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CHEMICAL ENGINEERING

February 2015

ESSENTIALS FOR THE CPI PROFESSIONAL

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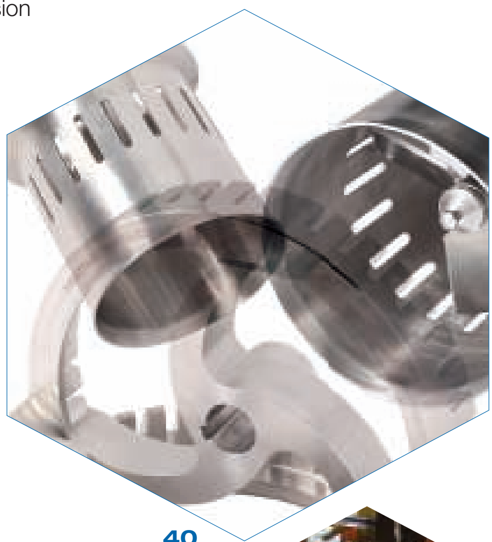
In the News

Technical and Practical



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Editor's Page

Inspiring Women in the CPI

Good role models can greatly influence the path of a person's career. While role models don't always receive awards, recent announcements of award recipients describe a number of professionals in chemistry and chemical engineering who have been singled out for their exceptional accomplishments. These women are indeed role models, and a source of inspiration to others in the chemical process industries (CPI).

A trailblazer

In November, President Obama honored the newest recipients of the National Medal of Science and the National Medal of Technology and Innovation — the highest honors bestowed by the U.S. Government for achievements in science, technology and innovation. One of the eight recipients of the National Medal of Technology and Innovation was Edith Flanigen, a chemist with UOP, a Honeywell company, who is now retired but remains an active consultant for the company.

Flanigen began her career at Union Carbide in 1952, a time when there were few women in chemistry. She worked on the purification and extraction of silicone polymers and the manufacture of molecular sieves, and she invented a process to synthetically manufacture gem-quality emeralds for use in early laser technology. Over the course of her 42-year career, Flanigen invented more than 200 synthetic materials and received 109 patents. In 1991, she was the first woman to be awarded the Perkin Medal, an annual award from the Society of Chemical Industry (SCI) that recognizes outstanding work in applied chemistry. The first Perkin Medal was awarded in 1906.

Winning careers

The Society of Women Engineers' (SWE) Suzanne Jenniches Upward Mobility Award, endowed by Northrop Grumman, recognizes a woman who has risen to a significant position in her organization, and has created a nurturing environment for other women in their workplaces. In November, SWE announced the latest recipient of this award: Janeen Judah, general manager of Chevron Corp.'s Southern African Strategic Business Unit. Judah, a Houston-area resident who holds degrees in petroleum engineering and law, received the award for her multi-disciplinary career achievements, as well as for inspiring other women in science, technology, engineering and mathematics (STEM).

Jacqueline Barton, the Arthur and Marian Hanisch Memorial Professor of Chemistry and chair of the Division of Chemistry and Chemical Engineering at the California Institute of Technology, will receive the American Chemical Society's (ACS) Priestley Medal in March and the American Institute of Chemists (AIC) Gold Medal in May of this year. Barton pioneered the application of transition-metal complexes to probe recognition and reactions of DNA. Her work has been useful in laying a foundation for the design of chemotherapeutics. She has trained more than 100 graduate and postdoctoral students.

We are grateful to these women and the many others who, by example, provide inspiration to others in the field. ■

Dorothy Lozowski, Editor in Chief

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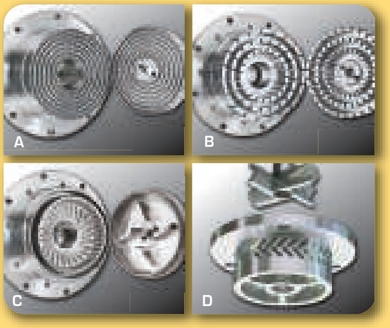

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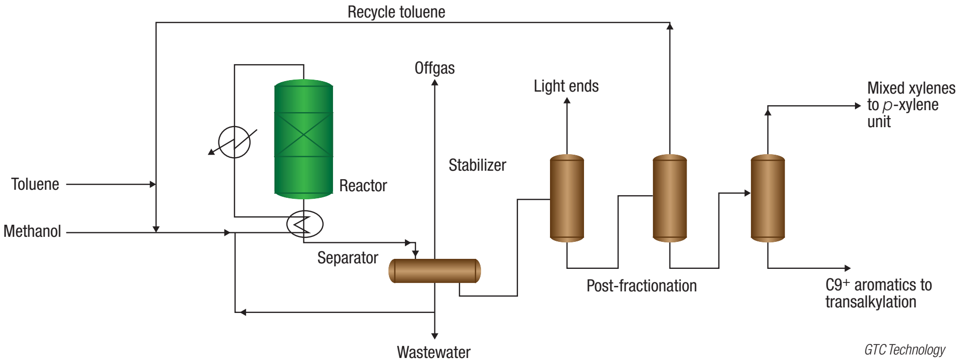
Xylenes production method takes advantage of low-cost methanol feedstock

Edited by:
Gerald Ondrey



GTC Technology

A new low-pressure process for making xylenes combines toluene with methanol to yield a xylenes product stream with the possibility of no benzene byproduct. Known as GT-TolAlk and developed by GTC Technology (Houston; www.gtctech.com), the new process requires no hydrogen addition and produces only water as a byproduct.

The first facility to use the process is currently in the design phase, and is slated for startup in 2016 at a Chinese petroleum refinery, says David Bridgeman, global licensing manager at GTC.

In the process (flowsheet), toluene and methanol are pre-mixed before entering a set of low-pressure, fixed-bed reactors where the aromatic ring of toluene is methylated over a zeolite-based catalyst. Products contain very low ethylbenzene levels, an impurity for xylenes. Bridgeman says the process is heat-integrated, so the overall energy input is modest.

The xylenes product proceeds to a recovery and purification stage in which unreacted toluene is recycled back to the beginning of the process. Subsequently, *p*-xylene is purified in any one of several commercialized routes, also licensed by GTC.

Bridgeman says the technology can be built in a new facility, or retrofitted into an existing aromatics complex.

Electrode design increases efficiency of suspended-solids removal

A specially designed electrode could improve the efficiency of removing suspended solids, oil or other contaminants from water in applications traditionally served by dissolved-air flotation (DAF). Developers at OriginOil Inc. (Los Angeles, Calif.; www.originoil.com) believe their electrolysis process overcomes limitations of DAF and improves on the efficiency of the company's earlier electro-flotation systems.

The patented electrode has a perforated cylindrical outer cathode that surrounds an inner anode rod. The perforated tube and rod system carries a current, which electrolyzes water and generates oxygen and hydrogen bubbles in the water flowing through the tube. The angstrom-scale bubbles adhere to contaminant particles to float them to the top of a tank, where they can be skimmed.

"Keeping close proximity between anode and cathode tubes lowers resistance to current flow, so a high current per unit area can be achieved at low voltage," explains inventor Bill Charneski, president of OriginOil's Oil & Gas Division. In addition, the smaller-sized gas bubbles generated by this electrode move solids more efficiently than the larger bubbles typically seen in DAF systems, Charneski adds. Finally, the electrodes can spread over the floor of the tank, so that microbubbles are generated in multiple locations at once, exposing all of the water to the bubbles.

OriginOil estimates the electrode design, which can be retrofitted into existing clarification tanks, increases the extraction effectiveness by 54% compared to earlier designs of its electro-flotation technology. The company's electro-flotation system has been field-tested at an oil-and-gas installation in the Niobrara and Permian Basins, and is now available for commercial licensing.

BIO SNG PILOT

Construction has been completed on a trailer-mounted pilot plant that will produce substitute natural gas (SNG) from the products of biomass gasification (H_2, CO_2 and CO). Built by researchers from the Karlsruhe Institute of Technology (KIT; www.kit.edu) as part of the DemoSNG project — a €4.5-million project coordinated by the German Technical and Scientific Assn. for Gas and Water e.V. (DVGW; Bonn, both Germany; www.dvgw.de) — the pilot plant has undergone initial tests in Karlsruhe, and will now be transported to Köping, Sweden where it will be integrated into the gas flows of a biomass gasification plant utilizing wooden residues. The goal is the reliable and efficient production of methane from biomass-based CO_2 and variable amounts of H_2 from "green" power.

The pilot plant features a new reactor concept for the methanation process, in which a honeycomb catalyst carrier is used to support the nickel catalyst. The honeycomb design is characterized by a high thermal conductivity and mechanical robustness with a low pressure loss, and also enables a compact construction. The pilot plant has the flexibility to handle both the products of biomass gasification as well as additional H_2 generated by electrolysis, when available, which can double the plant's volume flowrate and boost carbon utilization of the biomass to nearly 100%, says KIT.

METAL-FREE ATRP

Atom transfer radical polymerization (ATRP) is a relatively new process to

(Continues on p. 8)

Note: For more information, circle the 3-digit number on p. 70, or use the website designation.

form carbon-carbon bonds of well-defined polymers. Since its discovery in 1995, ATRP has been performed using transition-metal complexes, such as those of copper. This feature has limited the application of ATRP for making polymers for high-purity applications due to the difficulty in removing traces of Cu from the product polymer, for instance in microelectronics (where Cu is conductive) or medical applications (where Cu can be toxic). Now, researchers from the University of California, Santa Barbara (www.ucsb.edu) and The Dow Chemical Company (Midland, Mich.; www.dow.com) have discovered an alternative, metal-free ATRP process, which promises to greatly enhance the applicability of ATRP.

The method uses an easily prepared organic photocatalyst (phenothiazine) that is said to be highly reducing in its "excited state," which can be activated by simply irradiating with light-emitting diodes (LEDs). The reaction takes place at room temperature.

Cr^{+6}-FREE COATINGS

Praxair Surface Technologies, a division of Praxair, Inc. (Danbury, Conn.; www.praxair.com), has recently introduced a new line of ceramic aluminum coatings that are said to have the same performance as legacy chromium (VI)-containing coatings. The company's SermeTel CF and SermaLoy J CF systems are suitable for applications in the aerospace and power-generation industries, where they can be used to extend the useful lifetime of critical components, such as gas turbines and other industrial equipment, by providing protection from corrosion, heat degradation and fouling.

CO_2 CAPTURE

Chemists from Rice University (Houston; www.

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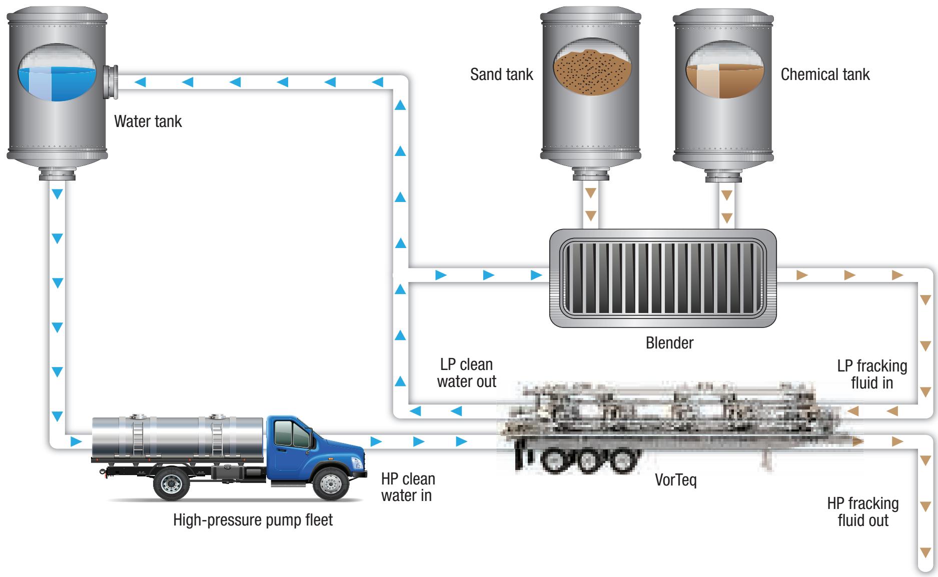
Reduce maintenance of high-pressure pumps



Energy Recovery

In hydraulic fracturing, high-pressure pumps force water bearing sand or ceramic proppants into a manifold, known as a missile, and subsequently into an oil or gas well. Exposure to the highly abrasive, proppant-filled fluids means the pumps require frequent maintenance and have shortened life spans. Energy Recovery Inc. (San Leandro, Calif.; www.energyrecovery.com) has developed a missile that allows the abrasive hydraulic-fracturing fluid to bypass the high-pressure pumps, reducing maintenance costs and pump failures. The new system will begin field-testing in the first quarter of 2015.

Named the VorTeq hydraulic pumping system, it employs a modified version of the Pressure Exchanger (PX) technology used by Energy Recovery in the desalination market. At a hydraulic fracturing site, several pump trucks are connected to VorTeq, which sits on a truck trailer. The pump trucks push clean, proppant-free water into the VorTeq at high pressure. Meanwhile, low-pressure (LP) hydraulic fracturing fluid containing proppant is fed into VorTeq from a blender (see diagram). Using a specially designed rotating cylinder, the LP fracturing fluid is briefly exposed to the high-pressure (HP) water on the pump side. The brief exposure instantly pressurizes the fluid at efficiencies up to 95%, sending it downhole at pressures of up to 15,000 psi. The clean water, now at low pressure, is re-circulated to the pumps for another cycle. The rotor at the heart of the VorTeq system is made from tungsten carbide, an extremely abrasion-resistant material.

At a recent investor event, Energy Recovery CEO Tom Rooney pointed out that separating the pumps from the hydraulic-fracturing fluid reduces maintenance costs by $1 million per fleet per year, and significantly extends their lifetimes. In addition to saving on maintenance, the VorTeq system can decrease the number of pumps required on each fracturing job because there are fewer pump failures, Rooney said. In the future, he added, VorTeq could enable a new pumping model that uses more efficient pumping options, such as centrifugal pumps, because the pumps will no longer be exposed to abrasive hydraulic-fracturing fluid.

