" are often added in by the design engineer to take into account not only fouling, but also the following:

- Uncertainties of the fluid properties or of the heat transfer coefficient
- Turn-down in process conditions, perhaps due to seasonal product demand
- Folklore warnings on fouling factors passed down from plant or design personnel (indicating "that is how it

has always been done")
- Perceived risk, due to the design engineer's awareness that the heat exchanger is critical to plant operation, leading to deliberate overdesign

It is easy to see how any, and, certainly some combination or all of the above can rapidly lead to overdesign of the heat exchanger, accelerating fouling as described earlier.

Fouling by common fluids

While there are some streams that generally do not foul, there are others that are known to foul heavily and some in which the fouling tendency is controlled with proper treatment.

a. Fluids that typically do not foul: DI, demineralized (DM) and purified water; refrigerants

b. Fluids that foul heavily: Crude oil, amines, hydrogen fluoride, particulate-matter laden streams, improperly treated cooling water and streams containing high scaling-potential salts and other compounds

c. Fluids whose fouling tendency is controlled with proper treatment: Treated cooling water, and treated fluids in closed-loop streams

Fouling mitigation in CHEs

Like all heat exchangers, CHEs can experience fouling due to the mechanisms outlined earlier, including : particulate matter, crystallization, chemical reaction, corrosion and bio-fouling. Of course, more than one mechanism can occur in a heat exchanger at the same time, potentially leading to more severe fouling than by a single mechanism.

Mitigating the effects of fouling in CHEs, as for all heat exchangers, is best done by proper design and by good operating practice. For the recognized mechanisms cited above, the author's experience for controlling fouling in CHEs by design and by operation yields the following suggestions:

Particulate-matter fouling. When considering fouling due to particulate matter in corrugated-plate heat exchangers, it is first important to distinguish between 1) plugging due to larger particles that have difficulty passing through the relatively narrow channels of these exchangers (macro-fouling) and 2) the buildup of finer particulates from silt, sediment and other suspended solids that may be in the fluid (micro-fouling). A good rule of thumb to prevent plugging (macro-fouling) in all corrugated-plate-technology heat exchangers is to limit the maximum diameter of particles in the fluids to 75% of the plate groove (also known as the pressing depth), which would translate to particles below 2.5 mm in plate exchangers and below 3 mm in fluted-plate block heat exchangers.

Although "wide gap" heat exchangers that can tolerate much larger particles are available from many manufacturers, the engineer must recognize that the wall shear stress and channel velocities can be much lower in these units. For protection against macro-fouling in corrugated-plate heat exchangers, a strainer should be used or a spiral heat exchanger (which has larger channel spacings) should be considered.

For finer particles in the fluid, the corrugated plate heat exchanger should be designed with high wall-shear stress, as defined by Equation (2):

$$\tau = \frac{\Delta P \bullet d_h}{4L} \qquad (2)$$

Where:

τ = wall shear stress, Pa or psi

ΔP = pressure drop through plate heat exchanger, Pa or psi

d_h = hydraulic mean diameter of channel, mm (in a plate heat exchanger, $d_h = 2s$, where s = plate pressing depth, mm)

L = effective plate length, mm (best obtained from the manufacturer, but approximately the centerline-centerline distance between top and bottom ports)

High values of wall shear stress, not channel velocity, should be the important design parameter when using corrugated plate heat exchangers for fluids with fine particulates. It is the author's experience that at least for the plate-and-frame type heat exchangers, the guidelines laid out by Novak [*5, 6*] for wall shear stress are effective and should be followed:

$\tau > 50$ excellent

$\tau = 25–50$ good

$\tau < 25$ poor, and shortened cleaning cycles may be experienced

τ = single digits should be avoided

The author has had specific and repeated experience in particulate-matter fouling applications at one client involving a highly fouling process fluid where removing up to one third of the plates in the heat exchangers greatly extended the time between cleanings, most probably due to the increase in wall shear stress. Of course, the pressure drop increased when the plates were removed (requiring, in some cases, an adjustment of pump speed and pump motor horsepower). Sometimes cooling water flows had to be increased to compensate for the reduction in heat transfer area, however the benefit due to the increase in time between cleanings was significant.

For the fluted-plate block heat exchangers, recent research [7] seems to indicate that fouling for this type of CHE follows the same rule: higher wall-shear stress is important. Research to confirm this assumption is still ongoing, and, for the fluted-plate block heat exchanger, the "target" values of wall shear stress similar to those listed above for plate-and-frame heat exchangers have not yet been established. However, the author, in his designs of the fluted plate block heat exchangers, opts for high wall-shear stress as well, whenever possible.

It should be noted here that for fouling applications involving shear-sensitive fluids (milk, colloidal suspensions and some emulsions), high wall shear stress can have the opposite effect of increasing fouling by breaking down the stability of the suspension or emulsion and causing solids to form. The author remembers when, as a young engineer, he ruined a $40,000 batch of product because, in an effort to shorten the loading time of a tank truck by increasing the pumping rate, the organic emulsion being cooled through a plate heat exchanger was literally converted to bits of rubbery polymer because the higher shear stress broke down the stable emulsion.

For spiral heat exchangers, Equation (2) cannot be used, because the channel

Alfa Laval

FIGURE 5. In spiral heat exchangers, the curved passage ensures that clean-in-place fluid has the highest velocity at the point of fouling

length, L, is not easily definable in a continuous curving passage. Here, the shear rate, dv/dy, at any local point in the flow channel is more applicable:

$$\frac{dv}{dy} = \frac{1{,}000 \cdot V}{s} \qquad (3)$$

Where:
dv/dy = shear rate, s^{-1}
V = channel velocity, m/s
s = channel spacing, mm

Shear rates as high as possible, consistent with allowable pressure drop and any experience with the fouling nature of the fluid, should be used for the spiral design.

Related mechanisms

Designing for high wall-shear stress or high shear rate increases the rate of deposit removal. This reduces the fouling tendency caused by mechanisms like particulate-matter fouling, brought on by surface deposition such as fouling due to crystallization, chemical reaction, corrosion and bio-related factors. However, in addition to design aspects inherent in CHEs that assist in minimizing fouling, there are modifications and procedures that the engineer should consider adding that can further help in mitigating fouling.

Mitigating fouling due to crystallization. The importance of wall temperature in minimizing fouling has been cited earlier in this article. In addition to high wall-shear stress or high shear rate to keep the crystals — once formed — from attaching to the heat transfer surfaces of the CHE, the engineer should ask the manufacturer to design the CHE such that the wall temperatures do not approach the crystallization temperature. Due to increased flow uniformity in the narrow heat transfer passages of the corrugated plates and in the single, curving flow passage of the spiral, the wall temperatures are more uniform. The manufacturer should be able to achieve a desired, uniform wall temperature by adjusting the inlet coolant temperature, adjusting the flowrates of the process fluid or cooling water, or, if need be, running the heat exchanger in cocurrent flow. Perhaps even more common than crystallization, especially in cooling tower and natural waters (city water, river and sea water) is the related phenomenon of scaling, which can be controlled in a similar manner once the scaling threshold of the foulant is known.

Mitigating fouling due to corrosion. CHEs are smaller and have less area than conventional shell and tubes, hence the metal heat transfer surface has less mass to it. This often allows the CHE with higher alloy metallurgy to be selected without economic penalty compared to a conventional shell and tube.

Mitigating bio-fouling. It is known that untreated waters with a temperature range of 15–50°C are ideal for microbial growth. High wall-shear stress can help in preventing organisms from anchoring on to the heat transfer surface. There are a great number of biological species that can cause such fouling. If high wall-shear stress is not sufficient to keep fouling in check, chlorination or other chemical treatment is probably the least expensive method for control. Of course, in this case, it is necessary to look at the potential for corrosion of the alloy surfaces of the CHE by chlorination or by the treatment chemical. Again, the smaller size and lower heat transfer area of the CHE often allows for higher metallurgy to be used that is resistant to the treatment process with little economic penalty.

Some forms of bio-fouling can be relieved by deliberately "spiking" the temperature of the cold fluid for short periods of time (easily accomplished by throttling back the coolant supply or allowing the hot fluid temperature to rise, if operating conditions permit.) Carrying this out in the CHE is more easily done than in a conventional heat exchanger without upsetting the process since the lower holdup volume of the CHE allows the temperature spike to be executed quickly before returning to normal temperature operation.

Adding mechanical features

Design for clean out. While the three types of CHEs discussed in this article are accessible for cleaning by removing their end covers, adding clean-out ports to the plate-and-frame and the spiral heat exchangers is inexpensive and always a good idea when designing for services where macro-fouling is a possibility. In the plate-and-frame type, installing a blind flange — on the movable cover of the heat exchanger opposite the port on the fixed cover where the fluid with the potential for macro-fouling enters — provides access to the area where macro-fouling is most likely to occur. The blind flange can be easily removed without the need to loosen the bolts and pull back the covers. In a spiral design, clean-out ports can be added to the inlet and outlet headers on the outer spiral wrap of the heat exchanger.

Plan for clean-in-place (CIP). CIP procedures are always a good idea with any heat exchanger. The low holdup volume of CHEs aids in keeping the time required for effective CIP to a minimum. In the case of the spiral heat exchanger, the same "single, curving passage for flow" feature that allows for self-scrubbing during normal operation (see box, p. 37) almost ensures that the CIP fluid has its highest velocity at the point of fouling, which is where it is needed (Figure 5). In addition, unlike parallel flow-path heat exchangers — wherein carrying out a CIP procedure for several hours doesn't guarantee that all the heat transfer area was wetted by the cleaning fluid — the single flow path of the spiral ensures that all the CIP fluid entering the inlet nozzle and discharging from the exit nozzle has contacted the entire spiral's surface area.

The effect of surface finish. The adhesion of substances on solid surfaces is mainly determined by surface roughness and surface energy. The surface roughness of corrugated plates is low, due to the fact that they are stamped and not welded and handled in several different fabrication steps.

In studies with plate-and-frame heat exchangers in food processing, where cleanliness of the surface is extremely important, electro-polished plates (readily available with the pressed plates of plate-and-frame heat exchangers) showed lower fouling than the standard stainless-steel plate [*8*]. In the same studies, several coatings were tested that showed some promise in reducing fouling. However, most of the coatings would not be suit-

Source: Ref. 1, with permission from Dr. Muller-Steinhagen

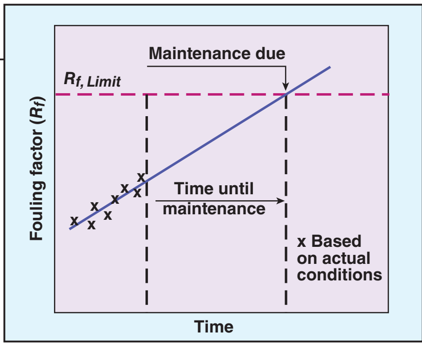


FIGURE 6. Plotting the fouling factor over time allows estimation of when a heat exchanger requires maintenance

able for use in a chemical process due to the temperatures or chemicals to which the coating would be subjected. In the reference just cited, PTFE coating of the plates — while acceptable for some chemical services — showed higher fouling than on a standard stainless-steel plate.