A bio-based crosslinker for polyurethanes

At the European Coatings Show (April 21–23; Nuremberg, Germany), Bayer MaterialScience AG (BMS; Leverkusen, Germany; www.materialscience.bayer.com) will launch Pentamethylene diisocyanate (PDI), a new isocyanate with 70% of its carbon content originating from biomass. The "eco-friendly" hardner component is being evaluated for use in coatings, adhesives and other applications.

First PDI-based products will be introduced in April. Commercial manufacturing will follow in 2016, with a production capacity of up to 20,000 m.t./yr. These products will be produced in existing plants using an energy-efficient, gas-phase technology, says BMS.

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Synthesizing adipic acid without generating N_2O

Adipic acid, a precursor for the synthesis of nylon, is usually produced through nitric acid oxidation of cyclohexane, a process which has disadvantages, such as the emission of nitrous oxide — a greenhouse and ozone-depleting gas — as well as low product yield, high energy consumption, and corrosion of reaction vessels by nitric acid. The amount of N_2O thus released into the atmosphere accounts for up to 8% of annual anthropogenic N_2O emission worldwide. An alternative adipic-acid route that eliminates the use of HNO_3 and thus the associated corrosion problems and N_2O emissions, has been discovered by professor Kuo Chu Hwang and researcher Arunachalam Sagadevan at National Tsing Hua University (Hsinchu, Taiwan; www.nthu.edu.tw).

The researchers were inspired by reports that ozone and ultraviolet (UV) irradiation were primarily responsible for oxidative degradation of most hydrocarbons in the atmosphere, and decided to see whether both treatments in combination could oxidize cyclohexane, which exclusively contains unactivated sp^3 C-H bonds. By bubbling O_3 gas through cyclohexane with concurrent UV irradiation at room temperature, a solid reaction product precipitated at the bottom of the reaction vessel after 2–8 h. The solid oxidation product of cyclohexane was found to be adipic acid. The yield of solid adipic acid was about 53 mol.% at room temperature. A stronger UV light and a longer irradiation time generally leads to higher adipic acid yields.

Subsequent experiments clearly show that ozone treatment and UV irradiation of cyclohexane leads to the formation of cyclohexanol, then cyclohexanone, and finally adipic acid.

A highly efficient heterogeneous catalyst for making THF and other chemicals from biomass

The research group of Keiichi Tomishige at Tohoku University (Sendai, www.che.tohoku.ac.jp/~erec), in collaboration with Daicel Corp. (Tokyo, both Japan; www.daicel.com/en), has developed a catalytic reaction system that is highly efficient for synthesizing tetrahydrofuran (THF) — a widely used solvent and raw material for making polyether resin.

The catalyst system consists of rhenium as the major active metal and palladium as a promoter, on a cerium oxide support. In laboratory trials, a THF yield of more than 99% is achieved for the hydrogenolysis of the two adjacent hydroxyl groups of 1,4-anhydroerythritol (which is made by the fermentation and dehydration

(Continues on p. 12)

(Continues from p. 11)

of sugar) in a dioxane solvent at 140–180°C and H_2 pressure of several tens of atmospheres. The catalytic reaction exhibited a turnover number velocity of 300 h^{-1}, and turnover number of 10,000, which is one order of magnitude larger than alternative homogeneous catalyst systems that use rhenium catalysts reducing agents, which are more costly than H_2.

The Re/Pd catalyst is not only highly active, but it is easily recovered by filtration and can be reused — without a loss in activity — after calcination to remove traces of organic compounds.

The chemists say the new catalyst system could be applied for the hydrogenolysis of other biomass-based sugar alcohols. For example, they obtained alcohols containing one hydroxyl group with more than 87% yield from sugar alcohols with an odd number of carbons, such as glycerine (C3) and xylitol (C5), as well as diols containing two hydroxyl groups with more than 85% yield from sugar alcohols with an even number of carbons, such as erythritol (C4) and sorbitol (C6).

Making biocrude and nutrients from algae

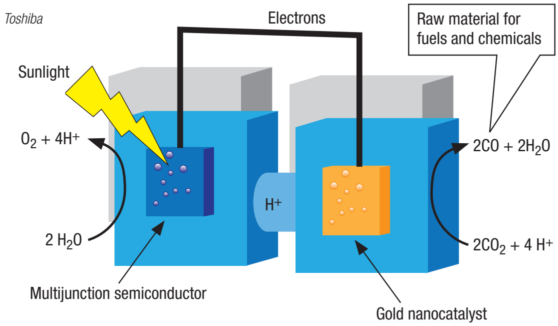
The hydrothermal liquefaction of algae has been the subject of many studies because algae exhibit high photosynthetic activity and growth rate compared to other biomass, leading to increased CO_2 absorption. The algae can grow in a wide variety of water resources and have a high moisture content that is suitable for use in the process of hydrothermal liquefaction. Most of the previous studies have been carried out in a batch reactor.

Now, researchers from Chulalongkorn University (Bangkok; www.chula.ac.th) and the PTT Research and Technology Institute (Wangnoi, both Thailand; www.pttplc.com) have studied the biocrude oil yield and nutrient recovery from *Coelastrum* algae by a two-step hydrothermal liquefaction process using a semi-continuous reactor. The semi-continuous system is said to avoid thermal decomposition of the product while improving the flexibility in the process.

The study was carried out using design of experiments (DoE), based on a response surface methodology and 2^k factorial design, to study the influence of the operating temperature, pressure and water flowrate. It also compared the product distribution obtained from the two-step process with that obtained from the one-step process. The best conditions for biocrude production have been reported to include a reaction temperature of 553–623K, giving a 15–50 wt.% yield of biocrude, depending on the algal species and its composition.

The team has reported a higher biocrude oil and nutrient recovery yield than in the case of a single-step process. According to the team, its two-step process gave a total biocrude yield of 36 wt.%, and nutrient recovery level (in terms of nitrogen-containing compounds) of 60 wt.% of protein content in the original algae as ammonium and nitrate ions, as well as protein and polypeptides.

A step closer to making CO by artificial photosynthesis



Researchers at Toshiba Corp. (Tokyo, Japan; www.toshiba.co.jp) have developed an artificial photosynthesis system that uses solar energy to convert CO_2 and water into CO with 1.5% efficiency — the highest efficiency achieved to date. The company believes the technology has the potential for utilizing CO_2 to make CO — a precursor for methanol and other chemicals normally made from petroleum- or coal-based synthesis gas.

Toshiba uses a gold nanocatalyst via nanoscale structural-control technology applied to a multi-junction semiconductor that absorbs light in the visible range with high light-utilization efficiency (diagram). The company says that a wired photovoltaic (PV) cell system with cobalt oxide (CoOx) and gold nanoparticle (AuNP) catalysts promotes the reduction of CO_2 to CO under simulated solar light, and that the solar-to-CO conversion efficiency achieved over 1.5% without external bias at the initial stage of the reaction. The efficiency is said to be comparable to that of some algae species. Although the efficiency falls to around 1% after 3 h, it is still higher than the 0.3% achieved by artificial photosynthesis, which Panasonic first reported using electronic materials that absorb only ultraviolet (UV) light.

Toshiba plans to enhance the efficiency (aiming at 10%) and improve the endurance of the system's conversion efficiency. Practical implementation could be possible in the early 2020s. The company's long-term goal is to develop a technology compatible with CO_2-capture systems installed at large facilities, such as power plants.

Reducing ground-level O_3

The Catalyst Div. of BASF (Iselin, N.J.; www.basf.com) has launched PremAir NXT, a next-generation direct ozone reduction (DOR) catalytic coating technology that can help automakers meet new U.S. Tier 3 and California LEV III emissions reduction requirements. When applied to a car's radiator, the PremAir NXT solution converts ground-level O_3 into O_2. PremAir NXt provides a 5 mg/mi credit towards vehicle emissions certification, which is applied to the total emissions of the vehicle over its lifetime.

rice.edu) are developing an asphalt-based powder that holds 114% of its weight in CO_2. The porous material, known as asphalt-porous carbon (A-PC) captures CO_2 as it leaves a natural-gas wellhead at room temperature and at the pressures supplied by the rising gas (about 30 atm), while allowing the methane to pass through. The CO_2 can then be recovered by simply releasing the pressure.

A-PC is made by mixing asphalt with potassium hydroxide at high temperature, and then made into a porous carbon with high (2,780 m^2/g) surface area. Further processing with ammonia and then H_2 boosted the material's CO_2-storage capacity from 93% to 114%. The A-PC is very inexpensive compared to conventional amine-based materials, which can only capture about 13 wt.% of CO_2, as well as being corrosive.

Isothermal compression gets practical

Mechanical engineering students have been taught that true isothermal compression, while ideal from an energy-efficiency perspective, is not achievable. However, a late 1800s' technology, the Taylor Compressor has delivered isothermal compression in large industrial applications for nearly a century. The largest installation of the Taylor compressor powered multiple local mining operations in Canada for over 80 years, with no moving parts and no maintenance. It drew air and water down a 342-ft shaft, where the weight of the water compressed the air. The air separated from the water in an underground storage cavern, and delivered 40,000 ft^3/min at 120 psi, equivalent to more than 5,500 hp.

Unfortunately, the Taylor compressor was geographically constrained to a large natural hydro resource, and is not suitable for most practical compression. Now, Carnot Compression LLC (Scotts Valley, Calif.; www.carnotcompression.com) has taken concepts from the Taylor compressor and removed the geographic constraint. Its technology creates a gas/liquid emulsion and compresses gas in a centrifugal field. The company uses centrifugal force, creating G-forces in the thousands, thereby enabling high pressures and flowrates. The company's system captures the heat energy of compression within its process, generating higher efficiencies, with estimated energy savings of 25–50% for typical applications, says Edward Beardsworth, an advisor at Carnot Compression. He points out that energy costs comprise roughly 75% of a typical compressor's lifetime cost of ownership. Besides energy savings, Carnot Compression's design delivers compressed air that is cool, dry and oil-free, without any post treatment, he adds.

Carnot Compression has demonstrated the proof-of-concept in a number of small prototypes, and is now completing construction of a 100-ft^3/min demonstration unit. Preliminary discussions have begun with major compressor manufacturers. The company is targeting multiple applications for its compression technology, including air and gas, refrigeration, air conditioning and energy storage.

In the U.S. and E.U. alone, air and gas compression consumes $24 billion in energy costs, says Beardsworth. ■

Plant Watch

Dresser-Rand, Ener-Core to provide cogeneration system to Pacific Ethanol

January 12, 2015 — Dresser-Rand (Houston; www.dresser-rand.com) will install a 3.5-MW cogeneration system at Pacific Ethanol Inc.'s (Sacramento, Calif.; www.pacificethanol.com) ethanol-production plant in Stockton, Calif. The system will utilize Ener-Core Inc.'s (Irvine, Calif.; www.ener-core.com) gradual oxidizer technology to convert waste gas into electricity and steam. The cogeneration system is expected to be operational by the second quarter of 2016.

Praj to provide EPC services for sugarcane ethanol plant in Uganda

January 8, 2015 — Praj Industries (Pune, India; www.praj.net) has signed a contract with Kakira Sugars for engineering, procurement and construction (EPC) services for a new ethanol plant in Uganda. The plant will process sugarcane molasses to produce fuel- and beverage-grade ethanol, and will have a capacity of 60,000 L/d. Praj will provide technology for fermentation, distillation, wastewater treatment and biomethanation.

Honeywell begins full-scale production of low-GWP material

January 6, 2015 — Honeywell (Morristown, N.J.; www.honeywell.com) has started full-scale commercial production of a low global-warming-potential (GWP) material at its facility in Baton Rouge, La. The new material, called by the industry designation HFO-1234ze, is used as an aerosol propellant, insulating agent and refrigerant.

Sipchem starts up production plant for ethylene vinyl acetate

December 29, 2014 — Saudi International Petrochemical Co. (Sipchem; Al Khobar, Saudi Arabia; www.sipchem.com) started up an ethylene-vinyl-acetate (EVA) films plant located in the Hail industrial zone in Saudi Arabia. The plant's production capacity is 4,000 metric tons per year (m.t./yr) EVA, to be used for the manufacture of solar panels.

Babcock &Wilcox Vølund consortium to build WTE power plant in Scotland

December 22, 2014 — B&W Vølund, the Denmark-based subsidiary of The Babcock & Wilcox Co. (Charlotte, N.C.; www.babcock.com), and its construction partner, Interserve, have been awarded a $230-million EPC contract for Viridor UK's waste-to-energy (WTE) power plant near Dunbar, Scotland. The plant is scheduled to start up in the fourth quarter of 2017.

Fund Energy project to license Ineos PP technology

December 19, 2014 — Ineos Technologies (Rolle, Switzerland; www.ineos.com) has licensed its Innovene PP polypropylene process technology to a subsidiary of Fund Energy Investment Holdings Co. in Changzhou, China. The plant will produce 300,000 m.t./yr of PP from propylene feedstock produced via a methanol-to-olefins (MTO) process.

Chevron Phillips to build polyethylene pilot plant in Oklahoma

December 18, 2014 — Chevron Phillips Chemical Co. LP (The Woodlands, Tex.; www.cpchem.com) plans to build a polyethylene pilot plant at its site in Bartlesville, Okla. The new pilot plant will facilitate polyethylene research, including new catalyst and polymer development. Construction is scheduled to begin in 2015, and completion of the new pilot plant is expected in 2017.

Eastman to increase ester alcohol capacity at Longview site

December 18, 2014 — Eastman Chemical Co. (Kingsport, Tenn.; www.eastman.com) plans to increase manufacturing capacity for Eastman Texanol ester alcohol in Longview, Tex. The plant expansion is expected to be complete in the second half of 2016, and will increase capacity by more than 20%.

Fluor begins construction work on ExxonMobil Antwerp refinery

December 17, 2014 — Fluor Corp. (Irving, Tex.; www.fluor.com) has begun construction activities on a new delayed coker unit for ExxonMobil Petroleum & Chemical BVBA at its Antwerp, Belgium petroleum refinery. Fluor's work on the project includes EPC services, module fabrication, transportation and installation.