Work is being done by some researchers to evaluate the use of thinner (nano-composite) coatings on plate surfaces to avoid the loss in heat conductivity due to the coating thickness. The author has seen the resistance to fouling improved even further in spiral heat exchangers by dipping the entire heat exchanger in a phenolic bath after the mechanical manufacturing steps have been completed to improve the fouling resistance of the surface.

Monitoring fouling in CHEs

The two most common indications that a heat exchanger may be fouled are an increase in pressure drop or a loss in heat transfer. The author's experience indicates that more heat exchangers are taken out of service for cleaning or maintenance due to an increase in pressure drop than as a result of reduced heat transfer. In CHEs, because of the relatively smaller flow channels, this increase in pressure drop can be caused by the macro-fouling by large particles, which are too big to pass through the channels, as discussed earlier.

While this is less likely to happen in the case of spiral heat exchangers, which can have larger flow passages (up to 25 mm), still the inlet distributor or the discharge header of the spiral could become constricted. Mitigation of this area of possible pluggage in CHEs was discussed earlier in this article, pointing out the need for accessibility. In the case of fouling brought on by surface deposits due to micro-fouling, this is less likely to happen in the high wall-shear-stress channels of CHEs.

While high pressure drop can certainly be an indication of fouling and can cause disruption of plant operation and additional costs, it must be remembered that even if fouling were to occur uniformly on the heat transfer surface, the thermal conductivity of the deposit as well as its thickness determine the effect the deposit has on heat transfer. So, if the increase in pressure drop is determined by the engineer to be tolerable, monitoring the heat exchanger's thermal performance at that point to determine how severely it is fouled may be in order before proceeding with taking it offline for cleaning.

With respect to monitoring, the author regrets to say that he has only seen it carried out in pilot plant operations or carefully supervised plant runs. There seems to be little time, manpower or more often, operating budget available in industry today to carry out monitoring of fouling in heat exchangers, although one wonders if the time and manpower were made available in some systematic fashion, what savings to the plant operating budget would result?

In addition, imagine having the ability to plan maintenance work on key heat exchangers in advance of critical failures or underperformance. While one could argue that this is the aim of preventive maintenance (PM) outages, how many times is PM carried out on a folklore basis without the engineer knowing the fouled condition of the heat exchanger? In other words, the PM may have been performed prematurely, incurring unnecessary expense and downtime.

The alternative approach to PM is maintenance after failure (MAF), which is, unfortunately, the path most often traveled in operating plants. With MAF, production is interrupted, resulting in downtime, disruption of shipping schedules, unhappy customers, possible overtime for cleaning crews and the emergency acquisition of spare parts or completely new heat exchangers. None of these is desirable nor reflects the most economical scenario. One other little-considered factor also occurs if MAF is the default philosophy: The author has seen many times the effect of allowing a fouling deposit to "age" on the surface of a plate-and-frame heat exchanger. Ageing seems to convert the deposit into a nastier, more resilient (hence, tougher to remove) form. Ageing occurs because the fouling layer is a static one, susceptible to constant high (or low) wall temperatures as well as possible chemical and physical reactions over the entire time the heat exchanger is in operation. This "ageing" effect would not occur in the bulk, moving fluid stream as it travels through the heat exchanger passages. Ageing is well described in the 2009 paper by Wilson [*9*], although the authors of that paper caution that the ageing model described in their work is based on simple assumptions and requires more research.

The intermediate approach between PM and MAF is perhaps best described by Christian Kuhlmann's writings collected by Muller-Steinhagen [*1*]. Kuhlmann's paper offers the concept of status-oriented maintenance (SOM). In SOM, the condition of the heat exchanger at any given time is determined as a result of calculating the U value of the heat exchanger, and thus, monitoring its thermal performance using the well-known equation:

$$Q = U \bullet A \bullet LMTD \qquad (4)$$

Or, rearranged,

$$U = \frac{Q}{A \bullet LMTD} \qquad (5)$$

Where $LMTD$ is the log mean temperature difference.

Knowing the end point temperatures of each fluid and their flowrates allows Q to be calculated using

$$Q = m \bullet C_p \bullet \Delta T \qquad (6)$$

(the engineer should compare Q_{hot} and Q_{cold} for accuracy). At the same time, $LMTD$ can be easily calculated as well, allowing U to be determined for that set of conditions. Knowing the U value at any given time and knowing the U_{clean}, which was either measured upon startup with a clean heat exchanger or validated through other means, the fouling factor at that point in time can be calculated simply by:

$$R_f = \frac{1}{U} - \frac{1}{U_{clean}} \quad (7)$$

Repeatedly carrying out these measurements and calculations at intervals during the steady-state operation of the heat exchanger allows the engineer to easily determine the status of how fouled the heat exchanger is at any point in time, by the ratio $R_f / R_{f,Limit}$, where $R_{f,Limit}$ can be calculated from Equations (5–7), knowing the minimum (or maximum) exit temperatures of the heat exchanger at which point the heat transferred, Q_{Limit}, is no longer acceptable.

By plotting R_f versus time, the engineer can estimate the period of time remaining until the fouling factor limit, $R_{f,Limit}$, is reached (Figure 6) and the heat exchanger requires maintenance, thus avoiding premature, unnecessary downtime and costs.

Of course, for reliable data, the engineer must be sure that the measurements of temperature and flowrate (for the subsequent calculation of Q and LMTD) are being taken after a reasonable amount of time at steady-state. CHEs offer a benefit here since due to the lower residence time of CHEs and the lower mass of metal in the heat transfer surfaces, the time at steady state prior to monitoring data can be reached more quickly than in conventional shell and tubes. As a basis of steady state in CHEs, the author uses about 1,000 × heat exchanger residence time in minutes.

While this approach does not guard against any accelerated fouling that could occur due to other factors (such as ageing of the deposit which was discussed previously), the author feels that Kuhlmann presents a very worthwhile tool for troublesome plant heat exchangers that are critical to service and known to foul. SOM seems to fill a valuable gap between unnecessary PM and very costly MAF. ■

Edited by Gerald Ondrey

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Author

Jeff Kerner is a heat transfer specialist of Jennings Alberts Inc. (P.O. Box 503, Pipersville, PA 18947. Phone: 215-348-0256; Email: jeff.kerner@jenningsalberts.com). He has been providing heat transfer solutions to the chemical process industries for over 30 years. A chemical engineering graduate of The Cooper Union (New York, N.Y.), he also received a M.S.E. Ch.E. from the University of Michigan. Previously, he worked at DuPont and Rohm & Haas. Kerner has been active in the American Institute of Chemical Engineers (AIChE), having served as chairman of the Philadelphia subsection and on AIChE's national committee on employment guidelines. He is a professional engineer registered in Pennsylvania, Delaware and New Jersey. He has authored and coauthored several papers on heat exchangers and speaks extensively on heat transfer and process equipment.

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Reduce Gas Entrainment In Liquid Lines

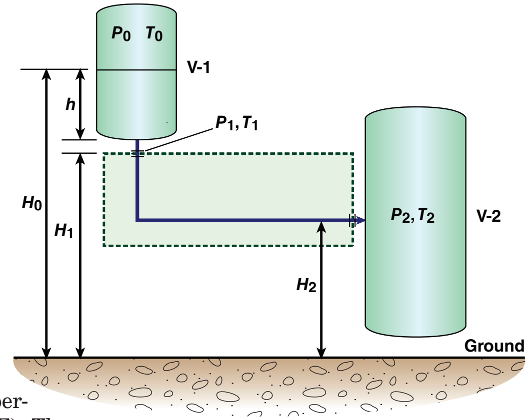

FIGURE 1. Shown here is a typical gas-liquid separator, with gravity flow from V-1 to V-2 [1]

Follow these tips to properly size self-venting lines and vortex breakers

Tamagna Ukil and **Thomas Mathew**
Reliance Industries Ltd.

A common practice in the chemical process industries (CPI) is to implement so-called value-maximization projects (VMP) to increase production or reduce production costs in order to increase profit margins. With such projects, one main objective of the design team is to incur minimum capital expenditures.

Because most VMPs aim to increase throughput or production yield, many such projects involve changes to the process that result in an increase in the volume of feed flowing into a gas-liquid separator (GLS). The system modifications that are required often call for:

- The design of a new GLS to accommodate the increased flow, or
- The modification of the vessel internals and associated piping to handle the increased feed flow

Increased feed flow into any GLS can lead to the entrainment of gases into the liquid lines. Such gas entrainment can lead to pulsating flows in the line, which can result in vibration and potentially destabilize the downstream processes. In many cases where GLS are provided with "gravity-flow pipelines" — a common approach, as it provides an inexpensive way to transport liquids — the use of self-venting pipelines coupled with properly sized vortex breakers can mitigate the problem of entrainment of gases into liquid lines.

Theoretical basis

A typical GLS arrangement with gravity flow is shown in Figure 1. The operating pressure of the first vessel (V-1) is P_0 (psig) and its operating temperature is T_0 (°F). The operating pressure and temperature of the second vessel (V-2) are P_2 and T_2, respectively.

The pressure and temperature of the liquid at the exit nozzle of V-1 are P_1 and T_1, respectively. In Figure 1, the region from the exit of V-1 to the inlet of V-2 is highlighted with a dashed outline. It shows that the associated piping of the system consists of pipes and elbows.

The following assumptions are considered for this system:

- Liquid flowing through the line is incompressible
- The system is in steady state
- There is no flashing of liquid
- Pressures P_0, P_1 and P_2 are constant
- The pipe size is uniform

System equations

Step 1. The pipeline is sized for liquid flow using a conventional line-sizing approach for typical velocity considerations and least annual cost. Table 1 shows typical liquid velocities in steel pipelines.

Table 1 shows typical velocities in steel pipelines with liquid flow [3]. It provides a good estimate for the preliminary selection of the pipeline size with respect to its nominal bore (N.B.) dimensions. As Table 1 provides generalized data, readers can use the values provided for any type of pipes, irrespective of metallurgy or material of construction.