Mergers & Acquisitions

Sulzer strengthens service activities offering with InterWeld acquisition

January 12, 2015 — Sulzer Ltd. (Winterthur, Switzerland; www.sulzer.com) has agreed to acquire InterWeld Inc. (Belfast, Northern Ireland), a specialized weld overlay company that offers corrosion and erosion solutions to the power, oil-and-gas, petrochemicals

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and pulp-and-paper industries. The acquisition will enhance Sulzer's offering of welding solutions.

Indorama acquires Polyplex PET plant near Istanbul

January 8, 2015 — Indorama Ventures Public Co. (IVL; Bangkok, Thailand; www.indorama.net) announced that its wholly owned subsidiary Indorama Netherlands B.V. will acquire a 100% equity stake of Polyplex Turkey, including a greenfield polyethylene terephthalate (PET) plant near Istanbul with a planned capacity of 252,000 m.t./yr.

Mitsubishi Heavy Industries and Siemens form metals JV

January 8, 2015 — Mitsubishi Heavy Industries, Ltd. (Tokyo, Japan; www.mhi-global.com) and Siemens AG (Munich, Germany; www.siemens.com) announced the formation of their joint venture (JV) Primetals Technologies, Ltd. Headquartered in London, the JV is focused on the metallurgical industry, and will provide plants, products and services for the iron, steel and aluminum industries.

SRF acquires DuPont's pharma-grade propellant business

January 5, 2015 — Refrigerant manufacturer SRF Ltd. (New Delhi, India; www.srf.com) has agreed to purchase DuPont's global HFC-134a medical-pharmaceutical propellant business. Under the transaction, SRF will own the DuPont Dymel brand, and will also receive technology for setting up manufacturing facilities for pharma-grade products.

Ferro sells Polymer Additives business for $154 million

December 22, 2014 — Ferro Corp. (Mayfield Heights, Ohio; www.ferro.com) sold its Polymer Additives business to Polymer Additives, Inc. for approximately $154 million. The transaction includes the company's four plants in the U.S., a manufacturing operation in Newport, U.K., certain assets at the company's former Baton Rouge plant, and its polymer additives laboratory in Independence, Ohio.

Mitsui and SKC to merge polyurethane businesses

December 22, 2014 — Mitsui Chemicals Inc. (MCI; Tokyo; www.mitsuichem.com) and SKC Co. (Seoul, Korea) have agreed to consolidate their polyurethane material businesses into a 50/50 JV, with headquarters in Korea. Closing of the merger is scheduled for April 2015.

Technip to acquire Zimmer polymer technology business

December 15, 2014 — Technip (Paris, France; www.technip.com) has agreed to purchase Air Liquide's (Paris, France; www.airliquide.com) Zimmer polymer technology business. Based in Frankfurt, Germany, the business includes technologies for the processing of polyesters and polyamides, as well as research and development facilities. ■

Mary Page Bailey

Circle 32 on p. 70 or go to adlinks.che.com/56194-32

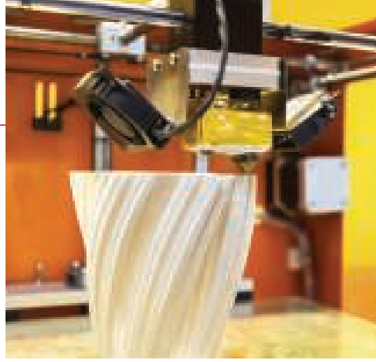


FIGURE 1. The 3-D printing market surpassed $3 billion in 2014, and more growth is expected

3-D Printing Accelerates, Creating CPI Opportunities

Activity in standards development, industry initiatives and R&D are fueling the growth of additive manufacturing (3-D printing) technology in industry

The field of additive manufacturing (AM) — often referred to as three-dimensional (3-D) printing — has seen explosive growth in the past three years, and seems poised to have a profound and lasting impact on manufacturing decisions across many industry sectors. Activity in the field has been largely motivated by the technology's potential to lower manufacturing costs, and enable revolutionary designs for a wide range of components and equipment that are simply not possible with traditional manufacturing methods. Further, a significant shift is underway in which AM technology is increasingly used for manufacturing final products for industrial use, rather than as a tool for prototyping and research and development (R&D).

However, the degree to which the well-hyped technology will infuse the industrial world in general, and the chemical process industries (CPI) in particular, depends greatly on how effectively industry stakeholders resolve a host of questions, including: How can the measurement of raw-material properties be standardized? How can the consistency and quality of final products be ensured? How will qualification and certification of final products be accomplished? How will the cost of production be managed?

Current developments in three main areas are now helping the industry address those questions and are serving to catalyze the more widespread use of AM as a commercial manufacturing method. These developments include drafting and adopting voluntary consensus standards for AM, the establishment of industry-wide consortia, and targeted R&D efforts, including the emergence of process simulation tools designed for AM.

"A confluence of factors is now coming together behind a maturing technology to accelerate the expansion of AM," says Brent Stucker, University of Louisville (UL; www.louisville.edu) industrial engineering professor.

The expansion and maturation of AM technologies are creating opportunities for CPI companies, including the use of AM-derived components to improve the performance and efficiency of chemical processes, as well as opportunities to meet a growing demand for new raw-material formulations specifically for use in one or more of the seven distinct processes that comprise AM (see box, p. 22).

Growth and promise

The 2014 edition of the annual *Wohlers Report*, an AM-industry publication authored by the firm of consultant Terry Wohlers (Wohlers Associates Inc.; Fort Collins, Colo.; wohlersassociates.com), estimates that the market for 3-D printing worldwide surpassed the $3-billion mark in 2014, and saw the highest compound annual growth rate (CAGR) for the industry in 17 years, at 34.9%. From 2011 to 2013, the industry CAGR averaged 32.3%, and strong growth is expected over the next several years, *Wohlers Report 2014* says.

Projections by Lloyd's Register (London; www.lr.org) suggest the market for AM is set to grow by 390% over the next seven years.

The report further notes that growth will be fueled by sales of "personal" 3-D printers, as well as by the expanded use of the technology for producing final parts (especially metal) that go into commercial use.

Wohlers Report 2014 found that revenues from the production of parts for final products now represent 34.7% of the entire market for AM. Since 2003, this market segment has grown from less than 4% to over one-third of the total revenues from AM products and services worldwide.

AM approaches enable significant advantages over conventional formative manufacturing processes. Shane Collins, director of program management at Incodema3D (Ithaca, N.Y.; www.incodema3d.com), says key advantages include "tool-less fabrication, just-in-time inventory control, point-of-sale manufacturing, freeform fabrication,

IN BRIEF

AM PROCESSES

GROWTH AND PROMISE

REPRODUCIBILITY AND MATERIALS

STANDARIZATION EFFORTS

INDUSTRY INITIATIVES

R&D AIMS

mass customization and design democratization."

"Without doubt, AM technologies present opportunities for tighter supply chains, reduced logistics costs, more complex designs and a greater degree of customization," adds Claire Ruggiero, technical vice president of inspection services at Lloyd's Register Energy.

In addition to complex internal features and highly customizable parts, AM processes also have the potential to allow variable material functionality for load paths and locally altered material for wear- and corrosion-resistance. AM processes also minimize material waste and reduce the time between design and production.

"When final parts or products require a complicated geometry, and when a good method of making something is lacking, AM processes tend to be very effective and economic at delivering," says Dave Bourell, professor of mechanical engineering and materials science at the University of Texas at Austin (UT; www.utexas.edu).

AM technologies allow for "tighter supply chains, reduced logistics costs, more complex designs and greater customization," Lloyd's Register's Ruggiero says

Reproducibility and materials

AM processes expose raw materials to different process physics than those in traditional manufacturing methods. And the different types of AM processes can have different raw-materials requirements. Understanding how process conditions affect the materials and the final products made from them is critical to the widespread use of AM. Questions such as "How dependent are the properties of final parts on the variables of the process?" and "How reproducible are mechanical property results?" must be addressed for AM to fluorish in industrial applications.

As AM approaches are more widely used in manufacturing final products, there is increased pressure to improve process reproducibility and to expand the range of materials that can be used in the processes. UL's Stucker sees reproducibility as a key limiting factor. "The materials that are currently available would be more widely adopted if we just had more predictability and repeatability," he says.

"Developing new materials for AM processes requires adapting the material for the thermal history associated with that process, which is different than what you would see in conventional processes like injection molding," explains Stucker. "Materials developed for injection molding often don't work well for AM," he says.

Establishing the correct process parameters for the properties of a given raw material is essential to obtaining a product with the desired properties, says John Slotwinski, a researcher at the Johns Hopkins University Applied Physics Laboratory (JHU-APL; Baltimore, Md.; www.jhuapl.edu).

"There is significant demand for

AM PROCESSES AND MATERIALS

Additive manufacturing (AM) refers to a set of seven distinct processes for applying successive layers of a raw material in a directed fashion, according to a computer file that renders objects in three-dimensions. All AM technologies begin with 3-D models created by computer-aided design (CAD) tools. The 3-D model is converted into stereolithography format, which "slices" the model into a series of cross-sections. AM machines are considered a form of industrial robot. They use the cross-sectional slices from the computer file to lay down layer upon layer of material, eventually forming a 3-D shape that matches that of the computer file that guides it.

Conceptually, the seven different processes are similar, but important technical differences exist. The descriptions here are adapted from the ASTM F2792 Standard on AM terminology. Several of the seven main types have various subcategories.

1. ***Binder jetting*** (used with metals, plastics and ceramics). Powder material is spread over a build platform, and a liquid binder adhesive is deposited to join powder materials.
2. ***Directed-energy deposition*** (metal only). Focused thermal energy is used to fuse materials by melting as they are being deposited. The focused thermal-energy source could be a laser, electron beam or plasma arc focused to melt materials being deposited.
3. ***Material extrusion*** (polymer only). Raw material is selectively dispensed through a nozzle or orifice. Examples include fuse-deposition modeling (FDM).
4. ***Material jetting*** (polymer). Droplets of build material are jetted onto a build surface, where it solidifies. Examples include photopolymers and wax
5. ***Powder-bed fusion*** (both metal and plastic). Thermal energy (for example, a laser or electron beam) selectively fuses regions of a powder bed.
6. ***Sheet lamination*** (metal sheets, paper and plastic sheets). Sheets of raw material are bonded together to form an object. Examples include ultrasonic additive manufacturing and laminated object manufacturing.
7. ***Vat photopolymerization*** (polymer only). Liquid photopolymer resin in a vat is selectively cured by light-activated polymerization.

"Powder-bed fusion processes, like polymer laser sintering, laser-metal sintering and electron-beam melting are the leaders right now, and they have a head start on being used for direct production and manufacturing of final products," says UL's Brent Stucker. "Other technologies are useful for niche applications, and could move ahead rapidly, but powder-bed fusion is the sweet spot right now," he says.

Materials used in AM are varied and include the following:

Polymers

- ABS (acrylonitrile butadiene styrene)
- PLA (polylactide), including soft PLA
- PC (polycarbonate)
- Polyamide (nylon)
- Nylon 12 (tensile strength 45 MPa)
- Glass filled nylon (12.48 Mpa)
- Epoxy resin
- Photopolymer resins

Metals

- Titanium alloy Ti6Al4V,
- Aluminum AlSi10Mg alloy
- Various types of steel (maraging steel, 15-5 PH stainless steel
- Cobalt-chromium alloy
- Inconel
- Gold and silver

Ceramic powders

- Silica/glass
- Porcelain
- Silicon carbide

the ability to use more different types of materials in AM, but so far, the leading companies have not really pushed the envelope in terms of really going after a wide range of new materials yet," Wohlers remarks. "There's going to be a lot of interesting activity in the area of expanding the materials, both in high-end performance materials to low-end, less expensive materials," he predicts.

UT's Bourell says one of the "holy grails" of AM is to have a systematic way of evaluating materials for use in AM, which doesn't exist yet, he says.

Currently, most AM materials are developed in-house by the vendors who also sell AM machines, as a way to help ensure that the materials will work well in the process. In the future, as standards come online, materials will come from a wider variety of sources, Wohlers explains, meaning a more competitive environment in the future.

"There are many opportunities for the chemical industry to develop new polymer formulations and material chemistries that work with AM processes," says UL's Brent Stucker.

Cost and qualification

To fully realize the potential of AM technology, the cost of producing parts by that method will be a key parameter. "If you dissect the part cost, it turns out that the largest segment arises from the AM machine cost, followed closely by the feedstock cost," explains UT's Bourell, so if machines get faster and less expensive, and that is coupled with low-cost feedstock, "the markets will boom."

However, to be able to reliably use a material in AM processing, a better understanding is required of the microstructure of a product and its degree of porosity, Bourell says.

With AM-derived products, consistency and quality control of the final parts are major concerns. "The use of final AM-made metal parts is limited primarily by the industry's ability to certify and qualify the parts," says JHU-APL's Slotwinski. "The industry is still trying to figure out how to do qualification and certification quickly and easily, but it's a tough problem." AM's full impact will be felt when that can be done routinely, he says.

Standardization efforts

Voluntary consensus standards represent a critical aspect of addressing the questions raised in the development of AM, and a committee at ASTM International (West Conshohocken, Pa.; www.astm.org) is working on that front. First established in 2009, ASTM Committee F42 on Additive Manufacturing Technologies now includes over 300 members from 22 countries. "We're seeing an important wave of activity around industry standards for AM," says Terry Wohlers, "but there's still much work to be done."

"Among the top industry barriers is a lack of standards," notes Slotwinski, an F42 member who chairs the Test Methods subcommittee. "Standards help ensure correctness, confidence, consistency and common terminology." Standardized practices, materials and techniques must be identified and validated for AM, he says.

"Currently, there is no standardized means of evidencing the safety and integrity of additive manufactured products," says Claire Ruggiero, technical vice president for inspection services at Lloyd's Register Energy. This is a major focus for Lloyd's Register Energy, including participation on the British Standards Institute Committee for additive manufacturing, which is working towards generating a collection of ISO standards.

"Consensus standards programs help provide a bridge between R&D work and commercialization," remarks Pat Picariello, ASTM director of developmental operations and staff manager of Technical Committee F42.

The efforts of ASTM Committee F42 will have a huge positive influence on the confidence of companies that want to use AM-produced parts, or those who want to enter the market as producers of raw materials, Picariello explains. "Standardization efforts have been incredibly helpful in making companies feel confident about entering the space, and using the technology," he says.

The F42 group includes four technical subcommittees (test methods, design, materials and processes; and terminology) that have developed 10 standards to date. Another 15–20 work items are in various stages of development, with several expecting approval in 2015. ASTM is working with the International Organization for Standardization (ISO; Geneva, Switzerland; www.iso.org) to jointly develop standards for AM.

Among the approved standards the Standard Guide for Characterizing Properties of Metal Powders Used for AM Processes. The document is expected be critical for determining the properties of the feedstock powder used in AM processes — a necessary condition, ASTM says, for establishing industry's confidence in powder selection and its ability to produce consistent components with known and predictable properties.

The standard will serve as a starting point for the future development of a suite of specific standard test methods that will address each individual property or property type that is important to the performance of metal-based AM systems and the components produced by them.

Industry initiatives

Many in the field recognize that realizing the potential of AM technology for production of engineered metallic components requires the collaboration and collective expertise of organizations involved in all aspects of the technology. And indeed, alongside the consensus standards efforts, there are also significant industry initiatives designed to foster those linkages.

Industry consortia will play a significant role in accelerating the adoption of AM, notes UL's Stucker.

For example, the organization America Makes (Youngstown, Ohio; www.americamakes.us) is a network of over 100 U.S. government agencies, companies, academic research institutions and non-profit groups focused on AM. And the Additive Manufacturing Consortium is a group operated by engineering and technology organization EWI (Columbus, Ohio; www.ewi.org) that is designed to foster technical interchange among academia, government and industry.

"Industry consortia will play a significant role in accelerating the adoption of AM," notes UL's Stucker

Incodema3D's Collins says industry-wide consortia will play a key role in creating the expensive material-properties databases that engineers can use to make accurate designs and that AM is currently lacking.

Meanwhile, Lloyd's Register recently announced a new Joint Industry Project (JIP) on AM that seeks to foster collaboration among the key parties in the industry, from material and machine suppliers, manufacturers, end-users and research organizations. By collectively considering the risks and control measures from different perspectives, the JIP hopes to shape best practice standards in AM.

R&D aims

As the adoption of AM gains steam, R&D work in the field will continue to be intense. UT's Bourell says "The AM research community needs to focus on the following areas: increase materials offerings, increase part-property reliability, reduce defects in final products, and enhance the user experience, through the development of better computer-aided design (CAD) software."

In addition to focusing on the predictability, repeatability and reproducibility issues, and developing new materials, UL's Stucker says that AM machine performance (speed) is an important focus of R&D, as is "learning to control material properties in the as-built and heat-treated state, and learning to overcome residual stress-induced inaccuracies."

JHU-APL's Slotwinski adds that developing a high-fidelity industry database of AM material properties, advancing qualification and certification protocols, and improving in-process sensing and control should be key research goals.

"In-situ process sensors and monitoring combined with closed-loop feedback will be the next step in process control capability," Incodema3D's Collins elaborates.

Another aspect noted by Slotwinski — developing physics-based modeling systems of AM processes — is something that UL's Stucker is heavily involved with, and one that Stucker thinks will have a huge impact. "Accurate simulation can dramatically reduce the need for experiments," says Stucker. "You can 'train' modeling software to evaluate a wide range of 'what-if' scenarios in AM proceses without spending as much time and resources on the experiments."

To date, growth in AM has been based on empirical experiments, he explains, and simulations designed for the complexity and details of AM are not currently available.

Stucker started a company known as 3DSIM (Louisville, Ky.; www.3dsim.com) to commercialize modeling software and tools to fill the gap. "Simulation ability of the software we are developing can significantly increase the rate of innovation in AM," says Stucker, because it moves the industry from an experiment-based paradigm for innovation to a simulation-based innovation paradigm. ■

Scott Jenkins

Additional quotes and information on additive manufacturing can be found in the online version of this article, at www.chemengonline.com

Valves for Extreme Service

To meet the needs of the chemical process industries, new valve materials and designs combat corrosion and leaks

In the grand scheme of any chemical process, a valve might seem an afterthought. However, in reality, valves play as critical a role as any reactor, separator, mixer or other integral piece of equipment. For this reason, the reliability of valves is a major concern. No matter the application or valve style, processors require valves that can stand up to harsh chemicals and process environments, while reliably containing liquids or gases. Fortunately, valve manufacturers are developing new materials and designs to help keep their valves, and your chemical processes, up and running.

Severe process environments

"One of the primary challenges we see regarding valves in the chemical processing industry is demanding service conditions," says Nang Chau, global product manager with ITT Engineered Valves (Lancaster, Pa.; www.engvalves.com). "Common chemical process applications may be corrosive, erosive, scaling or hazardous in nature; and are often at elevated temperatures and pressures."

And, these issues are becoming more of a concern as processes change to become more sophisticated or efficient, adds Doug Jones, president of Cooper Valves (Stafford, Tex.; www.coopervalves.com). "With the conversion of feedstocks to natural gas feeds and the desire to make processes more efficient, which is driving the increased use of catalysts and high-temperature applications, we are finding more and more chemical processors are faced with the need for valves that will remain reliable in challenging service environments," says Jones.

In addition, in critical services, valves must be capable of absolute shutoff while maintaining piping-system integrity. Valve manufacturers bring to the table expertise in materials science, alloys and polymers to help processors find a valve that is right for their individual process conditions. "For example," explains Chau. "We have many customers handling dry chlorine. Dry chlorine ball valves are susceptible to ferric chloride buildup, which can minimize seat life due to buildup on the ball. ITT developed an abrasion-resistant ceramic ball that eliminates ferric chloride formation, leading to extended seat life and more reliable valve performance."

Creative materials and valve designs can be found in just about every valve destined for use in a chemical application. For instance, Groth Corp. (Stafford, Tex.; www.grothcorp.com) also offers corrosion-resistant materials in its line of extreme-corrosion-service pressure and vacuum relief valves. The polymer valves operate in a similar fashion to metal and fiberglass counterparts, but are available in more resistant materials, says Greg Berdine, senior technical specialist with

Source: Cashco

FIGURE 1. Model 521 is a sliding stem, globe-style, bellows-sealed, pneumatically actuated control valve designed for maximum corrosion resistance in pure chemical service

IN BRIEF

SEVERE PROCESS ENVIRONMENTS

PREVENTING FUGITIVE EMISSIONS

Groth. The valves protect low-pressure atmospheric storage tanks from excessive pressure and/or vacuum, but the all-polymer internal construction enables them to operate in harsh chemical environments that would damage traditional metal and fiberglass valves. The non-metallic pressure/vacuum relief valves are available in polyvinylidene fluoride (PVDF), polypropylene (PP), high-density polyethylene (HDPE) and chlorinated polyvinylchloride (CPVC), which are resistant to chemical attack.

And because control valves also face corrosion and chemical compatibility challenges, Dan Ray, director of EPC management with Cashco (Ellsworth, Kan.; www.cashco.com), says his company offers their control valves not only in corrosion-resistant materials, but also with improved valve designs. For example, Model 521 (Figure 1) is a sliding-stem, globe-style, bellows-sealed, pneumatically actuated control valve designed to provide long-term performance and maximum corrosion resistance in pure chemical service. The design allows for all wetted internal parts to be machined from a solid block of isostatically compacted, virgin tetrafluoroethylene (TFE) to ensure maximum density and low permeability.

"The benefit of this design," says Ray, "is very thick walls, which result in longer life. This valve was designed for corrosive chemical use, including hazardous or toxic fluids. It provides ultimate performance when handling chlorine, bromine, hydrochloric, sulfuric, nitric and hydrofluoric acids and most industrial reagents. It also performs well in alkaline or strong basic fluids and most organics."

In addition to corrosion and chemicals, many valves used in the process industries encounter dirty or abrasive conditions, which can quickly take a toll on valve life. For this reason, Flowrox (Linthicum, Md.; www.flowrox.com) launched a new slurry knife gate product, the SKW valve, for use in the oil-and-gas, mining, minerals and metallurgy, power and wastewater industries, where abrasive or corrosive slurries, powders or coarse substances are processed. The valve was engineered at

FIGURE 2. QuadroSphere trunnion ball valves handle tailing, dirty mine waters and gas-and-liquid applications in the mining and steel industries

full-bore with no flow restrictions, allowing processes with damaging fluids, such as lime or mineral slurries, to move without compromising performance. Because of the full-bore design, the valve itself becomes an integral part of the pipe and allows it to process the same fluids in the harshest of conditions.

Similarly, Val-Matic (Elmhurst, Ill.; www.valmatic.com) offers its Quadro-Sphere trunnion ball valves (Figure 2) for service in tailing, dirty mine waters and gas and liquid applications in the mining and steel industries. The trunnion-mounted ball has lip edges that clean the seating surfaces whenever the valve is operated. The recessed surfaces on the ball provide for self-flushing of the inner body to prevent scale and solids buildup.

Meanwhile, as oil-and-gas production moves to even more challenging geographic areas, the standard –40 to 85°C environment tolerance is no longer sufficient. In particular, more stringent regulations originating from North America, Russia and China have made it necessary for valve controllers to be certified for even more extreme temperatures. To meet these evolving needs, Metso Corp. (Helsinki, Finland; www.metso.com) recently launched an Arctic option that expands its Neles ND9000 intelligent-valve-controller family and enables the controller to withstand temperatures from –53 to 85°C. The Arctic-temperature option is available in aluminum and stainless-steel flameproof enclosures. For both material options, an intrinsically safe option is also available.

FIGURE 3. ITT offers a bellows assembly that removes all dynamic sealing surfaces and is hermetically sealed

FIGURE 4. Accuseal metal-seated ball valves offer Omni-Lap 360 , which mate-laps the entire ball and seat for optimal roundness, producing 100% ball-to-seat contact

Preventing fugitive emissions

"The valve industry is also focused on preventing leakage and emissions in the most critical services," says Chau. "Stem seal leakage is generally a primary concern when considering compliance with emis-

FIGURE 5. The 1660A pilot-operated relief valve is used to prevent structural damage due to excess internal pressure or vacuum

FIGURE 6. Unibody back-pressure and pressure-relief valves feature single-piece construction with union connections machined together with the valve body to form a solid piece of material

sions regulations and safety."

Improvements to typical stem-seal designs can often address these problems. "For example," says Chau, "ITT offers a bellows assembly which removes all dynamic sealing surfaces and is hermetically sealed; thus delivering a solution that inherently eliminates packing gland adjustment and stem packing leakage" (Figure 3).

Jones agrees that seal design plays a major role in eliminating fugitive emissions. He says Cooper's Accuseal metal-seated ball valves (Figure 4) are an excellent example of unique design, including a proprietary mate-lapping technology. Omni-Lap 360 produces a tight, reliable seal. All metal-seated ball valves rely on continuous, unbroken contact between the metal ball and seat to create an isolating seal. Omni-Lap 360 mate-laps the entire ball and seat for optimal roundness, producing 100% ball-to-seat contact, regardless of positioning.

Traditional cup-lapping methods, explains Jones, mate only the sealing band of the ball-to-seat surfaces, creating ridges that distort the ball's roundness and compromise the coating thickness. The sealing "sweet spot" originates a leak path if even slightly misaligned, resulting in reduced valve life, more maintenance and higher actuation costs. Vacuum testing of every Accuseal ball and seat prior to assembly verifies 100% ball-to-seat seal to Class VI shutoff. "All this means there's minimal chance of leakage happening," says Jones.

Fugitive emissions are of a particular concern where volatile organic compounds (VOCs) are present, says Groth's Berdine. "We have many requests from customers in the solvents and paints industry concerning the reduction of VOC emissions into the atmosphere," he says. "The Environmental Protection Agency is re-

"One of the primary challenges we see regarding valves in the [CPI] is demanding service conditions."

Nang Chau, ITT Engineered Valves

ally watching manufacturers in these industries with a close eye."

He says as parts of its mandate to protect public health, the U.S. Environmental Protection Agency (EPA; Washington, D.C.) has issued a protocol designed to detect and eliminate fugitive VOC leaks in a wide array of process equipment, including valves. "Method 21 currently allows for no more than 500 ppm [parts per million] leakage," he says. In response, Groth offers its 1660A pilot-operated relief valve (Figure 5) for liquid storage tanks and other process vessels or systems to prevent structural damage due to excess internal pressure or vacuum. The valve has two principal advantages over standard relief valves, says Berdine. First, it's bubble-tight to set pressure and, second, it is fully open at less than 10% above set pressure. These characteristics permit an operating pressure nearer to the maximum allowable working pressure of the tank. High operating pressures reduce evaporation and total venting volume, thereby reducing product loss and cost of processing emissions. "This valve meets the requirements of Method 21 testing, as it offers premium seat tightness," says Berdine.

Fluid leaks are also a big issue in the chemical process industries (CPI) since what they are processing is likely to be corrosive or harmful, notes Colin Black, president of Griffco Valve (Amherst, N.Y.; www.griffcovalve.com). "Threads provide a path for the chemical to walk down and drip, so in many instances, chemical processors are looking for a solution to leaks in an effort to protect personnel and equipment."