By applying the lowest-annual-cost approach as stated by Moharir [3], the cost of the pipe material per unit length for a run of pipe with diameter D is calculated using Equation (1):

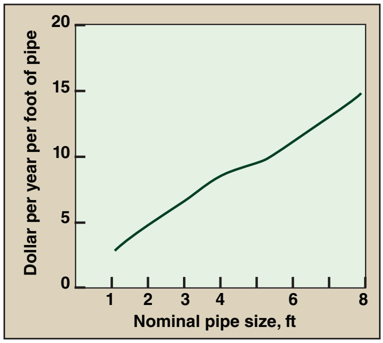

FIGURE 2. The relationship between amortized capital cost per foot of pipe and nominal pipe size is shown here [3]

$$C_D = 0.353XD^{1.5} \quad (1)$$

Along with the pipe, the cost of accessories and fittings must also be factored in, hence their number must also be computed on a per-unit-length basis. For instance, if a pipeline of 100 ft has 5 gate valves, 4 long-radius elbows of 90 deg, 2 tees and 7 weld joints, then its per-unit fitting cost can be taken collectively as a factor F. If the amortization rate is A_M and the annual maintenance cost is a fraction G of the capital cost, then the annualized capital plus maintenance cost of the pipeline, C_P, is calculated using Equation (2):

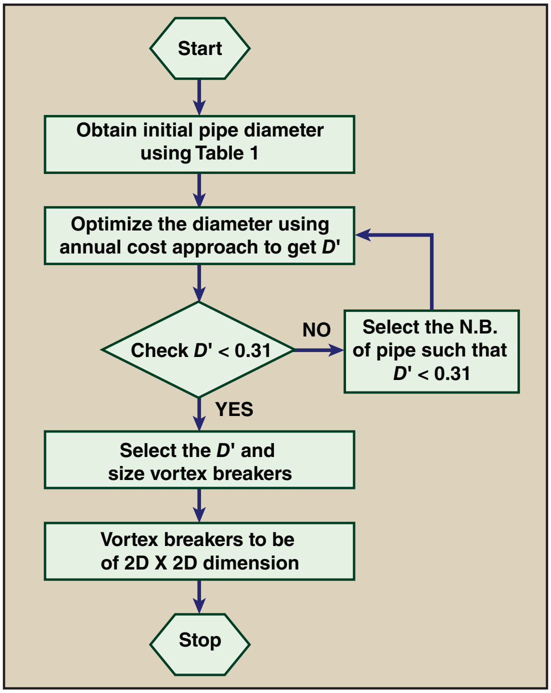

FIGURE 3. This flowsheet illustrates the types of decisions that must be made to properly size gravity flow lines and vortex breakers, to reduce gas entrainment

TABLE 1. TYPICAL VELOCITIES IN STEEL PIPELINES WITH LIQUID FLOW [*3*]

Nominal pipe size, in.	2 or less	3 to 10	10 to 20
Liquid and line	Velocity, ft/s	Velocity, ft/s	Velocity, ft/s
Water			
Pump suction	1 to 2	2 to 4	3 to 6
Pump discharge (long)	2 to 3	3 to 5	4 to 7
Discharge heads (short)	4 to 9	5 to 12	8 to 14
Boiler feed	5 to 9	5 to 12	8 to 14
Drains	3 to 4	3 to 5	—
Sloped sewer	—	3 to 5	4 to 7
Hydrocarbon liquids			
(Normal viscosities)	1.5 to 2.2	2 to 4	3 to 6
Pump suction	2.5 to 3.5	3 to 5	4 to 7
Discharge heads (long)	4 to 9	5 to 12	8 to 15
Boiler feed	3 to 4	3 to 5	—
Drains	—	—	—
Viscous oils			
Pump suction	—	—	—
Medium viscosity	—	1.5 to 3	2.5 to 5
Tar and fuel oils	—	0.4 to 0.75	0.5 to 1
Discharge (short)	—	3 to 5	4 to 6
Drains	1	1.5 to 3	—

$$C_P = (A_M + G)(1+F)C_D \quad \textbf{(2)}$$

Rearranging Equations (1) and (2) produces Equation (3):

$$C_P = (A_M + G)(1+F)XD^{1.5} \quad \textbf{(3)}$$

In most cases, another component, C_F, is needed to calculate is the operating cost. However, in this case, the operating cost component C_F is not considered due to the absence of any rotary equipment. Differentiating C_P with respect to D, to obtain optimum diameter of the pipeline (D') and setting it to zero, Equation (3) can then be simplified as follows:

$$\frac{dC_P}{dD} = 1.5(A_M + G)(1+F)XD^{0.5} \quad \textbf{(4)}$$

Figure 2 shows the relationship between the amortized annual cost per unit length of pipe (ft) and nominal pipe size (nominal bore).

From the two methods described above, D' is obtained as an initial line size in terms of nominal pipe size (nominal bore) of the pipe.

Step 2. The next step is to carry out the Froude number analysis for the line using the diameter obtained from Step 1. As per Simpson's article [*2*], if the fluid inside a vessel does not rotate and if the liquid level in the vessel is below a certain height, then gas will get sucked into the liquid line. A conservative estimate of this level was derived by Harleman et al. [*1*], Harleman's equation is:

$$\frac{V}{\sqrt{gD''}} = 3.24\left[\frac{h}{D''}\right] \quad \textbf{(5)}$$

Equation (5) can be used to estimate the height of the liquid inside V-1 below which the gas would be sucked into the liquid line.

Experiments on 13/16-in. pipeline and on 1-in. to 4-in. pipelines by Simpson and Webb [*2*], respectively, show that if the Froude number in the pipeline is less than 0.31, then gas will not be entrained. If the Froude number of the liquid flowing in the pipeline is greater than 0.31, then gas starts getting swept up by the liquid. High, two-phase pulsating flow is observed when the Froude number is between 0.31 and 1.

This is the basis of design for self-venting lines: Any provision for self-venting lines should ensure that the Froude number remains between 0 and 0.31. The typical velocity of liquid in self-venting pipelines is in the range of 1 ft/s.

Step 3. When the flow inside a vessel is rotational, vortex breakers should be provided to prevent gas entrainment into liquid lines. If V-1 has a feed entry point that is tangential to the vessel, it will induce a swirling motion in the liquid, like a whirlpool. If this swirling motion is strong enough to reach the liquid exit nozzle of V-1, then it would lead to entrainment of gas into the liquid pipeline. Borghei's experiments [*4*] in pipelines of 2-in. to 4-in. show that vortex breakers with dimensions double the nominal bore of the pipe are highly efficient in reducing the vortex effect inside the vessel.

Thus in V-1, with a self-venting liquid exit line, the vortex breaker arrangement should be in the form of a cross (+). When the vertical and horizontal dimension of the plates that are used to fabricate the vortex breaker have a dimension of $2D'$, each can substantially reduce the entrainment of gas into the liquid exit. The steps described above can be summarized in the flowsheet shown in Figure 3.

NOMENCLATURE

- A_M Amortized cost per unit length of pipe, \$/ft
- C_D Cost per unit length of pipe, \$/ft
- C_P Total capital cost per unit length of pipe, \$/ft
- F Pipe fitting cost per unit length of pipe, \$/ft
- G Maintenance cost per unit length of pipe, \$/ft
- g Acceleration due to gravity, ft/s^2
- h Height inside V-1, ft
- D Initial pipe dia., in.
- D' Optimum pipe dia., in.
- D'' Dia. of self-venting line, in.
- P_0, P_1, P_2 Pressure shown in Fig. 1, psig
- T_0, T_1, T_2 Temperature shown in Figure 1, °F
- V Velocity of the liquid through the pipeline, ft/s
- X Cost per unit length of 2-in. nominal bore pipe of the same material and schedule, \$/ft

The following conclusions can be made from the discussion above:

1. The line size full of liquid will always be smaller than the self-venting line.
2. The work described in Refs. *2* and *4* are based on small lines (up to 4-in. nominal bore).
3. If liquid flow varies during operation, the pipe should be sized to accommodate the maximum possible flow.
4. *D''* obtained from Equation 5 should be rounded off to the higher nominal bore of pipe of standard available size. ■

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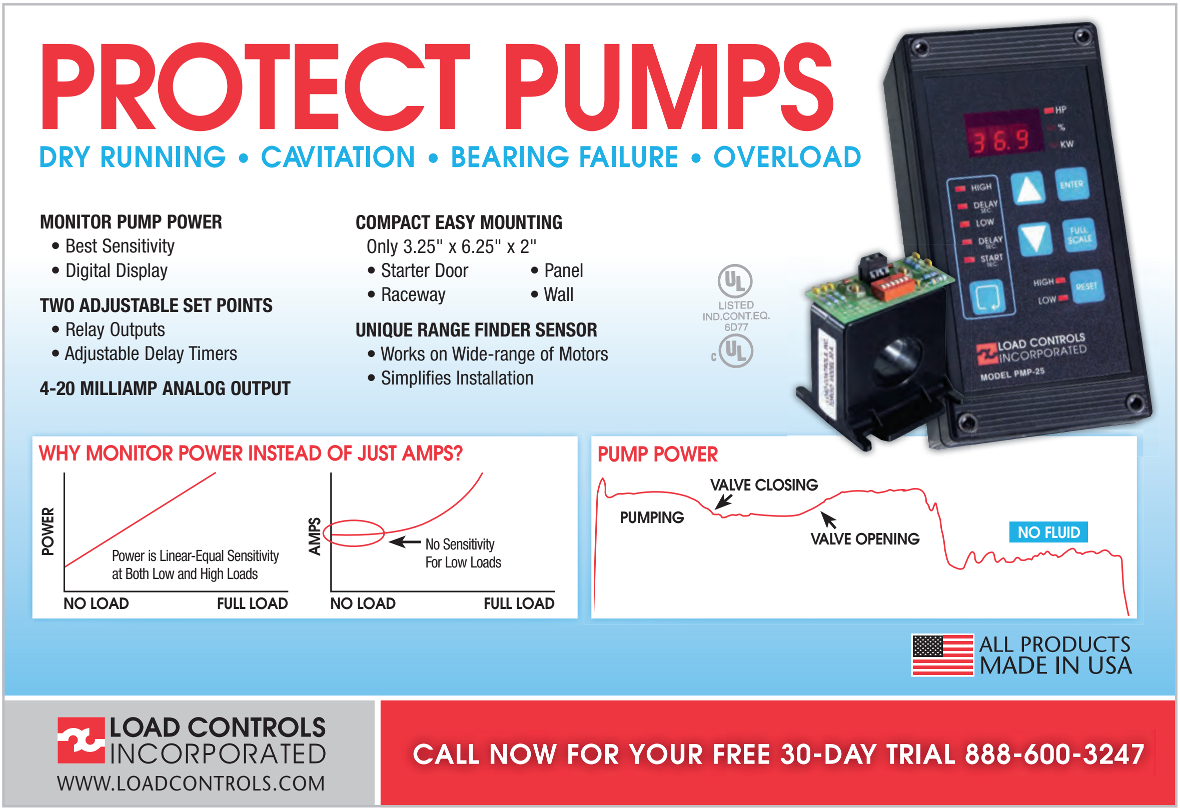
Authors

Tamagna Ukil is the Manager of PTA-Process at Reliance Industries Ltd. (Reliance Corporate Park, Ghansoli, 7-B Ground Floor, Navi Mumbai Maharashtra, India; Phone: +912-244-783-452; Email: tamaga.ukil@ril.com). He holds a B.S.Ch.E. from Utkal University. He is a Certified Piping Engineer from IIT Bombay, and has been working with Reliance Technology Group, PTA Division, to provide advanced technical services in the field of design, simulation and process optimization for the manufacture of purified terephthalic acid (PTA).