Often, he says, the problem can be solved using flanges and union connectors, but in applications such as chemical feed, metering and dosing pump systems, a valve made from a solid block of material is often the best solution. Griffco's leak-free Unibody back-pressure and pressure-relief valves feature single-piece construction with union connections machined together with the valve body to form a solid piece of material (Figure 6). Trouble-free and leak-free operation is possible because there are no threads, gaskets, glues or welds to cause problems. Designed for hard-to-seal or troublesome piping systems, the valve is engineered to be reliable and to safeguard the chemical feed system by applying a continuous back pressure to the chemical feed pump, while also acting as an anti-siphon valve. ■

Joy LePree

Industrial Housekeeping

Safeguard industrial workwear and tools with this rugged bin

This company's lockable industrial storage bin (photo) is available for gathering soiled workwear for laundering, used sorbent products (non-hazardous materials), maintenance tools and related industrial hygiene items. Its metal-free interior safeguards the stored goods. Its one-piece, rotationally molded lid and door, made from 100% waterproof, ultraviolet (UV)-resistant polyethylene, ensures a tight seal in inclement weather, and it will not crack, fade or deteriorate, allowing it to be used outdoors. The unit cannot harbor bacteria or mold and wipes clean with common cleaning agents, says the company. — *Meese Orbitron Dunne Co., Ashtabula, Ohio*
www.modlaundry.com.com

Durable floor decals provide clear safety instructions

This company's Smart Signs (photo) allow facilities to clearly and efficiently communicate information and safety instructions with stickers placed on floors or walls. The peel-and-stick messages are made of durable, high-bond acrylic with a 5-mil polyvinyl chloride (PVC) laminate layer that is slightly textured, with scratch-resistant and anti-skid properties. This construction allows them to withstand heavy foot and forklift traffic. They are available in three sizes: 12- and 17-in. round or 14-by-20-in. rectangles with rounded corners. — *Byron Center, Mich.*
www.visualworkplace.com

Device safely extracts fumes during tank and tote filling

The Fill Tube with Fume Eliminator assembly (photo) is designed to simplify the venting of noxious, dangerous or hazardous fumes when filling drums, totes or tanks with solvents or chemicals. It features a one-piece, closed-system fill-tube design with a built-in chamber to control filling and eliminate fumes. The stainless-steel product has two large handles for easy installation and removal into standard 2-in. bung hold flanges. It comes in a variety of sizes, is available with multiple inlets (male and female), quick connectors, and I-line and S-line connectors. The outlet ends can be made to any length or configuration (such as straight or J-shape). — *American Machining, Fenton, Mich.*
www.ibcresource.com

Reduce worker risk with these antiseptic nitrile gloves

BioGard is said to be the first antimicrobial-treated, single-use glove designed to reduce the risk of transient microorganisms. These "self-cleaning" gloves have been shown to kill up to 99.999% of bacteria they contact. BioGard gloves work by combining the company's antimicrobial technology with polyhexamethaline biguanide (PHMB), a powerful yet safe antiseptic, says the firm. Nitrile rubber construction makes them safe for latex-sensitive skin, and textured fingertips promote a safer grip. — *Ansell Ltd., Iselin, N.J.*
www.ansell.com

This versatile device crushes drums, or their contents

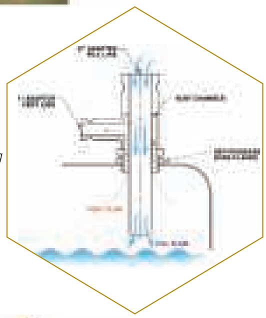
The Sahara explosion-proof drum crusher and compactor (photo) helps facilities to reduce waste volumes and enable more economical disposal of drums, which can be flattened to 4 in. Its totally explosion-proof construction makes it ideal for use in NFPA Class 1, Div. 1 areas. It provides 60,000 lb of compaction force, rugged welded-steel construction and a non-sparking compaction chamber. A quick-change head allows the device to provde in-drum compacting, as well. — *Benko Products, Sheffield Village, Ohio*
www.benkoproducts.com

Cleaning and inspection device targets subsea flexible joints

The Flex Joint Cleaning Tool (FJCT) was originally designed for one major oil company to help clean flexible elastomeric elements in joints with diameters ranging from 4 to 24 in.,


Meese Orbitron Dunne

Visual Workplace


American Machining


Benko Products

Note: For more information, circle the 3-digit number on p. 70, or use the website designation.

Acoustiblok

Morgan Advanced Materials

New Star Environmental

Kafko International

against excessive marine growth — an essential step to allow for reliable operation and proper inspections. This company now operates a rental fleet to enable companies to use the FJCT. The product offering allows users to work with various inspection cameras, 3D modeling, lasers, temperature probes and cleaning tools, and to collect various types of information, data and images to guide subsea inspection and maintenance operations. — *Seanic Ocean Systems, Houston*
www.seanicusa.com

Sound-abatement solutions help curb industrial noise

Quiet-Cloud Industrial Sound Absorption Panels (photo) reduce noise from industrial environments. They rely on Acoustiblok, a propietary viscoelastic polymer material with a high-density mineral content. As sound waves cause the material to flex, internal friction occurs and the acoustical energy is dissipated via an isothermal adiabatic principal. The panels can be installed without major construction changes, special tools or skilled labor and is approved for use in more than 375 fire-rated wall, floor and ceiling configurations. The company's Industrial All Weather Sound Panels, designed for outdoor use, have a noise-reduction coefficient of 1.00, and are engineered to withstand damage from water, moistur, humid salt air and salt water, dirt, dust, constant ultraviolet light, grease and harsh chemicals. — *Acoustiblok, Tampa, Fla.*
www.acoustiblok.com

Sprayed refractory cement provides reliable fire protection

FireMaster FireBarrier 135 is a sprayed refractory-cement product that provides fire protection and is easy to install (photo). Its use can help safeguard concrete tunnels, ventilation shafts, escape tunnels and refuge spaces, as well as critical conduit systems used for water mains and communication cables. It can be applied to concrete or metal substrates using standard spraying equipment. It is adhesive to most construction materials and can be flattened with a trowel, and fixtures can be attached to it. It can also be cast into sheet form and installed as a dry board or shape for applications where spraying is not convenient. It meets NFPA 502 requirements. — *Morgan Advanced Materials, Windsor, U.K.*
morganadvancedmaterials.com

Capture air samples with chain-of-custody confidence

The patented VeriAir Flex Manual Inflating Sample Bag (photo) is designed for emergency-response situations, where an atmospheric air sample can be collected in a hot zone and then moved to a safe zone for immediate testing with a portable gas chromatograph or other analytical instrument. The design allows an atmospheric grab sample to be collected directly without the need for a calibrated sampling pump or other equipment, says the company. It has multi-layer foil construction, is rated at 5,800 lbs tensile strength, and offers excellent barrier properties. It has a built-in volumetric pump and valve, and has no batteries to replace. Each VeriAirFlex includes a unique identifying number on the label that allows the user to ensure reliaable chain-of-custody handling and support sample-retention records. — *New Star Environmental, Roswell, Ga.*
www.newstarenvironmental.com

Absorbent, tear-proof flooring helps improve worker safety

The absorbent Oil Eater Tuff Rug (photo) is a durable flooring material that provides long-wearing durability needed to keep floors dry and safe in high-traffic areas, including forklift aisles and walkways in manufacturing plants and other industrial settings. It is made of 100% recycled materials and available in rolls with 36-in. width and 150-ft length. — *Kafko International, Skokie, Ill.*
www.oileater.com

Capture vent gases using water or reagents

The ScrubPac Vent Clean packaged scrubber systems are designed to capture and remove emissions of acids, ammonia, alcohols, formaldehyde, amines, sodium bisulfite, hydrogen sulfide and many other water-soluble contaminants that arise during breathing and filling operations from storage tanks and rail-

cars. The VentClean is now available in four model sizes to handle gas capacities through 1,500 ft^3/min. Two configurations are available to adapt to a variety of scrubbing liquid preferences. Type 1 is configured to use water on a once-through basis. Type 2 uses a special circulation pump that reduces water consumption, or allows for the use of chemical reagents, such as sodium hydroxide on a recirculated batch basis. — *Bionomic Industries, Mahwah, N.J.*
www.bionomicind.com


TLV Corp.

This air vent is suitable for sanitary applications

The VS3 Air Vent (photo) is designed for sanitary applications requiring an air vent for a liquid line or filter. Three-point seating and a rubber valve seat allow for tight sealing. The compact device can function as an air vent or a vacuum breaker, and thanks to its size, it is suitable for use in confined or tight spaces. With a crevice-free design that allows for easy cleaning and free drainage of liquids without pooling, the VS3 meets specific requirements for materials, surface treatments, component configuration and industry standards set forth by FDA and USP. The VS3 is available with a variety of internal and exernal electropolished surface finishes, some as fine as 0.5 µm Ra. — *TLV Corp., Charlotte, N.C.*
www.TLV.com

Portable lighting solutions ease tank cleaning

A broad range of products are designed to provide portable, explosion-proof lighting tools — both handheld and cart-mounted — to support tank-cleaning operations. Different options are available to provide either broad square footage of illumination or intense focused light for close work. — *Larson Electronics, Kemp, Tex.*
www.larsonelectronics.com

Barrier systems reduce workplace hazards

The Guardian Defender is an automated barrier door that is designed to guard machinery, contain processes and protect employees from robotics and machine-movement zones. Compared to its predecessor, the Slimline, the latest version includes patent-pending upgrades to its non-contact safety switch configuration, control systems and interlocking capabilities, says the firm. Variable-frequency drive control is available to manage curtain speed and quick-disconnect cables allow for easier installation and integration than comparable barrier doors. The barrier is designed to increase worker safety

related to robotic welding cells, material-handling operations, automated assembly systems, palletizing and packaging machinery and others that require electronic safeguarding devices. — *Rite-Hite Machine Guarding, Milwaukee, Wisc.*
www.ritehite.com

Move drums without the need for a forklift

The Pig Poly Deck with Pallet Jack Pockets (photo) is the latest product to join this company's spill-containment product offerings. Using this device, operators can move drums without the need for a forklift. Because the Poly Deck has fork channels that are sized and spaced to fit most pallet jacks, it can be moved quickly and easily using a pallet jack, even when fully loaded. Its low-density polyethylene construction helps to resist damage from UV rays, rust, corrosion and most chemicals. The 2,000-lb capacity will support two fully loaded steel and poly drums without buckling. The 22-gal. sump catches leaks and drips during drum transfer. — *New Pig, Tipton, Pa.*
www.newpig.com


New Pig

Capture fumes with this streamlined hood

The Purair 20 Ductless Fume Hood (photo) is designed to provide operator protection when hazardous substances are present. A face velocity at 100 foot/min ensures containment of fumes and an alarm alerts the operator when the airflow falls to an unacceptable level. All switches and electrical components are isolated from the dirty airflow to prevent contamination. The device is 49 in. wide, 27.5 in. deep and 47.5 in. high. A larger version with width of 96 in. is also available. To capture a range of organic compounds, solvents, acids, mercury and formaldehyde, 14 types of carbon filter are available. The filter is required by ANSI Z9.5 section 4.12 4.2. — *Air Science USA, Fort Myers, Fla.*
www.airscience.com ■


Air Science

Suzanne Shelley

New Products

Molecular structure database now has 750,000 entries

Over 750,000 entries are now available to the scientific community through the Cambridge Structural Database (CSD). This fully validated database, established in 1965, contains all small-molecule chemical structures ever published, and is an essential resource to scientists around the world. Information derived from crystal structures is vital to structural chemistry research, in particular to pharmaceutical drug discovery, materials design and drug development and formulation. — *Cambridge Crystallographic Data Center Inc., Cambridge, U.K.*
www.ccdc.cam.ac.uk

Head-mount transmitter for hazardous area applications

The M100 (photo) is a two-wire transmitter for liquid analytics in the pharmaceutical and chemical industries. The M100 is said to be the world's first transmitter for analytical measurement based on a compact head-mount design, and without a local interface. This new member of the company's transmitter portfolio offers global approvals for hazardous-area use, and combines multiparameter measurement with remote access to predictive sensor-diagnostic tools over the HART communication protocol. The transmitter covers pH/ORP (oxidation-reduction potential), dissolved oxygen and conductivity measurements. — *Mettler Toledo, Process Analytics Div., Urdorf, Switzerland*
www.mt.com/pro-m100

Two new self-loading regulator valves

With the introduction of the new SLR-1 and SLR-2 self-loading regulator valves (photo), this company now offers more choices for pressure regulation. The SLR-1 consists of a DA4 high-performance, pressure-loaded, flow-to-open, pressure-reducing regulator with either this company's P1 or Fairchild Model 10 pressure-reducing regulator mounted onto it. The inlet of the main valve will divert into the P1/Fairchild, which in turn reduces the pressure to the level that is required inside the cover dome in order to maintain the setpoint of the main valve. Similar to the SLR-1, the SLR-2 employs a P1/Fairchild valve mounted onto a DA4 pressure-reducing regulator. However, unlike the SLR-1, the P1/Fairchild used on the SLR-2 is not self-relieving. Instead, the cover dome pressure will constantly bleed through a filter and check valve, and dump back into the outlet of the main valve. — *Cashco, Inc., Ellsworth, Kan.*
www.cashco.com

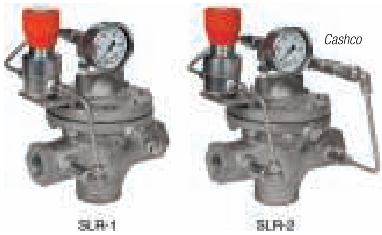
Slash mine-ventilation electricity costs with this smart system

The SmartVentilation system (photo) is a complete solution to the challenge of providing fresh air and venting toxic gases from subterranean mines. It also minimizes energy use by ventilating only those areas of a mine that require it. The company estimates that this ability to work "on-demand" could reduce an operator's electricity bill by up to half. The SmartVentilation system is divided into three "implementation levels" — SmartBasic, SmartMid and SmartPerfect. These give different degrees of control over the operation of the mine's intake and exhaust fans. The fans and their drives come in modular form and are controlled with the company's System 800xA automation platform. — *ABB, Baden, Switzerland*
www.abb.com

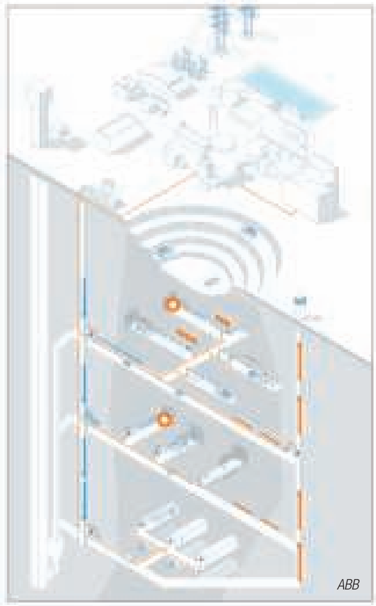
This scanner can accept up to 16 process variables

The Vantageview PD6730X Modbus scanner (photo) is designed for accurate display of and quick access to information, locally or remotely, in wet or dirty environments. The scanner can accept up to 16 individually programmed process variables (PVs) from multiple devices, and four math channels allow for calculations on multiple PVs. The pulse input accepts a wide range of flow-transmitter signals, such as millivolt input from a magnetic flowmeter and high-frequency signals. The PD6730X includes backlighting, two open-collector outputs, and an analog output as standard. The scanner is housed in a durable, injection-molded thermal plastic enclosure. — *Precision Digital Corp., Holliston, Mass.*
www.predig.com

Mettler Toledo



Cashco



ABB

Precision Digital

A new solenoid valve variant for high-pressure applications

This company's Type 6027 solenoid valve (photo) is now available in a new, high-pressure version for pressures up to 250 bars. The new variant of the type 6027 seals the valve seat with a ceramic ball seal. This seal is self-centering and provides reliable and longterm protection against leaks. The ball material (aluminum oxide; Al_2O_3) is highly resilient against both abrasion and wear, and also features excellent resistance to chemicals. In addition to the ceramic ball seal, the material used for the seat of the solenoid valve is polyether ether ketone (PEEK), which is extremely temperature-resistant. — *Bürkert Fluid Control Systems, Ingelfingen, Germany*
www.burkert.de

Bürkert Fluid Control Systems

An intelligent valve actuator with integrated safety function

The TriVAX (photo) and TriVAX flex intelligent electrohydraulic valve actuators are as easy to install and handle as an all-electric drive unit, yet are as powerful, robust and durable as an actuator that is entirely hydraulic. The intelligent electronics ensure simple and intuitive operation. TriVAX replaces conventional valve-control units that may not yet feature certain safety functions, such as quick action or explosion protection, and do not comply with the latest standards. In addition to direct operation using the integrated electronics of the TriVAX unit featuring an intuitive human-machine interface (HMI), the valve can also be actuated via a remote-control console. Thanks to integrated interfaces to standard fieldbuses (in preparation: Profibus PA, HART, Foundation Fieldbus), TriVAX can also be incorporated into existing automation concepts. — *Hoerbiger Automation Technology, Vienna, Austria*
www.hoerbiger.com

Hoerbiger Automation Technology

AODD air-distribution system is now available in stainless steel

The energy-efficient Pro-Flo Shift Air-Distribution System (ADS) is now available in 316 stainless steel and polypropylene plastic (photo) materials of construction, joining the original aluminum and nickel-plated aluminum offerings. The introduction of the stainless-steel and plastic options allows the company's air-operated, double-diaphragm (AODD) pumps to be offered for a greater number of new and existing applications, including sanitary (food and beverage, personal-care products and pharmaceuticals), hazardous chemicals and corrosive environments. The ADS is ATEX-compliant for use in potentially explosive areas. — *Wilden Pump and Engineering, part of Pump Solutions Group, Grand Terrace, Calif.*
www.wildenpump.com

Universal display module for point-level sensors

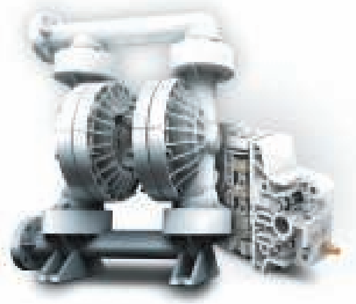
Vega Grieshaber

With the new plicsLED display module (photo), the switching status of a sensor can be read from afar, even in strong sunlight. The module is compatible with all of the sensors in this company's "plics" family with relay output: VegaSwing series 60, VegaVib series 60, VegaWave series 60, VegaCap series w60 and VegaMIP series 60. Since external wiring is unnecessary, the time needed for installation is reduced to a minimum. Power is supplied via the relay electronics. The second relay output is used to control the switching status display. Depending on the module version, the switching status is displayed in the color combination red-green or yellow-green. PlicsLED is installed directly inside the plics sensor housing which gives it a high degree of protection from dust and water ingress. Operating temperatures range from –40 to 80°C. — *Vega Grieshaber KG, Schiltach, Germany*
www.vega.com

Compatibility updates for this overpressure protection software

The newest version of the Process Safety Pressure Protection Manager (PS PPM) software, 1.4 PS PPM, includes a number of comprehensive overpressure-protection solutions that support critical equipment. This version's enhancements allow the software to be installed on more operating systems worldwide. Also

Wilden Pump and Engineering



included among the version's updates are capabilities for converting default units of measure and improved reporting capabilities. The software suite's Inlet Control of Valve Failure Calculation Method allows for users to easily ensure that design standards are met. — *Siemens Industry Inc., Alpharetta, Ga.*
www.usa.siemens.com

Samson

A new actuator for hygienic applications

The new Type 3379 Pneumatic Actuator (photo) is tailored to the requirements of hygienic applications. All moving parts are contained in a housing with a smooth stainless-steel finish, making it easy to clean. The internal air-routing prevents dirt or water from entering the actuator. Together with the new Type 3724 Positioner and the company's diaphragm or angle valves, the actuator forms a compact automated unit with components that are perfectly tailored to one another. The travel is reliably measured by a non-contact magnetoresistive sensor in the positioner. The two software limit contacts indicate when the valve travel exceeds or falls below an adjustable switching value. After automatic initialization, operation is intuitive using three keys. Navigation within the menu on the display has been adopted from the company's Series 3730 Positioners. — *Samson AG, Frankfurt am Main, Germany*
www.samson.de

This data-acquisition system has three new amplifier modules

This company has introduced three new amplifier modules for its SomatXR Data Acquisition System (photo, p. 37). The new amplifier modules are especially suitable for taking measurements under very harsh operating conditions, making SomatXR systems suitable for drive and durability testing of machinery used in construction, manufacturing, agriculture or mining applications. All three modules are rated to be dust-tight and water-tight, and have an extended operating temperature range of –40 to 176°F, while also meeting stringent tolerance requirements for shock and vibration. The SomatXR data-acquisition mainframe can perform a broad range of onboard data processing, including custom computed channels, triggers, gates and Boolean expressions. — *HBM, Inc., Marlborough, Mass.*
www.hbm.com

A new panel simplifies control-valve-related functionalities

Automated process valves using pneumatic actuators always require a range of various instrumentation components to build specific func-


HBM

tions for each application. In conventional single-engineered solutions, components are typically assembled all around the actuator. To date, valve assembly-related instrumentation has been a selection of individual components and functionalities, resulting in a complex mix of components and systems within a plant. This company's instrumentation panel makes valve instrumentation simpler by providing a compact solution to enable users to achieve their objectives of efficiency and reliability when building up instrumentation functionalities, lowering the overall cost of ownership. With its highly compact, modular design, the Panel centralizes all instrumentation components on one panel plate. This allows simple installation and easy maintenance access to all components from a single side. — *Metso Corp., Helsinki, Finland*
www.metso.com

This instrument measures adhesion strength


Paul N. Gardner

The P.A.T.T.I. Micro (photo) is an adhesive-testing instrument that quantitatively measures the adhesion strength of numerous coating materials, including: paints, polymers, ceramics, inks, films, adhesives and thermal or arc-sprayed metals. Designed for both laboratory and field use, the device can collect measurements on rough, smooth, porous, flat or curved test surfaces, in an operating temperature range of 50–120°F. Custom-machined pull-stubs are available at any size, either flat or with a radius to match curved surfaces. Even with its lightweight and portable design, the P.A.T.T.I. Micro features internal memory slots to hold test data for up to 100 pull tests. Software for computer interface is included. — *Paul N. Gardner Co., Pompano Beach, Fla.*
www.gardco.com ■
Mary Page Bailey and Gerald Ondrey

Dimensionless numbers in fluid dynamics

Department Editor: Scott Jenkins

Dimensionless numbers refer to physical parameters that have no units of measurement. These numbers often appear in calculations used by process engineers. As long as consistent units are used, dimensionless numbers remain the same whether metric or other units are used in the equations. Here are some dimensionless numbers often used in chemical engineering fluid dynamics calculations:

Reynolds number (Re). Reynolds numbers express the ratio of inertial forces to viscous forces in a flowing fluid, and represent a way to quantify the importance of these two types of forces under a given set of flow conditions. When calculating pressure, heat transfer or head loss in pipes, it is important to know whether a fluid is exhibiting laminar flow, turbulent flow, or a mixture of the two. Re is typically used as a criterion for determining whether pipe flow is laminar or turbulent. High Reynolds numbers are associated with turbulent flow, where inertial forces dominate and flow is chaotic and characterized by eddies and vortices. Low Reynolds numbers are associated with laminar flow, where flow paths are smooth and viscous forces dominate as defined by Equation (1). The term is named for U.K. physicist Osborne Reynolds.

$$Re = (\rho v L) / \mu \quad \textbf{(1)}$$

ρ is fluid density
v is fluid velocity
L is characteristic linear dimension (traveled length of the fluid)
μ is fluid's dynamic viscosity

Prandtl Number (Pr). Prandtl numbers represent the ratio between kinematic viscosity and thermal diffusivity of a fluid. It is used in calculations that involve heat transfer in flowing fluids because it provides a measure of the relative thickness of the thermal and momentum boundary layers. A fluid's Prandtl number is based on its physical properties alone. For many gases (with the notable exception of hydrogen), *Pr* lies in the range of 0.6 to 0.8 over a wide range of conditions. Named after German physicist Ludwig Prandtl, *Pr* can be calculated using the following equation:

$$Pr = (C_P \mu) / k \quad \textbf{(2)}$$

C_P is fluid specific heat capacity
μ is dynamic viscosity
k is thermal conductivity

Nusselt number (Nu). In heat transfer at the boundary or surface of a flowing fluid, the Nusselt number is the ratio of convective to conductive heat transfer across the boundary over a given length. When *Nu* is close to one, convection and conduction are of similar magnitude, which is characteristic of laminar flow. Larger Nusselt numbers are associated with higher convection and turbulent flow. Named for German engineer Wilhelm Nusselt, *Nu* can be calculated with the following equation:

$$Nu = (hl) / k \quad \textbf{(3)}$$

h is heat transfer coefficient
l is characteristic length (for heat transfer in pipes, l is equal to the pipe diameter)
k is thermal conductivity

Sherwood Number (Sh). Somewhat analogous to the Nusselt number, but for mass transfer, rather than heat transfer, the Sherwood number is a ratio of convective and diffusive mass transfer in a fluid. Named for American engineer Thomas Kilgore Sherwood, *Sh* can be calculated using the following equation:

$$Sh = (h_D l) / D \quad \textbf{(4)}$$

h_D is mass transfer coefficient
l is characteristic length
D is molecular diffusivity

Froude number (Fr). As the ratio between inertial and gravitational forces, the Froude number can be used to determine the resistance of an object moving through a fluid. Named for English engineer William Froude, *Fr* can be calculated with the following equation:

$$Fr = v / (g\, l)^{1/2} \quad \textbf{(5)}$$

v is velocity
l is characteristic length
g is acceleration due to gravity

Grashof Number (Gr). The Grashof number expresses the ratio of buoyancy to viscous force in a fluid. It can serve to correlate heat and mass transfer due to thermally induced natural convection at a solid surface immersed in a fluid. Named after German engineer Franz Grashof, *Gr* is shown in the following equation:

$$Gr = (L^3 \beta g \Delta T) / v^2 \quad \textbf{(6)}$$

L is characteristic length
β is volumetric thermal expansion coefficient
ΔT is the difference between surface temperature and bulk temperature of the fluid
v is kinematic viscosity
g is acceleration due to gravity

Mach number (Ma). Mach number is the ratio of fluid velocity to the velocity of sound in that medium. In chemical engineering, *Ma* is commonly used in calculations involving high-velocity gas flow. The Mach number is named for Austrian physicist Ernst Mach. It can be calculated with the following equation:

$$Ma = u/v \quad \textbf{(7)}$$

u is velocity of the fluid
v is the velocity of sound in that medium

Schmidt number (Sc). The Schmidt numbers is the ratio of kinematic viscosity to diffusivity in a fluid, and characterizes fluid flow where there are molecular momentum and mass-diffusion convection processes occurring simultaneously. Named for German engineer Heinrich Schmidt, the number can be calculated using the following equation:

$$Sc = \mu / \rho D \quad \textbf{(8)}$$

μ is dynamic viscosity
ρ is fluid density
D is diffusivity ■

'Green' Ethylene Production

By Intratec Solutions

With a global nominal capacity of about 140 million ton/yr, ethylene is among the main petrochemicals produced worldwide, and is a key building block for the industry. Ethylene is produced mostly via steam-cracking of petroleum-based feedstocks, such as naphtha. Ethylene is a raw material for the manufacture of polyethylene, polyvinyl chloride (PVC), ethylene oxide and other products.

Global concerns about sustainability and global warming have prompted the chemical industry to develop production routes for ethylene that utilize non-petroleum resources. Renewable ethylene-production alternatives have begun to emerge in this context.

"Green" ethylene can be produced by the dehydration of ethanol, which can be produced from renewable feedstocks such as sugarcane and corn. Ethanol-derived ethylene is chemically identical to traditional ethylene, so downstream processing is equivalent.

The process

A process for ethylene production via ethanol dehydration similar to the processes developed by Chematur Technologies AB (Karlskoga, Sweden; www.chematur.se) and Petron Scientech Inc. (Princeton, N.J.; www.petronscientech.com) is depicted in Figure 1. The reaction occurs in four fixed-catalyst-bed adiabatic reactors.

Reaction. Ethanol is vaporized, heated in a furnace and fed to the first reactor. During reaction, the temperature drops and the output stream must be re-heated before entering the next reactor. This is repeated until the fourth reactor, where ethanol reaches 99% conversion. Next, the reactor-product stream is cooled in a waste-heat boiler, generating steam.

Quenching, compression, caustic washing and drying. After reaction, the product stream's water content is reduced in a quench column. The ethylene stream leaves by the overheads and is compressed before entering the washing column, where impurities are removed with a caustic solution. Process water is also supplied to this column to avoid caustic entrainment along with the ethylene overhead stream, which is cooled by interchange with the ethylene product stream. Water separated in the compression and cooling stages is recycled to the quench column. Next, the gas stream is dehydrated in a molecular sieve unit.