Thomas Mathew is president of Reliance Industries Ltd. He graduated as a Chemical Engineer from Kerala University (Trichur Engineering College), and spent the first 16 years of his career involved in the production of ammonia from numerous raw materials, including natural gas, naphtha, fuel oil and coal. Mathew participated in the startup of two coal gasification plants and served as plant manager for five years in the coal gasification plant at Ramagundam, India. He joined Reliance in 1985 and took charge of the commissioning and startup of several petrochemical plants, before heading the manufacturing operations of the Reliance's Patalganga Complex. He leads the Centre of Excellence in PTA and Gasification within Reliance.



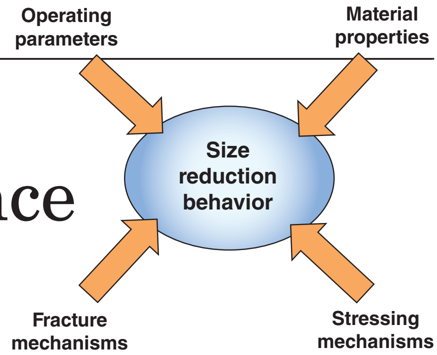


FIGURE 1. Desired performance of size reduction can be achieved by matching the machine design with particle properties and mode of operation

Maximizing Performance In Size Reduction

Expect more in selection and scaleup, prediction of energy consumption and reliability

Shrikant Dhodapkar and **Joerg Theuerkauf**
The Dow Chemical Company

Very seldom is a product of desired size manufactured directly in a process. Size reduction, coupled with screening (classification), is commonly used to achieve desired particle size. In many instances, the final application dictates requirement of small particle size to enhance performance. For example, fine particles enhance dispersion of pharmaceutical ingredients, increase surface coverage of paints, and increase taste and homogeneity of food ingredients.

Size reduction, comminution, grinding, milling and pulverizing are often interchangeably used to essentially mean "purposeful reduction in particle size". This unit operation is prevalent in chemical, food, mineral, pharmaceutical, coal, pulp-and-paper and agricultural industries. The technology is as old as human history when man learned to grind grain to make bread.

Despite continuing progress and innovations in the field — especially current advances in manufacturing processes for nanoparticles — selection and scaleup of equipment, prediction of energy consumption and equipment reliability continue to challenge process engineers. As shown in Table 1, the energy efficiency of size reduction equipment tends to be low, and improvement in energy efficiency continues to be a key issue.

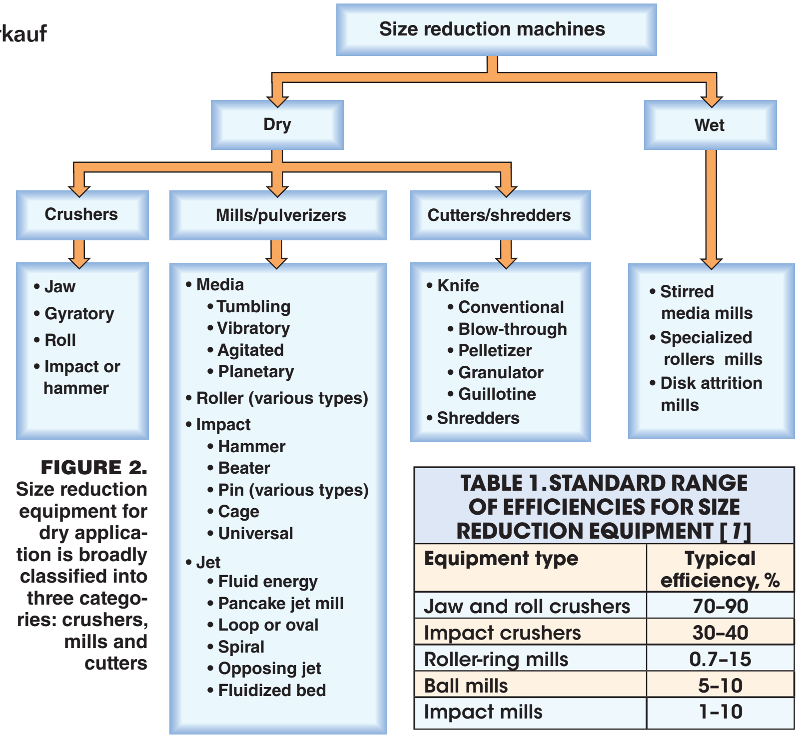


FIGURE 2. Size reduction equipment for dry application is broadly classified into three categories: crushers, mills and cutters

TABLE 1. STANDARD RANGE OF EFFICIENCIES FOR SIZE REDUCTION EQUIPMENT [*1*]

Equipment type	Typical efficiency, %
Jaw and roll crushers	70–90
Impact crushers	30–40
Roller-ring mills	0.7–15
Ball mills	5–10
Impact mills	1–10

Basic concepts

Key mechanisms. Seven different types of stresses can be imparted to achieve size reduction:

1. Compression between two rigid surfaces
2. Compression between two rigid surfaces and against an adjacent bed of solids
3. Shearing (or tearing, cutting, shredding and cleaving) by mechanical means
4. Shearing forces due to surrounding media
5. High-velocity impact against a rigid surface — particle impacting a stationary surface or moving surface impacting a particle
6. Particle-particle impact causing breakage and shattering
7. Abrasion during particle-wall and particle-particle impacts

Various machines generate one or more of these types of stresses on the particle. Desired performance of size reduction can be achieved by matching the machine design with particle properties and mode of operation (Figure 1).

Key material properties. The following properties of the material must be evaluated for suitable selection of equipment and to understand its size-reduction behavior [*2*].

- Particle size distribution in feed
- Particle shape
- Bulk density
- Flowability, cohesiveness or adhesiveness
- Corrosivity and composition
- Moisture content
- Hardness, brittleness, friability
- Fibrous morphology
- Abrasiveness
- Stickiness
- Elasticity, plasticity, ductility

- Dust explosion characteristics
- Temperature sensitivity — degradation, stickiness, phase change
- Toxicity
- Oil or fat content, especially release during grinding
- Reactivity or release of gases
- Shock sensitivity or explosivity

TABLE 2. EXAMPLE OF SIZE REDUCTION EQUIPMENT SELECTION CHART BASED ON PRODUCT PARTICLE SIZE [4]

Size reduction equipment	<1 mm	1 - 10 mm	10 - 50 mm	50-150 mm	15-500 mm	500 - 1,000 mm	1 - 5 mm	> 5 mm
Cutting mill								
Crusher								
Universal and pin mills								
Hammer mill								
Jet mill								
Stirred media mill								

Classifying equipment

It is not possible to come up with a unique classification of size reduction equipment because the nomenclature has evolved, and depends on the way manufacturers have positioned themselves in certain markets. Many devices are used for a wide range of applications, and it is difficult to assign them to a particular category. Size reduction equipment for dry application is broadly classified into three categories: crushers, mills and cutters (Figure 2). Some authors have proposed further classification based on particle size of the feed, for instance:

Crushing: Refers to coarse size reduction of particles from 60 in. to 1 in.

Grinding or milling: Refers to medium size reduction of particles from 1 in. to 150 µm

Pulverizing: Refers to fine size reduction to product size less than 150 µm

It should be noted that some equipment performance straddles various categories, despite their common names. For instance, a hammer mill can be used as a crusher and as a mill, depending on the application.

Selecting equipment

The selection process is complex because a number of machines can perform the same job. Total cost of ownership, which includes purchased cost and operational costs (energy and maintenance) along with process performance must be used as metrics for selection. Prior successful experience of manufacturers in similar applications and the scale of implementation must be considered while selecting a vendor.

Key application questions. The following determinations should be made for each application:

- Define key process objectives: What is the desired particle size distribution of the product or acceptable fines content? What is the design throughput?
- Is the process suitable for wet grinding or dry grinding?
- Is cryogenic grinding a viable option? For soft and rubber materials, where final product size is fine, cryogenic grinding may be the only viable option
- Should the operation be batch or continuous?
- For energy efficiency or to achieve desired product size, should a grinding circuit be considered instead of a single pass operation? Screening is an essential component of a grinding circuit. Suitability of various screening equipment must be independently evaluated.
- How is the material being fed? Is the feedrate steady (metered) or surging? Is the unit being operated in starved fed mode or flood fed mode?
- Can the feed particle-size distribution vary during operation? What controls are available to maintain the product size within specification?
- Is pre-screening of feed required to eliminate chunks or the fines fraction? How well does the equipment handle the presence of unwanted chunks?
- Is the downstream process capable of handling the product with a smaller particle size?
- Is the installation indoors or outdoors?
- What is the operating temperature?
- What is the acceptable noise level?
- If the product introduces dust explosion concerns, what safety measures must be taken?
- If the product is toxic, what containment measures are required?
- If the application has sanitary requirements, such as food and pharmaceuticals, what design features are available for ease of cleaning, quick disassembly and preventing cross-contamination?
- Is the material abrasive? Do you need to take special measures (hardened surfaces) to minimize equipment wear or minimize metal contamination in the product?

Key steps for selection

The process of choosing size reduction equipment should be conducted in the following key steps [3]:

1. ***Define key process objectives and key requirements***
2. ***Characterize the feed material (and any future variations that are expected).***
3. ***Review the current process***
   a. Understand the effects of upstream process on variability in material properties of the feed material.
   b. Can the sequence of unit operations be altered or combined with comminution to achieve a reliable process?
   c. For multiproduct plants, consider the desired particle size for each of the various products
4. ***Identify the types of size reduction equipment commonly used in similar industries and product families.***
   a. Ask for references and understand typical issues on such equipment.
   b. Understand the differences in material characteristics and process requirements for references applications.
   c. Seek data to estimate energy efficiency, equipment reliability and product quality.
5. ***Establish the need for wet or dry grinding, cryogenic grinding and the need for grinding circuits.***
6. ***Make preliminary selection***

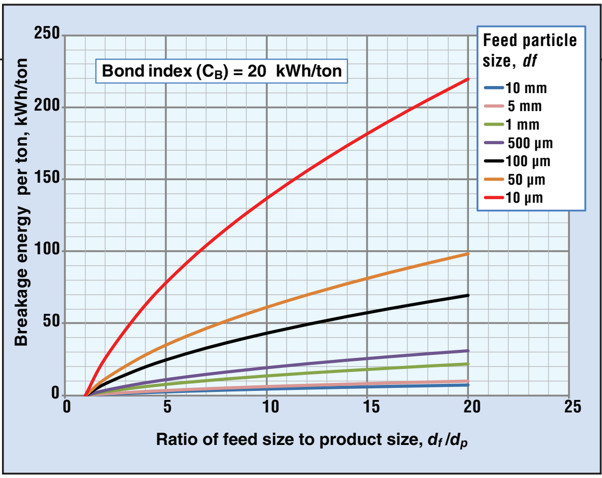


FIGURE 3. This plot illustrates a sample calculation of breakage energy for typical coal using Bond's approach

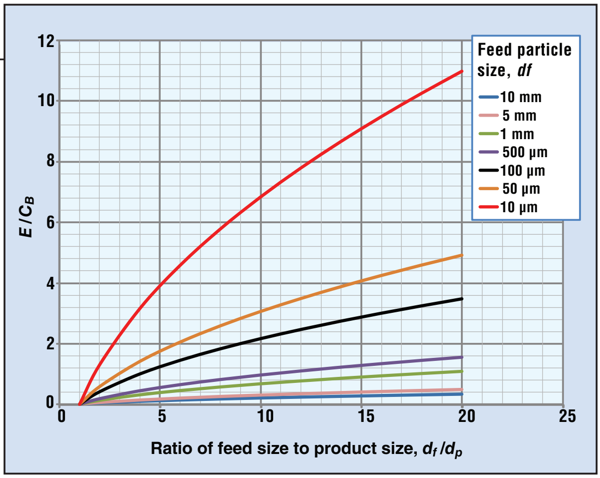


FIGURE 4. This generalized version of Figure 3 is useful to estimate breakage energy required for unknown materials

(short-list) of suitable equipment based on tables available in literature (similar to Table 2).

7. ***Prepare a document outlining specification and performance expectations.*** Ask each of the equipment suppliers to provide a preliminary proposal for the "system", which includes ancillary equipment. If the proposed system is a "grinding circuit", then make sure all components (screener, dust collector, conveyor) are itemized. Make sure that the equipment suppliers are aware of upstream and downstream unit operations, and the potential impact on their equipment's performance.
8. ***Conduct systematic tests on the equipment of interest.***
   a. Use representative material along with process extremes.
   b. Conduct tests at a reasonable scale.
   c. Let the equipment vendor experiment with and suggest variations in features that will best suit your application
   d. For continuous systems and grinding circuits, do not be limited to batch testing.
   e. For longer term tests (especially wear testing), consider installing a pilot scale unit using a side stream or use a toll vendor.
9. ***Make sure that the final selection criterion includes total cost of ownership, which includes total installed cost, maintenance cost and operating cost.***

Estimating breakage energy

The energy required for particle size reduction is the key to designing and specifying grinding equipment.

Various approaches. As indicated earlier, particle size reduction is a complex process where quantification of each contributing component (including mechanical inefficiencies) is extremely difficult. It is possible to make reasonable approximations using empirical relationships developed by Rittinger (1867), Kick (1885) and Bond (1952). More detail can be found in Refs. 5 and 6.

Rittinger postulated that the energy required for particle size reduction is directly proportional to the amount of new surface area created.

$$E = C_R\left(\frac{1}{d_p} - \frac{1}{d_f}\right) \quad (1)$$

Where
C_R = Constant, kWh-m/ton
E = Breakage energy per unit mass of feed, kWh/ton
d_f = Particle size of feed, m
d_p = Particle size of final product, m

Applying fundamentals of plastic deformation theory, Kick proposed that the energy required for particle size reduction was proportional to the ratio of volume of feed particle to product particle. The expression that Kick proposed does not account for the "absolute" change in particle size, just the ratio of the feed size to product size.

$$E = C_K \ln\left(\frac{d_f}{d_p}\right) \quad (2)$$

Where
C_K = Constant, kWh/ton
E = Breakage energy per unit mass of feed, kWh/ton
d_f = Particle size of feed, µm
d_p = Particle size of final product, µm

Suggested approach. Bond's approach, which gives reasonable approximation for most common size reduction processes, was based on industrial and laboratory data.

$$E = C_B\left(\sqrt{\frac{100}{d_p}} - \sqrt{\frac{100}{d_f}}\right) \quad (3)$$

Where
C_B = Bond's work index, kWh/ton
E = Breakage energy per unit mass of feed, kWh/ton
d_f = Particle size of feed defined as the sieve size through which 80% of the feed would pass through, µm
d_p = Particle size of product defined as the sieve size through which 80% of the product would pass through, µm

Bond's work index, by definition, is the energy required per unit mass to reduce the particle size from infinity to 100 µm. It is independent of particle size but does depend on the machine and mechanism of size reduction.

A sample calculation using typical Bond's work index for coal is plotted in Figure 3. For unknown materials, a generalized version (Figure 4) is useful for estimating breakage energy. Bond's work index values are often available in open literature or can be estimated by fitting the constant if laboratory, pilot or plant data are available. The calculation procedure is as follows:

1. Measure the feed size distribution using sieve analysis and estimate d_f
2. Based on the process requirements, estimate d_p. Calculate d_f/d_p.
3. Using Figure 4, estimate the E/C_B value.

4. Get Bond's work index value (C_B) from literature or use regression analysis on existing plant data to generate best estimate.
5. Calculate breakage energy per unit mass (E).

Wet grinding

In contrast to dry grinding, where the surrounding medium is a gas, wet grinding is performed with liquid as the surrounding medium. Wet grinding is often chosen for the following reasons:

- Material is prone to dust explosion and static charging
- Material is toxic and dust containment is difficult
- The final product size is extremely fine. (With wet grinding, production of nanoparticles is possible)
- Feed material is available in suspension and final product is desired as a suspension. (Wet grinding eliminates drying and re-dispersion steps)

Summary

Successful selection and application of size reduction equipment requires due diligence in material characterization, definition of process requirements and system selection. A partnership with a competent equipment supplier is critical, since the expertise in design and scaleup resides with them. ■

Edited by Rebekkah Marshall

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Authors

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

Jörg Theuerkauf is a senior research scientist in the Dow Wolff Cellulosics process R&D group at The Dow Chemical Co. (Bld. 1603, Midland MI 48640; Phone: 989-638-5033; Email: jtheuerkauf@dow.com). Theuerkauf is a graduate of the Technical University of Braunschweig (Germany), where he earned his *Diplom-Ingenieur* and Ph.D. in mechanical engineering. From 2000 to 2008 he worked in the solids processing laboratory in the area of particle technology. Since then he has worked in process R&D for Dow Wolff Cellulosics for new process and product development.

Cybersecurity for Chemical Engineers

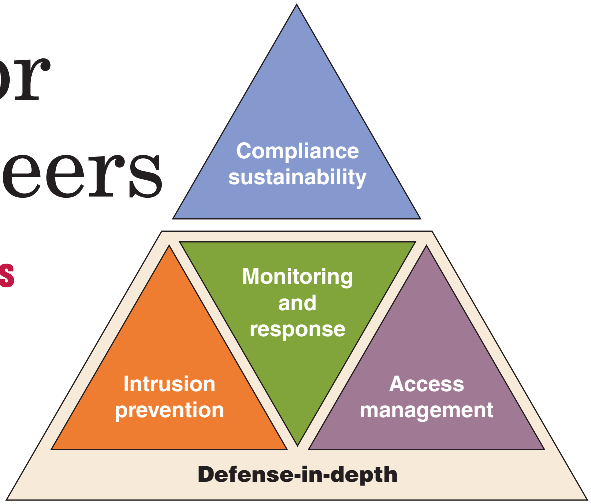


FIGURE 1. Defense-in-depth is a multi-pronged approach to security

Securing control systems in CPI facilities is gaining attention as threats become more sophisticated and overall plant security is in the spotlight

Andrew Ginter
Waterfall Security Solutions

Walt Sikora
Industrial Defender

There was a time, not long ago, when most groups responsible for industrial control systems (ICS) in the chemical process industries (CPI) were not much worried about security. They had their firewalls in place and their remote access servers, and overall that worked for them. Rarely, a virus would sneak in and usually do little damage. The affected computers would need to be shut down and cleaned out, but this could often be done without even scheduling a shutdown of the process.

Now, however, malware has become much more sophisticated, and all users of industrial control systems need to be aware of the threats. A basic understanding of cybersecurity can be helpful in keeping control systems secure. This article describes concepts such as "defense-in-depth," as well as emerging practices in this field.

The increasing threat

It seems that the more people learn about cybersecurity these days, the more worried they get. Today's most widely circulating malware is no longer produced by individual hackers, but is professionally written by programmers who come to work, produce malware all day long, and go home at night. The malware itself is supported professionally, and networks of malware-compromised machines are leased, bought and sold in a sophisticated underground economy.

Advanced, professional groups are thought to be behind the world's most sophisticated malware — so called "advanced persistent threats" (APT). This new class of threat appears to be managed by teams of specialists — a team to break into your network, another to propagate "low grade" malware in your network, a team to milk the most valuable information from your network, and a fourth team to monitor the health of the malware in your network. If that team sees you start to clean out the malware currently installed, they can escalate and seed your network with higher-class malware that is harder to detect, harder to clean out, and just as effective at stealing information. Estimates are that up to several hundred of the world's largest firms have been hit by APT in the last 24 months.

The game changing worm: Stuxnet. That said, these professional groups seem to have paid little attention to control systems computers, until very recently. Even though the sophistication of widespread malware has increased enormously in the last 24 months, control systems administrators had still felt as though their systems were not under specific attack. Any damage inflicted on ICS components by advanced threats was incidental and generally easily mitigated. All that has changed with Stuxnet.

The new Stuxnet worm (see box on p. 51) is a very sophisticated piece of malware that targets a specific control system. Most experts believe that Stuxnet will not be the last sophisticated attack to focus on control systems.

At the same time as this escalation of threats, two other factors have been at play: the Chemical Facility Anti-Terrorism Standards (CFATS) legislation in the U.S.; and a trend among large corporations to extend "governance, risk management and compliance" (GRC) initiatives to the entire enterprise — operations facilities included. As a result of these three trends, ICS administrators are receiving increasingly urgent calls to improve security measures for their control systems over the next few years.

CFATS

CFATS is security legislation specifically designed to protect the integrity of the U.S.'s most dangerous chemical facilities. CFATS is "risk based," which means that chemical site and transportation risks are evaluated based on the types of chemicals involved and their volumes.

The CFATS regulations themselves are fairly terse, and touch on a complete security program, from policies and procedures, to personnel screening, training, incident response, incident reporting, audits and yes, cybersecurity. CPI facilities are required to submit information about the chemicals and volumes they handle, and the sites are classified into four tiers based on a risk assessment. U.S. Dept. of Homeland Security (DHS) auditors are currently reviewing the security plans for some 30–40 highest-risk sites per month. Those auditors decide whether the plans are adequate or need improvement, and if necessary, specify deadlines for compliance and ultimately penalties for non-compliance. (For more on CFATS see Securing the CPI, *Chem. Eng*., September 2010, pp. 17–20; and Chemical Plant Security, *Chem. Eng*., September 2009, pp. 21–23.)

The DHS has also issued guidance for "risk-based performance assessments" of CFATS security plans. This guidance does not have the force of law, but since the DHS has issued the advice, and it is DHS auditors who evaluate CFATS security plans, it is safe to assume that the DHS auditors will give the DHS advice considerable weight when auditing a security plan.

While modern control systems do still use equipment like programmable logic controllers (PLCs) and other controllers that look very little like conventional computing systems, the majority of equipment in modern control systems is very similar to equipment in use on enterprise networks. As a result, the DHS guidance for CFATS draws heavily on security standards for enterprise networks. The guidance document really contains a subset of the advice in the DHS "Catalog of Control Systems Security: Recommendations for Standards Developers" document, which itself was an adaptation of NIST 800-53. The NIST (National Institute of Standards and Technology) standard has no force of law outside of federal government agencies, but is highly regarded by enterprise security professionals worldwide.