Purification. After cooling by interchange with the ethylene product, the dehydrated stream is fed into the ethylene column, where heavy residues are removed. Next, light impurities are removed in the stripper column. The two columns share a single condenser, which uses propylene refrigerant. The polymer-grade ethylene (99.9 wt.%) product is obtained in the bottoms of the stripper column and used to cool process streams in heat integrations.

Economic performance

An economic evaluation of the process assumes the following:

- A facility capable of producing 300,000 ton/yr of green ethylene constructed on the U.S. Gulf Coast, partially integrated with a polyethylene complex
- Storage capacity equal to 20 days of operation for ethanol and no storage for ethylene

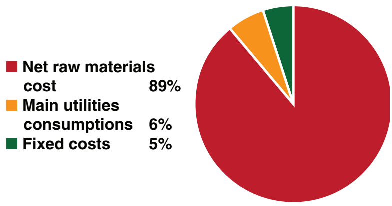


FIGURE 2. Operating expenses for green ethylene

The estimated capital expenses (total fixed investment, working capital and initial expenses) to construct the plant are about $260 million, while the operating expenses are estimated at about $1,400/ton of green ethylene.

Global perspective

The cost of manufacturing ethylene from ethanol dehydration is highly dependent on raw material cost (Figure 2). Because ethanol is used as a biofuel and the crop feedstocks used in its production are also part of the food market, ethanol prices may vary according to the market dynamics of both food and biofuels.

However, a niche consumer market may pay higher prices to obtain environmentally friendly products. Therefore, it is possible to commercialize green ethylene at a premium price, sufficient to offset the higher production costs of green ethylene. ■

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

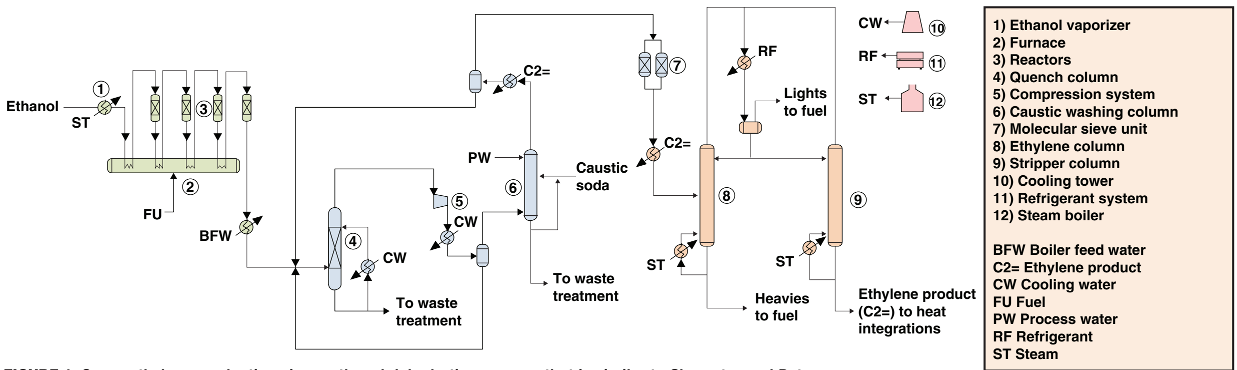


FIGURE 1. Green ethylene production via an ethanol dehydration process that is similar to Chematur and Petron processes

Fundamentals of High-Shear Dispersers

Successful dispersion depends on a basic understanding of dispersion equipment and how dispersers should be used

David S. Dickey
MixTech, Inc.

IN BRIEF

HIGH-SPEED DISPERSION

HIGH-SHEAR DISPERSION

LIQUID BLENDING

FORMULATIONS AND REACTIONS

QUALITY CHECKS

SAWTOOTH DISKS

ROTARY-HEAD DISPERSERS

BOTTOM-MOUNTED DISPERSERS

ROTOR-STATOR DISPERSERS

INLINE DISPERSERS

CHOOSING MIXERS

MixTech

FIGURE 1. These three types of baffles can be adjusted while the tank is filled

High-shear mixers typically operate at high rotational speeds and are used for mixing applications that are best described as dispersion processes. They can be used in a variety of applications, such as to speed additions, wet powders, break lumps and provide process intensification. Many dispersion problems are caused by incorrect use of equipment, when simple operational changes may give better results. While the inherent intensity of high-shear dispersers sometimes provides limited success even when they are misused, successful dispersion depends on a basic understanding of how the dispersers should be employed. This article focuses on the use of these dispersers during the addition of powders and liquids to liquids. Best practices for successful dispersion and the different types of dispersers are discussed.

BASIC PRINCIPLES

The high rotational speeds of high-shear dispersers are often the motor speeds, including speeds at the electric power frequency. Most dispersers operate at a single speed, although some large dispersers may have variable speed control. The dispersions may be powder dispersions in a low-viscosity liquid, or liquid dispersions of miscible or immiscible liquids. In a few instances, gas bubbles may be dispersed in a liquid for a transport process or to create a foam. The

HIGH-SHEAR MIXING: DO

Submerge the impeller. The disperser impeller should remain fully submerged, unless gas dispersion is the purpose of the process. When the disperser remains fully submerged, it provides maximum energy input with the greatest amount of hydraulic shear. When gas passes through a rotating impeller, the power input and liquid flow are drastically reduced. The power and flow loss may be continuous or cyclical. In either case, vibration or surging place additional mechanical loads on the disperser and reduce the effectiveness of powder or liquid dispersion. When gas passes through the impeller, it creates a rumbling sound and mechanical vibration.

Control vortex depth and rate of addition. In cases where the mixing equipment is designed to handle the vibration of air going through the impeller and air bubbles do not adversely affect the process, a tradeoff exists between vortex depth and rate of powder addition. A deep vortex may allow for more rapid liquid or powder addition, but blending and dispersion will be reduced. The balance between vortex depth and rate of addition is too often left to the discretion of the production operator. To achieve consistent product quality and mixing results, both vortex depth and rate of addition must be controlled.

Maintain liquid levels. The primary and preferred means used to prevent gas entering the impeller region is adequate liquid coverage. Mixing tanks designed for use with high-shear dispersers are sometimes taller than the tank diameter, to as much as 125% of the tank diameter. Adequate liquid coverage may be at least one-third the tank height or often half the tank height. The off-bottom location of the rotating impeller will influence the minimum liquid level for mixing and coverage to maintain submergence.

Make additions carefully. Any additions on the surface should be made about halfway between the tank wall and the mixer shaft, away from solid surfaces. Additions near the tank wall or mixer shaft are likely to accumulate on the equipment surfaces and be difficult to dislodge and disperse. All powder additions should be slow enough that individual particles have time to wet and air between particles is allowed to escape. Rapid powder addition will carry gas bubbles into the liquid. Some liquids may be added along a tank wall to reduce splashing and possible foaming, but any material sticking to the wall should be washed into the batch.

purpose of dispersion is rapid formation of a suitably uniform fluid. For processes involving soluble solids, the equipment may be called a dissolver. With dispersed thickeners or emulsion formation, the fluid viscosity may increase.

This lengthy description is needed because different processes and applications can be accomplished with variations on similar equipment (see section on Types of High-Shear Dispersers). The open impellers for high-speed dispersers may be sawtooth disks, short-bladed impellers or slotted heads. Some rotating impellers are mounted inside a stationary cage having either holes or slots, through which the fluid is forced. These mixers are usually called rotor-stators, but may also be called homogenizers. The primary mechanism causing dispersion is hydraulic shear, although some mechanical shear is also present, especially with rotor-stator mixers. Even within the general category of high-shear mixers, some are used primarily for rapid initial dispersion, while others use multiple recirculation passes for improved dispersion and uniformity. Hydraulic shear is rarely sufficient to grind or reduce the size of individual particles, but it will break agglomerates or lumps. Some particle breakage may occur with weak organic or biologic particles. Other types of mills or grinders are used when particle-size reduction is needed.

Although most of the high-shear dispersers are mounted either on-center or slightly off-center, they may be either top or bottom mounted. To control the fluid swirl created by the rotating impeller, the tanks often have

FIGURE 2. Typical types of high-shear sawtooth blades are shown here

The Blade Shop

HIGH-SHEAR MIXING: DON'T

Allow deep vortices. Don't allow a surface vortex to extend all of the way to the rotating impeller, except in some very forgiving processes. The presence of dispersed air usually does not add value to a liquid product and can be difficult to remove, especially from a viscous liquid. Often mistaken for "good mixing" a deep surface vortex is usually a sign of "poor mixing." If the surface vortex reaches the impeller, power and flow are lost. Rumbling and vibration are signs of air entrainment. When a deep vortex is present, the primary flow pattern in the remainder of the tank may be rotational, with insufficient radial and vertical mixing. In rotational flow, the fluid moves in solid-body rotation, which neither mixes liquids nor suspends solids.

Bypass the impeller. The purpose of tank baffles is to control the surface vortex and promote vertical mixing. While vigorous surface motion aids or speeds the addition of powders and liquids, the direction of motion must include flow across the surface and toward the center of the tank. If a vortex reaches the impeller, surface additions will go through the impeller without wetting by the bulk liquid. Initial bypassing of the impeller by surface additions means that additional recirculations are required to obtain the desired dispersion. That additional circulation time may allow agglomerates or lumps to form. The presence of adjustable baffles is intended to allow vigorous surface motion without having the vortex reach the impeller. If additions to a batch increase the liquid level or fluid viscosity, adjustment of the baffles may be necessary.

MixTech

FIGURE 3. This rotary-head disperser is mounted offset from the center

APV Liquiverter

FIGURE 5. This box-type disperser contains a high-shear mixer in the bottom

Admix - Rotosolvers

FIGURE 4. Rotary-head dispersers create more local flow through the impeller than sawtooth disks

one or more baffles. Too much rotational flow and a surface vortex that draws air into the impeller can reduce dispersion and create unwanted air bubbles in the product. Flow through a stator eliminates much of the rotational flow from the discharge of rotor-stator mixers. Single or dual baffles may be adjustable to control a surface vortex. In other disperser designs, off-center mounting or tanks with square cross-sections are used to reduce the need for baffles. A deep vortex with rotational flow does not provide good mixing (see the boxes for High-Shear Mixing: Do and Don't, pp. 41–42).

High-speed dispersion

To create "dispersions" of solids, gases or immiscible liquids, a disperser must break the added components into individual particles, gas bubbles or liquid droplets. A high-speed disperser also allows the rapid addition of miscible liquids or soluble solids. Whether the process is batch or continuous, rapid addition usually results in greater productivity and sometimes better quality.

Solids dispersion. For solids dispersion, individual particles need to be surrounded by liquid and initially suspended. To make sure that individual particles are exposed to the liquid, the rate of addition must be controlled. If solids are added too rapidly, clusters of particles will carry trapped air into the liquid and the partially wetted powder may

Breddo - Likwifier

FIGURE 6. A variety of bottom-mount high-shear impellers is available

form lumps. If the particles hydrate in the liquid, the particles must be separated and suspended quickly.

If the solids are soluble, the rate of dissolution is determined primarily by equilibrium solubility and particle size. Fluid motion may enhance the external mass transfer around the particle, but concentration uniformity in the fluid provides the most effective driving force for dissolution.

For insoluble solid particles, the typical objective is continued suspension with some degree of uniformity. The degree of suspension and uniformity is determined by the liquid velocity and flow pattern. If rotational flow is not adequately controlled by baffles or off-center mounting, some solids may never be suspended off the bottom of the tank. Since most high-speed dispersion impellers are radial flow, they need to be near the bottom of the tank to create a flow pattern that will lift and suspend settling particles.

Liquid dispersion. For liquid dispersion of an immiscible liquid, nearly all of the actual droplet breakage occurs in the fluid velocity gradients near the impeller blades. The rate of addition must be controlled so that the disperser can break the liquid into individual droplets. The ultimate drop size and dispersion uniformity are closely related to the impeller tip speed or peripheral velocity of the disperser. However, viscosity difference and surface tension also influence the drop size. The rate at which a dispersion is formed may depend on how many passes through the disperser are required for uniformity.

Gas dispersion. Gas dispersion by a high-speed disperser is typically less effective than sparged gas dispersion, where the gas enters from below the impeller. Gas dispersion brought from the surface by a vortex may be difficult to control, since it is affected by both liquid-level coverage and baffle adjustment. For dispersion of solids and liquids, gas entrainment should be avoided or closely controlled.

High-shear dispersion

Shear effects are responsible for the creation of dispersions. However, some dispersions are more shear-dependent than others. The dominant shear mechanism for most high-speed impellers is hydraulic shear, resulting from velocity gradients around the impeller. The high velocity of the rotating blades creates locally high fluid velocities in the liquid. The velocity gradients responsible for fluid shear may be associated with trailing vortices near the tips of the blades. Sawtooth blades will create multiple fluid vortices, with one forming behind each blade tip. Sawtooth blades may contribute mechanical shear when large or dense particles strike the blade tips.