IT / OT integration

The trend toward "corporate" security standards, which include control systems components, is something that the authors regularly encounter. Not only are security standards converging, we also see many CPI firms with corporate information technology (IT) and plant operations technology (OT) groups integrating. Today, most "integrated" groups remain distinct with separate responsibilities, both reporting to the same level of management. However, a steadily increasing number of firms have completely integrated IT and OT departments, and apply a consolidated management discipline to both enterprise and to plant network and computing assets.

Such integration is not easy, nor is it without cost. In enterprise networks, the security priorities "mantra" is "CIA" — confidentiality first, then integrity, then availability. You don't want the Web store to go down, because that is how orders come in. But you would rather take the Web store down than have the orders' database corrupted. And you would take the Web store down in a heartbeat if it looked like customer credit card numbers or corporate intelligence were leaking out to the world.

In control system networks, the mantra is reversed (AIC) because safety comes first. Nothing is risk-free, but under no circumstances can a site afford to subject employees, the public or the environment to a higher-than-approved risk of injury. While a site generally has several levels of safety systems, the control system human-machine-interface (HMI) and the human operators are generally regarded as the two highest levels in the safety system. In many cases, dangerous chemical processes may not be operated for more than a few seconds if human oversight of the process is lost. As a result, the availability and integrity of the control system are far more important than confidentiality.

What IT needs to learn

The CIA / AIC inversion is only the tip of the iceberg in terms of problems to expect when integrating IT and OT teams. As many IT and OT organizations have discovered to their dismay, blindly applying corporate IT security policies to control systems networks leads to safety shutdowns. In short, corporate IT has had to learn the following:

- You can't just start installing software updates on control systems. Indiscriminate updating (or patching, as it is called) voids ICS vendor support agreements, and can lead to malfunction and safety shutdowns
- You can't just apply anti-virus software to control systems. Indiscriminate application of anti-virus technologies again voids support agreements and frequently leads to malfunction. Any change to control systems must go through a vendor review, change review and testing process
- You have to change some service level agreements (SLAs). For example, enterprise repair personnel may be accustomed to 4–6 h turn-around on failed routers, but faster response may be necessary to preserve availability in the ICS space
- Some OT systems really are special and can't be managed like enterprise systems. PLCs and PLC communications protocols, for example, are completely foreign to most IT teams and most IT management software

Often, IT teams learn "the hard way" how different OT systems are. For example, process shutdowns can be triggered by activities as simple as a network vulnerability scan. Corporate IT personnel carry out such scans on enterprise equipment routinely, without even thinking about it. Yet, such scans can cripple certain PLCs or other ICS equipment.

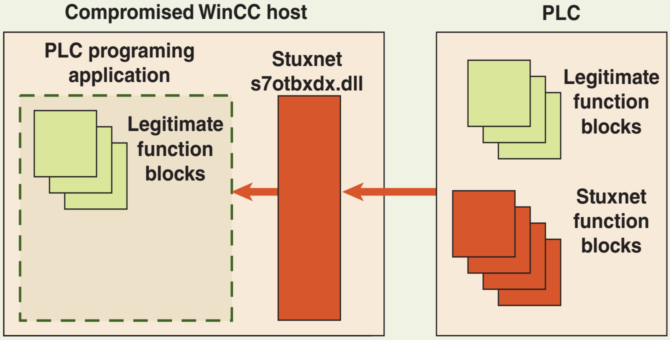
What OT needs to learn

But there is another side to the coin. There are things OT teams need to learn as well, in this world of increased threats, increased regulations and increased imperatives for good corporate governance:

- You have to start patching control systems. Even though patching control systems is difficult, sites need to start working with their vendors and make this happen. Even if patches take longer to install in the ICS world, they do provide protection against a great number of threats
- You have to start applying anti-virus technology to control systems. Even though the application of anti-virus remedies can crash some older components, modern components all support anti-virus solutions, and again, this technology provides real protection against a large number of threats
- You can't change some SLAs. There may be large, complex third-party agreements or other impediments to change. OT personnel must continue to maintain some equipment,

THE STUXNET WORM

The Stuxnet worm is a sophisticated "rootkit" for Siemens S7 PLCs. While there is only circumstantial evidence as to who wrote the worm and what the worm's target was, most analysts suggest the worm was created by a military or intelligence agency, and targets gas-centrifuge uranium enrichment facilities. The Stuxnet worm is the first clear, public evidence of sophisticated adversaries using computer malware to sabotage control systems. Given that many nations have announced funding for cyber-warfare capabilities, few analysts believe that this worm is the last we will see of malware designed for industrial sabotage.



The Stuxnet worm contains some 70 PLC function blocks and can send some or all of those blocks to PLCs that are connected to a compromised targeted host (diagram). Not only does the worm change PLC programs, it also hides the malicious programming from users of compromised hosts.

The worm hides the modified PLC programs by marking the malicious function blocks and then "wrapping" the library that the programming tools use to read and write function blocks in PLCs. The wrapper recognizes the worm's marked function blocks and filters them out when programming tools look at the blocks in a PLC. When you start a PLC programming tool on a compromised WinCC host and try to look at a PLC whose programming the worm has changed, the programming tool shows you only the function blocks legitimately in the PLC — everything else is invisible to the tool.

The worm takes advantage of five Windows vulnerabilities and some aspects of the control system design. The targeted PLC and indeed most vendors' PLCs accept new programs from any computer that connects to them. Sensitive functions like changing PLC firmware or PLC function blocks are not generally protected by special administrative accounts or passwords. As a rule, PLCs do not require cryptographic signatures for new function blocks before accepting those function blocks.

The bottom line on prevention is that while anti-virus technologies and patches are now available to protect against Stuxnet, sites with active anti-virus and patch programs were still vulnerable during the 3–4 months the mature version of the worm circulated undetected. During that period, virus signatures for the worm did not exist, nor did patches for four of the five Windows vulnerabilities used by the worm. Firewalls, physical security and other perimeter security were no help either, because the worm could propagate past such measures on infected USB sticks carried by trusted personnel. Disabling USB mass storage on all control systems hosts would have prevented the worm at some sites, but some functions of the targeted control system require the use of USB sticks.

The existing technology that would have provided the strongest protection against Stuxnet is HIPS technology. Control-system security practitioners should become familiar with this kind of technology as soon as is feasible. ❑

or enough hot spares must be purchased to make IT SLAs acceptable for those OT components

- Some OT systems really aren't special, and should be managed like enterprise systems. This is especially true of firewalls, remote access managers and other security equipment facing the enterprise network

As a rule, control systems can continue to work safely and correctly without connectivity to enterprise networks. This means that while perimeter security equipment may be business-critical, it is not safety-critical. Equipment that is only business-critical should be managed the way any other business-critical equipment is managed in the enterprise — with a strong firmware and patch management program.

What the business needs to learn

In the end, though, security does not come for free. Increased integration of IT and OT teams, and also of security policies, only works if the business learns some lessons:

- You have to spend money on test beds, people and redundancy. You need enough test equipment to be able to set up a "close enough" copy of your production control system. You need to be confident that if software updates and new anti-virus signatures and other changes installed on your test system do not impair that test system, then they will not impair your production environment either. You need enough redundancy in your control system to be able to roll out software updates and anti-virus signatures to only some of your equipment. If those changes malfunction in production in spite of your best testing, you need to be able to take the malfunctioning equipment out of service and undo the changes without impairing the control system overall
- You have to capture knowledge. OT people are retiring in large numbers. Businesses need a program to capture the long experience of these people, both to train a new generation of OT staff, but also to spread among the IT team for those functions enterprise IT people can help with
- IT and OT need to be held accountable. For example, IT management must be accountable if IT personnel trigger shutdowns because of failure to follow OT change control procedures. OT management must be accountable if they fumble the security program and release malware into the enterprise

In addition, the business needs to engage with OT vendors and persuade them to implement programs to promptly support operating system patches, to support anti-virus or other malware protection technologies, and to make PLC and other device network communications more robust, and with stronger authentication protections.

Defense-in-depth

All the points discussed so far can be regarded as drivers for a strong security posture, but what does a strong security posture actually look like? The key is something called defense-in-depth. Like safety, security is not a boolean value. You never say "there — now I'm secure," just as you would never say "there — now I'm safe." Given enough time, enough money and enough smart people, any adversary can defeat any security measure.

A defense-in-depth strategy then, is three-fold:

1. Layers of protection on your assets — firewalls and remote access protections, proxies, host hardening, patching and host malware protections
2. Intrusion detection and continuous monitoring — systems to detect unauthorized changes to or activity on your industrial hosts and networks
3. Incident response plans and teams to respond quickly when an intrusion is detected and to shut down the attack before it breaches additional layers of defenses

The goal is not just to protect your systems, because a determined adversary can get through any protection. Instead, you both protect and monitor. The layers of protection will slow down an adversary to the point where your monitoring systems detect their attack, enabling your response teams to take the time to analyze the attack and respond to it. Just as for every defense there is an offense, for every attacker's offense, there is a defense. If you can detect the attack, and you have enough time, you can stop it.

Emerging practices

There is an evolution of security practice at CPI sites that the authors' companies personnel see regularly. Historically, CPI facilities started their security programs by protecting electronic perimeters with firewalls and remote access controls. Currently, many sites are in the process of improving those security postures by deploying patch programs and anti-virus technologies. In addition, many sites are starting to install additional defense-in-depth measures, including the following:

- ***Network intrusion detection systems*** (NIDS), which continuously monitor network traffic inside the perimeter to allow sites to detect and respond to malicious activity that has somehow made it past the perimeter, perhaps on a USB flash stick, or because of an insider attack
- ***Host intrusion detection systems*** (HIDS), which continuously monitor host activity like process execution, sockets opening and closing, and file modifications — again to detect malicious activity that has bypassed the security perimeter
- ***Security event management systems***, which aggregate security information from many sources into one place, apply rules to identify suspicious or anomalous activity and raise alerts in realtime about such activity

In addition, many sites are looking at further segmenting their networks. Instead of just two security segments — the "enterprise" network and the "plant" network — many sites are creating additional segments. The most-common additional segmentation is the addition of "demilitarized zones" to the plant-enterprise interface. These zones house systems, such as plant historians that need information from the control network, but that are accessed by users on the enterprise network. Less commonly, but increasingly, we see firewalls protecting the "real" control network: the network of PLCs, I/O controllers, distributed control systems (DCS) and HMI workstations that directly control the chemical processes.

Emerging technologies

Two technologies are emerging that warrant close inspection: *host intrusion prevention systems* (HIPS) and *compliance management systems*.

HIPS technology. Also known as "whitelisting" or "application control" systems, HIPS systems store cryptographic checksums of applications, libraries and other executables on protected machines, and rules for which applications can and cannot run. When an application starts up or a library is loaded, the hash is recalculated; if the executable is unchanged and still approved for execution, execution continues normally, otherwise execution is blocked.

HIPS is new in the control systems protection space, but has been receiving a lot of attention recently. Worms, viruses and other malware are not on the approved list of software for any machine, so even if patches or new anti-virus signatures are not yet available for such malware, the malware is not approved to execute, and so execution is blocked. Better yet, HIPS systems are much more stable in terms of change control programs than are anti-virus systems. Anti-virus systems require new signatures as often as several times per day. Testing these signatures for false positives is costly, but necessary to ensure that the signatures do not flag legitimate control system software as malware and quarantine it. HIPS has no signatures, but you do need to update the list of approved cryptographic hashes as part of your change control program every time you change the software on your control system hosts.

Compliance management software. This tool is also new in the control systems space. Security programs incur labor costs beyond patching and testing. DHS guidelines for CFATS security plans include maintaining an inventory of equipment on control networks, an inventory of what software, firmware and versions are running on each equipment, an inventory of what services are running and what communications ports are open and other details of equipment configuration, such as users and permissions. Further, CFATS guidelines require log archiving and retention, reviewing logs and accounts regularly, and reviewing certain summary reports and other reports as part of internal and external audit processes.

For a large facility with hundreds or thousands of components in several control systems applications, gathering, summarizing and reviewing all of these data manually can incur significant costs. Compliance management software automates these activities. Device, host, software, firmware, user and other information is automatically gathered, usually daily. Logs are archived, inspected, summarized and reported automatically, and anomalies that require immediate attention are called out quickly and automatically. Customers with even one or two large sites report savings of up to several full-time-equivalent positions after installing compliance management solutions.

Looking forward

In the future, we can expect the DHS to more rigorously apply CFATS rules. The CPI should expect CFATS to evolve to become more prescriptive, similar to the evolution of the NERC CIP regulations in the electrical industry. Further, with or without new regulations, operations personnel should expect steadily increasing scrutiny of their operations by corporate security personnel and corporate audit committees as part of a steady migration toward better corporate governance. We also need to expect that the threat environment will become steadily more challenging as sophisticated control-system-targeted attacks continue to emerge.

All of this means that, like safety programs fifteen years ago, security programs need to become pervasive at CPI facilities. There was a time when "the safety people do safety." This has evolved at most sites to where safety is everybody's job — everyone from purchasing to construction to maintenance and operations people. The same evolution is under way for security programs. Like safety programs, security programs are working their way into every aspect of the design, maintenance and operation of CPI facilities. ■

Edited by Dorothy Lozowski

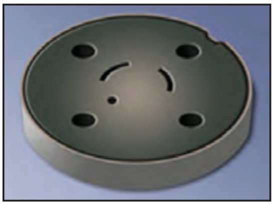
Authors

Andrew Ginter Andrew Ginter is the director of industrial security at Waterfall Security Solutions (Calgary, Alberta, Canada; Email: andrew.ginter@waterfall-security.com; Website: www.waterfall-security.com; Blog: controlsystemsecurity.blogspot.com). Before Waterfall, Ginter led research and development teams at Industrial Defender, Agilent Technologies and Hewlett-Packard, producing both control system and security products. Ginter holds a B.Sc. in applied mathematics and an M.Sc. in computer science, both from the University of Calgary, in Calgary, Alberta, Canada. He also holds ISP, ITCP and CISSP accreditations.

Walter Sikora is vice president of security solutions at Industrial Defender (16 Chestnut St., Suite 300, Foxborough, MA 02035; Email: wsikora@industrialdefender.com; Phone: 508-718-6706). Sikora has more than 27 years of industrial experience with SCADA, DCS and PCS systems, and security. He previously spent 21 years with Invensys, Inc. as director of service engineering and development, where he was responsible for developing services and tools for UNIX and Windows NT as well as security solutions for Foxboro Intelligent Automation users. He holds an Associate Degree in engineering technology from Massasoit Community College, a B.S. degree in electrical engineering from Northeastern University, and is currently an M.B.A. candidate at the Gordon Institute of Tufts University.

FOCUS ON

Seals and Gaskets



E.I. du Pont de Nemours

Handle abrasion and wide pH swings with these diaphragms

The recently upgraded Wil-Flex diaphragms for air-operated double-diaphragm (AODD) pumps (photo) can handle abrasion and wide swings in pH values, making them idea for use in paints and coatings applications. Designed with a flat profile, the Wil-Flex diaphragms are easy to install, and can be an excellent low-cost alternative to PTFE (polytetrafluoroethylene) diaphragms. Wil-Flex diaphragms are made from Santoprene, a thermoplastic elastomer that links ethylene propylene diene monomer with rubber and polypropylene. Because of their thermoplastic qualities, the diaphragms have inherent tensile strength and do not need fabric reinforcement. — *Wilden Pump and Engineering Co., Grand Terrace, Calif.*
www.wildenpump.com

Extend seal life with this engineering polymer

Designed for extended part life in sealing and bearing applications, this company's Vespel SCP-5009 (photo) is a engineered polyimide that can be used in lubricated, high-friction environments. Its high heat- and pressure-resistance capabilities make it a good candidate for helping to realize performance advantages in the areas of materials handling, analytical instrumentation, energy and medical devices. The company says Vespel SCP-5009 can help bring cost savings and higher performance to many sealing challenges because the polymer combines resistance to temperatures above 300ºC, high compressive and mechanical strength, broad chemical resistance and a low coefficient of friction. — *E.I. du Pont de Nemours & Co., Wilmington, Del.*
www.dupont.com

A seal-face coating that combats dry-running wear

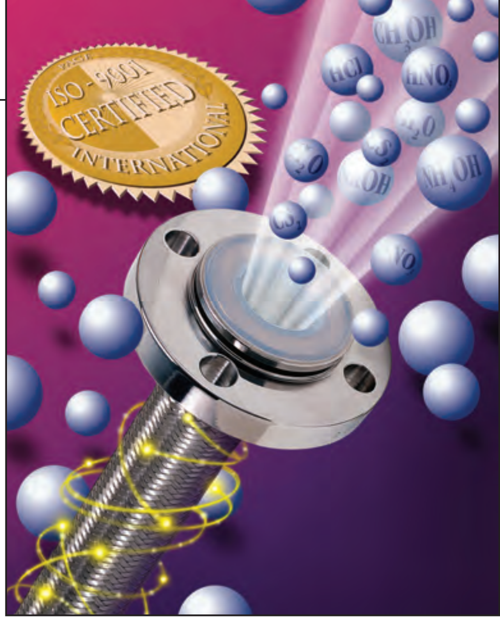
DiamondFaces is a coating for the seal face of mechanical seals that prevents pump failures due to inadequate lubrication or dry running. The synthetically manufactured DiamondFaces coating has the same chemical and physical characteristics as natural stone. A DiamondFacesmicrocrystalline coating of 8-µm thickness on a silicon carbide seal face extends the life of the seal, reducing maintenance costs and minimizing lifecycle costs for pump users, the company says. Combining SiC seal faces with the coating allows dry-running periods up to several hours without excessive heat buildup. — *EagleBurgmann, Houston*
www.eagleburgmann.com

Rubber material with high resistance to flex fatigue

Gaskets and seals manufactured with this company's Santoprene thermoplastic vulcanizate (TPV) feature excellent resistance to flex fatigue, as well as harsh temperatures and chemicals. The longterm sealing performance of Santoprene TPV is useful for a wide range of industrial applications requiring both static and dynamic seals, and is available in a number of bonding grades. The material is fully recyclable in the polyolefin stream. — *ExxonMobil Chemical Co., Houston*
www.exxonmobilchemical.com

Prevent bacterial entrapment with these seals

With a PTFE lining that passes through the tube fitting and is flared over the fitting face, the Page PTFE Flare Seal (photo) provides 100% PTFE coverage of all wetted surfaces. The flared seal eliminates flow restrictions from the tube, and prevents trapping of bacteria for sanitary applications. Chemically resistant and durable, the Flare Seal is available with a stainless-steel braid, a polypropylene braid or other material. Flare Seal tubing is also available in a variety of lengths and diameters. — *Parker Hannifin Corp., Fort Worth, Tex.*
www.parker.com



Parker Hannifin

Wilden Pump and Engineering

Handle high temperatures with this polymer

The Perlast G75TX perfluoroelastomer can boost sealing performance by overcoming the poor compression response normally associated with perfluoroelastomers at high temperatures. The compound's high temperature resistance is combined with enhanced mechanical and chemical resistance, the company says, adding that the Perlast's low compression set of just 8%, compared with the more typical 38%, gives the elastomer a longer service life in valves, pumps and mechanical seals. — *Precision Polymer Engineering (PPE) Ltd., Blackburn, England*
www.prepol.com

This expansion joint is designed for slurries

Series 271 rubber expansion joints feature a superwide flowing-arch design that is self-cleaning, making them

Note: For more information, circle the 3-digit number on p. 62, or use the website designation.

Ashcroft

ideal for use with slurries. The 271 Series absorbs directional movement, as well as vibration and noise. The expansion joints are ideal for use with fiberglass-reinforced plastic (FRP) piping systems, the company says. — *Proco Products Inc., Stockton, Calif.*
www.procoproducts.com

Shield instruments from caustic media with these seals
This company's Type 510 and 511 diaphragm seals (photo) are instrument media isolators, suitable for protecting pressure gages, transmitters, switches and other instruments from the effects of caustic substances. The all-welded seals can be used from vacuum pressure up to 5,000 psi, and can be either threaded onto a standard, National Pipe Thread (NPT) fitting or welded directly. The seal models also feature a choice of diaphragm materials, fill fluids, and in the case of the 511, a lower housing flush port. — *Ashcroft Inc., Stratford, Conn.*
www.ashcroft.com

These seals are designed specifically for agitators
The ChemSeal is the newest line of mechanical seals designed specifically for agitator service. The seal features high runout, reverse rotation and reverse pressure capability. Designed for easy installation and maintenance, the ChemSeal cartridge seals can be readily removed from the agitator as a complete assembly and repaired on the workbench. ChemSeals are available in a variety of materials to meet different temperature and pressure ratings, as well as four standard sizes. ChemSeals can be retrofitted onto existing agitators made by this company. — *Chemineer Inc., Dayton, Ohio*
www.chemineer.com

These gaskets minimize cold-flow problems
The Gylon Series of PTFE gaskets is manufactured by a unique process that minimizes cold-flow problems typical of skived and expanded PTFE sheets. The gaskets have excellent bolt-torque retention, and withstand a wide range of chemicals, including strong caustics, moderate acids, chlorine, steam and others, allowing for extended service life in a variety of applications. The Gylon Series includes models with different filler materials, such as graphite, barium sulfate, silica and others. — *Garlock Sealing Technologies, Palmyra, N.Y.*
www.garlock.com ■

Scott Jenkins

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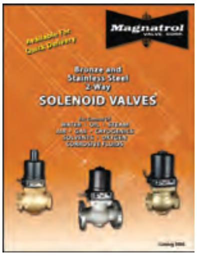

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BUSINESS NEWS

PLANT WATCH

Strategic partnership for acrylonitrile and sodium cyanide in the Middle East

April 29, 2011 — Saudi Basic Industries Corp. (SABIC; Riyadh, Saudi Arabia; www.sabic.com), Asahi Kasei Chemicals Corp. (Tokyo; www.asahi-kasei.co.jp) and Mitsubishi Corp. (Tokyo; www.mitsubishicorp.com) have signed a joint venture (JV) agreement to form a limited liability company, Saudi Japanese Acrylonitrile Co. (SHROUQ), which will be located at Al-Jubail, Saudi Arabia. SABIC will own 50% of the venture and Asahi Kasei Chemicals and Mitsubishi will together own 50%. The company will build a plant for the manufacture of 200,000 metric tons per year (m.t./yr) of acrylonitrile and 40,000 m.t./yr of sodium cyanide at a SABIC affiliate's site in Jubail Industrial City, Saudi Arabia. Final decisions on capital expenditure are expected to be made during 2012.

KBR receives EPC contract for biomass-to-crude project in Mississippi

April 20, 2011 — KBR, Inc. (Houston; www.kbr.com) has been awarded an engineering, procurement and construction (EPC) contract by KiOR, Inc. (Pasadena, Tex.; www.kior.com) to build a facility in Columbus, Miss., designed to process approximately 500 ton/d of wood biomass and produce over 11 million gal/yr of fuel. KiOR's technology is designed to convert biomass into drop-in biofuels, such as gasoline and diesel blendstocks.

World's first cellulosic biobutanol refinery to be built in Michigan

April 19, 2011 — Cobalt Technologies (Mountain View, Calif; www.cobalttech.com) and American Process Inc. (API; Atlanta, Ga.; www.americanprocess.com) have announced an agreement to build a cellulosic biorefinery to produce biobutanol. Under the agreement, Cobalt Technologies and American Process will integrate Cobalt's patent-pending continuous fermentation and distillation technology into American Process's Alpena biorefinery, currently under construction in Alpena, Mich. Slated to begin ethanol production in early 2012 with a switch to biobutanol in mid 2012, the API Alpena biorefinery will produce 470,000 gal/yr of biobutanol.

Lanxess to expand capacities for high-performance rubber in U.S.

April 15, 2011 — Lanxess AG (Leverkusen, Germany; www.lanxess.com) is expanding its capacities to produce solution styrene butadiene (SSBR) and neodymium polybutadiene (Nd-PBR) rubbers. An additional 20,000 m.t./yr of the high-performance rubbers will come on stream at the company's site in Orange, Tex., by the 3rd Q of 2012. The expansion represents a €10 million investment. At the same time, Lanxess has completed its debottlenecking project to increase production of Nd-PBR by 15,000 m.t./yr at its site in Orange.

Technip wins a contract for a methionine plant in China

April 14, 2011—Technip (Paris, France; www.technip.com) has been awarded a contract by Bluestar Adisseo Nanjing Co. for a methionine plant in Nanjing, Jiangsu Province, China. The plant, which will be the first integrated liquid methionine unit in China, will have a production capacity of 140,000 ton/yr. The mechanical completion is scheduled for the 2nd Q of 2012.

SOCC selects Samsung Engineering to construct TEAL facility

April 11, 2011 — Saudi Organometallic Chemicals Co. (SOCC), a JV equally owned by SABIC affiliate, Specialty Chem (Saudi Specialty Chemical Co.) and Albemarle Netherlands B.V., a wholly owned subsidiary of Albemarle Corp. (Baton Rouge, La.; www.albemarle.com), has selected Samsung Engineering to provide EPC services for a manufacturing facility in Jubail, Saudi Arabia. The SOCC facility will initially manufacture 6,000 m.t./yr of triethyl aluminum (TEAL). The mechanical completion date is projected for the 3rd Q of 2012.

Praxair to build new plant in Argentina

April 11, 2011 — Praxair Argentina, a subsidiary of Praxair, Inc. (Danbury, Conn.; www.praxair.com) will build a new plant in Argentina. Scheduled to start up in 2013, the plant will produce 400 ton/d of oxygen, nitrogen and argon.

AkzoNobel to boost production of microspheres in Sweden

April 6, 2011 — With an investment of €30 million, AkzoNobel (Amsterdam, the Netherlands; www.akzonobel.com) is boosting capacity for its Expancel expandable microspheres. The extra capacity — due to come on stream in early 2012 — will be added at the company's site in Stockvik.

MERGERS AND ACQUISITIONS

BASF to acquire ultrafiltration specialist Inge Watertechnologies AG

April 28, 2011 — BASF SE (Ludwigshafen, Germany; www.basf.com) has signed an agreement with the investor group of Inge Watertechnologies AG (Greifenberg, Germany; www.inge.ag) to acquire the company and its ultrafiltration membrane business. The investor group and BASF have agreed not to disclose financial details of the deal. The transaction, which is subject to approval by competent merger control authorities, is expected to close within the 3rd Q of 2011. With the acquisition of the water treatment business as part of the Ciba acquisition in 2009, BASF has become a leading supplier of organic flocculants and coagulants, which are key technologies for water treatment processes.

Avantium spinoff creates a new pharmaceutical company, Crystallics

April 19, 2011 — Avantium Pharma BV (Amsterdam, the Netherlands; www.avantium.com) has been spun out from Avantium Holding BV in a management buy-out to create Crystallics (www.crystallics.com). The new company will remain in Amsterdam and will specialize in solid state research and pre-formulation for pharmaceutical, biotechnology and agrochemical companies.

Dow and OPXBio collaborate on renewable route to acrylic acid

April 11, 2011 —The Dow Chemical Co. (Midland, Mich.; www.dow.com) and OPX Biotechnologies, Inc. (OPXBio; www.opxbio.com) are collaborating to develop an industrial scale process for the production of bio-based acrylic acid from renewable feedstocks. Dow and OPXBio recently signed a joint development agreement to prove the technical and economic viability of an industrial-scale process to produce acrylic acid using a fermentable sugar (such as corn or cane sugar) feedstock with equal performance qualities as petroleum-based acrylic acid. The companies will discuss commercialization opportunities that could bring bio-based acrylic acid to market in three to five years. (For more, see Bio-based Chemicals Positioned to Grow, *CE*, March 2011, pp. 19–23) ■

Dorothy Lozowski

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

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FOR MORE ECONOMIC INDICATORS, SEE NEXT PAGE

Economic Indicators

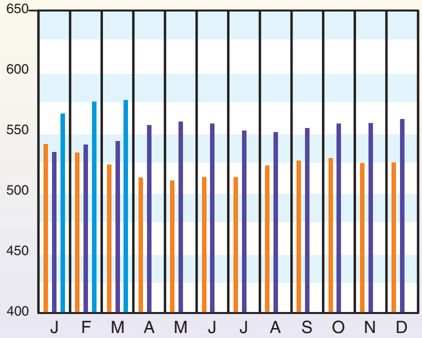
2009 2010 2011

DOWNLOAD THE *CEPCI* TWO WEEKS SOONER AT WWW.CHE.COM/PCI

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Mar.'11 Prelim.	Feb.'11 Final	Mar.'10 Final
***CE* Index**	575.9	574.6	541.8
Equipment	698.7	696.6	645.5
Heat exchangers & tanks	657.5	654.4	592.5
Process machinery	662.1	653.5	614.0
Pipe, valves & fittings	862.8	868.3	801.7
Process instruments	438.7	440.8	421.0
Pumps & compressors	898.5	892.6	903.4
Electrical equipment	499.4	498.0	472.1
Structural supports & misc	738.6	732.1	665.6
Construction labor	324.3	326.2	328.2
Buildings	514.2	509.9	504.3
Engineering & supervision	334.3	334.9	341.8

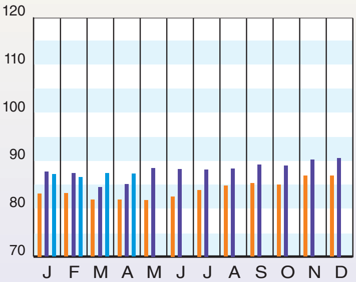
Annual Index:
2003 = 402.0
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8



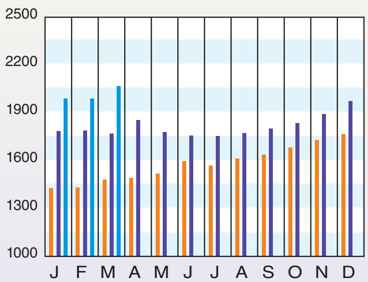
CURRENT BUSINESS INDICATORS

	LATEST		PREVIOUS				YEAR AGO	
CPI output index (2007 = 100)	Apr.'11	= 87.3	Mar.'11	= 87.4	Feb.'11	= 86.6	Apr.'10	= 85.1
CPI value of output, $ billions	Mar.'11	= 2,068.5	Feb.'11	= 1,990.4	Jan.'11	= 1,989.2	Mar.'10	= 1,770.2
CPI operating rate, %	Apr.'11	= 75.2	Mar.'11	= 75.3	Feb.'11	= 74.6	Apr.'10	= 72.6
Producer prices, industrial chemicals (1982 = 100)	Apr.'11	= 322.7	Mar.'11	= 312.9	Feb.'11	= 304.2	Apr.'10	= 275.1
Industrial Production in Manufacturing (2007=100)	Apr.'11	= 89.7	Mar.'11	= 90.1	Feb.'11	= 89.5	Apr.'10	= 85.7
Hourly earnings index, chemical & allied products (1992 = 100)	Apr.'11	= 155.3	Mar.'11	= 156.2	Feb.'11	= 154.2	Apr.'10	= 151.2
Productivity index, chemicals & allied products (1992 = 100)	Apr.'11	= 111.8	Mar.'11	= 113.0	Feb.'11	= 112.9	Apr.'10	= 110.8

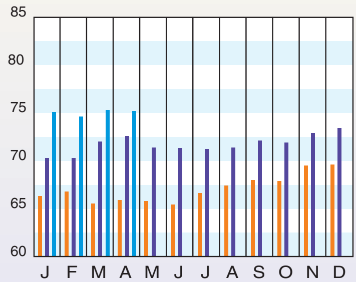
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



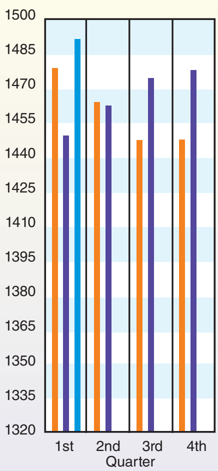
Current Business Indicators provided by Global Insight, Inc., Lexington, Mass.

MARSHALL & SWIFT EQUIPMENT COST INDEX

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

Annual Index:

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



CURRENT TRENDS

Capital equipment prices, as reflected in the *CE* Plant Cost Index (CEPCI), increased slightly from February to March. But the year-on-year margin narrowed slightly.

Meanwhile, according to the American Chemistry Council's most-recent weekly economic report at *CE* press time (Arlington, Va.; www.americanchemistry.com), overall production rose strongly in April with gains centered in specialty chemicals, plastics resins, synthetic rubber and man-made fibers. The rail-car-loadings data indicate that this growth continued into May.

Visit www.che.com/pci for more and other tips on capital cost trends and methodology. ■

Circle 3 on p. 62 or go to adlinks.che.com/350666-03