High-shear impellers composed of a rotating blade surrounded by a station-

MixTech

FIGURE 7. A deep vortex can be created by bottom-mounted high-shear dispersers

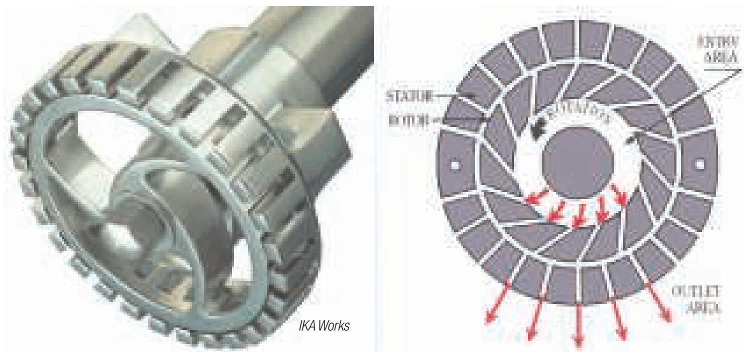


FIGURE 8. The flow pattern (right) of a slotted rotor-stator disperser (left) is between the rotating slots and through the stationary slots

TIPS FOR SUCCESSFUL HIGH-SHEAR DISPERSION

1. Good surface motion with some swirl and strong flow toward the center is necessary to add and disperse powders or liquids successfully. A controlled surface vortex will assist the addition of floating powders.
2. To avoid air entrainment, a surface vortex should not extend more than halfway from the surface to the impeller. Most high-speed dispersers have only a single rotational speed with an impeller near the bottom, so surface motion must be controlled by liquid level and baffle adjustment. To prevent a vortex from reaching the impeller, the liquid level and/or baffle effect need to be increased.
3. The liquid level usually needs to be at least one third of the tank diameter, but may be greater than the tank diameter.
4. A periodic or continuous rumbling with vibration means that air is being sucked into the impeller. Air drawn from the surface or added with powders will form bubbles that will be difficult to remove. The formation of air bubbles should be avoided if possible.
5. Controlled addition of powders is a good way to get rapid dispersion and avoid lump formation. The addition point for powders or liquids should be approximately midway between the side and the center of the tank.
6. If additions of powders or liquids change the liquid level or viscosity, the baffles may need to be adjusted to maintain surface motion.
7. The quantities of powders or liquids should not exceed the capacity of the liquid to disperse, suspend or dissolve them.
8. Stopping the disperser at the end of a batch will allow an opportunity to check the quality of the dispersion. A screen may be used to scoop material from the surface to check for lumps. In a clear liquid, a check for undissolved particles may be possible. Large air bubbles coming to the surface show that dispersed air has been trapped around the impeller.

ary grid, are commonly called rotor-stator dispersers or even homogenizers. The dispersion mechanisms with rotor-stator dispersers are a complicated combination of primarily fluid shear with some mechanical shear. Any significant amount of mechanical shear will wear or damage the disperser head. The rotor of some dispersers looks like a typical bladed impeller. The stator may have either slots or holes, through which the dispersion passes. In other rotor-stators the rotating element is more like a vertically slotted cylinder, which rotates inside a similarly slotted stationary cylinder. However, to control mechanical vibration, the number of slots in the rotor is lower than the number of slots in the stator. The unequal number of slots means that only two or three of perhaps ten to twenty slots are aligned and open at any instant in the rotation.

Several types of flow and mechanisms contribute to the hydraulic shear in a rotor-stator. Some shear occurs with an inrush of flow as a pair of slots begin to align. The shear is caused both by flow through a narrow slot and that flow resulting in a vortex in the stator slot. The flow is caused by a pressure differential between the inner rotor flow and the outer slot flow. Flow through an open slot contributes to the shear effects. As the slot alignment begins to close, the fluid momentum creates another jet of fluid that also swirls in the stationary slot. The small gap between the rotor and the stator creates a velocity gradient and shear effects associated with the differential speed. Some combination of differential velocities, changing directions, and interrupted flow contribute to the hydraulic shear effects.

Shear effects in rotor-stator mixers contribute to the breaking of agglomerates or lumps. Agglomerates often form when particles of thickeners begin to soften and become sticky. If particles are added too quickly or not dispersed well enough, the agglomerates may develop a sticky outer surface that limits penetration of liquid into the nearly dry or only partially hydrated material inside the lump. If rapid dispersion of particles is not sufficient to avoid formation of lumps, then mechanical shear may be necessary to break the lumps. As the particles of thickener continue to hydrate, fluid shear is necessary to stretch and fold the increasingly viscous fluid created by the thickener.

FIGURE 9. Some rotor-stator dispersers have an impeller with blades rotating inside a stator with slots or holes

Charles Ross & Son

COMMON APPLICATIONS

Liquid blending

Most liquid blending applications do not require high-shear dispersers for uniform blending. As with many types of mixing equipment, however, multiple purposes

Silverson

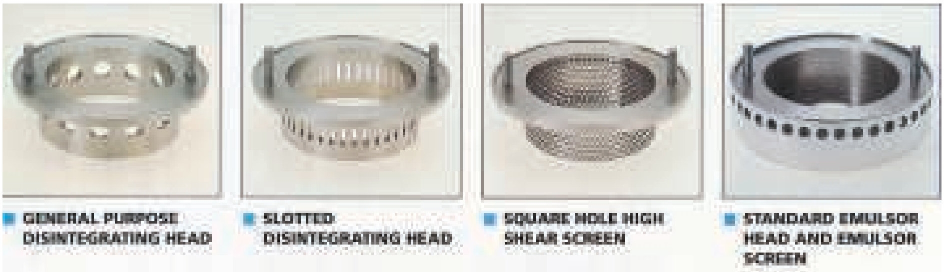


FIGURE 10. Many types of stator heads are available

left - Charles Ross & Son, right - Greerco

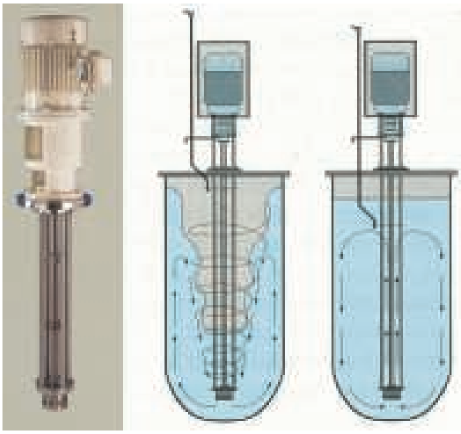


FIGURE 11. Some rotor-stator dispersers employ vertical-flow impellers

can be served by the same type of mixer. High-speed dispersers may be used simply to achieve rapid liquid addition and blending. Dispersers are often used for a multi-step batch process that may involve both the addition of miscible liquids and dispersion of solids for dissolving. The addition of miscible fluids with differing viscosities may require dispersion to effectively combine the fluids. The high power requirements of high-speed dispersers may not be energy efficient, unless the rate of addition or the heat added by power are important to the overall process.

Formulations and chemical reactions

Some applications for high-speed dispersers involve only the physical combination of ingredients or components. Such formulation applications may not involve any chemical reactions and only involve forms of blending for a uniform composition. Dispersions may be composed of liquids with solids, gases or immiscible liquids. The quantities of added powder or liquid should not exceed the capacity of the base liquid to disperse, suspend or dissolve the additions.

Other applications may involve composition changes associated with chemical reactions. Some chemical reactions may only

IKA Works

FIGURE 12. High-shear dispersers are also used in laboratory applications

take advantage of the rapid and intense mixing in the impeller region. Other chemical reactions may involve mass transfer between dispersed solids, immiscible liquids, or gas bubbles. For multi-phase reactions, the effects of the dispersers promote both dispersion and rapid mixing for chemical reaction.

Quality checks

When additions to a batch are finished, some observational checks may be made. First, the disperser must be stopped for safety. Then a screen might be used to scoop material from the surface to check for lumps. If the liquid is clear, a check for undissolved particles may be possible. Bubbles or foam on the surface will show that dispersed gas is present. If large bubbles come to the surface, dispersed gas may have accumulated around the impeller. Drawing a vacuum on a batch may aid in the removal of air bubbles, but only if fluid with dissolved gas is circulated to the surface. Any other non-uniformities on the surface may be signs

FIGURE 13. Some inline dispersers add powders to liquid

of mixing problems. Continued operation of the disperser may be sufficient to reduce some problems.

TYPES OF HIGH-SHEAR DISPERSERS

Most high-shear dispersers are top-mounted on cylindrical tanks. The tanks may be baffled, partially baffled, or unbaffled depending on the process and fluid viscosity. At low viscosity as an alternative to baffles or to improve vortex control, the disperser may be off-center mounted. The off-center location is typically from 15 to 40% of the radius from the center of the tank.

Vortex formation is difficult to predict and strongly dependent on liquid level. To control the vortex formed with a high-shear disperser effectively, adjustable baffles may be used. Figure 1 shows three different types of adjustable baffles, all of which can be adjusted while the tank is filled. Some baffles can be adjusted while the disperser is operating.

High-shear sawtooth disks

Sawtooth disks are the simplest high-shear dispersers. Typical examples are shown in Figure 2. Sawtooth blades are usually bolted to the bottom end of the mixer shaft. Sometimes the mixer drive can be raised and lowered while the disperser is operating to more effectively mix all of the tank contents.

Most of the dispersion by a sawtooth disk is a result of hydraulic shear. Trailing vortices that are shed from the teeth on the blades contribute to high local velocity gradients. Some agglomerates may be dispersed by physical contact with the teeth on the disks. Abrasive wear on high-shear disks is common and requires periodic disk replacement. Most of the flow patterns generated by high-shear disks are rotational or radial. Disks with angled blades or flow pockets may create some axial flow.

High-shear disks may be used in high-viscosity fluids or emulsions. Viscous drag across the disk surface creates a radial discharge and flow pattern. The high-power input associated with the high-speed blades overwhelms the resistance to flow in high-viscosity fluids. High power input adds heat to the fluid, resulting in a temperature increase.

Rotary-head dispersers

High-shear, rotary-head dispersers are typically mounted in baffled or partially baffled tanks and may also be offset from the center. Figure 3 shows an offset-mounted rotary-head disperser in a tank with an adjustable baffle.

Rotary-head dispersers, also called closed-rotor dispersers, like those shown in Figure 4, create more local flow through the impeller than sawtooth disk impellers.

Because the rotary-head-style dispersers typically operate at lower tip speeds in lower viscosity fluids than sawtooth disks, they are less susceptible to mechanical wear. The lower tip speeds may not provide as intense dispersion as is possible with the sawtooth disks. The rotary-head dispersers are often used for addition of miscible liquids, soluble powders or viscosity modifiers.

Bottom-mounted dispersers

Many high-shear dispersers are manufactured and sold as disperser-in-tank packages, because the sizes are transportable and the combination simplifies purchasing and installation. Some tank and mixer combinations have a square cross-section with rounded corners, like the one shown in Figure 5.

Many different types of bottom-mount high-shear blades are available for different applications (Figure 6). Some of these impellers are designed to chop frozen foods or create emulsions.

Bottom-mounted high-shear dispersers can create a deep vortex, even with baffles in the tank (Figure 7).

Rotor-stator dispersers

Rotor-stator dispersers have an impeller, with blades or slots, rotating inside a stationary cylindrical housing. The stationary housing may have either slots or holes depending on the type of dispersion required for the process. The impeller typically draws incoming flow primarily from below the head to limit vortexing. Figure 8 shows a slotted rotor inside a slotted stator. The flow pattern is between the rotating slots and through the stationary slots.

Unequal numbers of slots in the rotor and the stator allow flow through only a few slots at a time. The partial alignment of slots limits noise and vibration caused by flow pulsed through the slots.

Some rotor-stator dispersers have an impeller with blades rotating inside a stator with slots or holes (Figure 9). Many different types of stators are available to create dispersions of different-sized particle agglomerates or immiscible liquids (Figure 10).

Flow through the stator is strictly radially outward, with no rotational flow in the discharge. The only rotational flow comes from the inlet side of the rotor or additional impellers mounted on the rotating shaft above the rotor-stator. To create vertical motion in a rotor-stator mixed tank, axial flow impellers can be attached to the rotating shaft. Reversing the direction of the mixer rotation can either draw liquids and powders down from the surface or draw flow up from the bottom (Figure 11).

Laboratory dispersers

Various types of laboratory high-shear dispersers are available for accomplishing small-scale tasks similar to the large-scale dispersers (Figure 12).

Inline dispersers

Not all high-shear dispersers are mounted in tanks. Some are installed in a line feeding a tank or in a recirculation loop connected to a tank. A few applications may use the inline disperser only to combine ingredients and send them to other equipment for further processing. Many inline dispersers are designed to draw in powdered ingredients and disperse them immediately into a liquid (Figure 13).

Powdered ingredients may be soluble materials or thickening agents that hydrate in the liquid. Rapid and intense contacting helps wet particles quickly and reduces the chance of lumps forming.

The heads for inline dispersers are similar to other rotor-stator heads (Figure 14).

Choosing equipment

The high-shear dispersers discussed in this article are not the only types of equipment that can be used for dispersion. Turbine impeller mixers, with conventional or special purpose impellers, will be effective in some

FIGURE 14. Heads for inline dispersers are similar to other rotor-stator heads

dispersion processes. For difficult emulsions inline rotor-stators, high-pressure homogenizers, and colloid mills will create finer dispersions. These inline or pressure-driven dispersers also require an external pump. Some dispersers are an integral part of a system with other types of impellers, including turbines or sweeps to handle a range of viscosities. Inline dispersers can be used in an external loop connected to a conventionally mixed tank. The primary purpose of dispersers used in multiple-impeller systems is to provide intense mixing at a point in the process.

No matter what a vendor's sales representative can tell you about your process and available equipment, testing is an essential part of high-shear disperser selection. Actual materials, process objectives, and quality controls are all factors in the selection of appropriate high-shear dispersers. Any equipment or process must be sufficiently robust to handle expected upsets, process variations and ingredient changes. Few processes or products are so well controlled and defined as to remain completely unchanged for long periods. Some knowledge of high-shear dispersers only comes from experience. ■

Edited by Dorothy Lozowski

Related stories, such as Ten Things You May Not Know About Liquid Mixing Scaleup, *Chem. Eng.*, August 2013, Increase Productivity Through Better Gas-Liquid Mixing, *Chem. Eng.*, October 2007, and Mixing Systems: Design and Scaleup, *Chem. Eng.*, April 2006, can be found online at www.chemengonline.com

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Part 1

Evaluate Heat-Exchanger Tube-Rupture Scenarios Using Dynamic Simulation

Applying dynamic simulation models to tube-rupture scenarios can help ensure more accurate sizing and hazard assessments

Soumitro Nagpal
Fluor Daniel India Pvt. Ltd.

IN BRIEF

FIGURE 1. Heat exchangers in many CPI applications can experience tube rupture, and these scenarios must be evaluated and addressed in order to ensure continued safe operations

Tube rupture in heat exchangers is an extremely serious issue in the chemical process industries (CPI; Figure 1). Heat-exchanger tube-rupture scenarios can be evaluated by various means, including dynamic and steady-state process simulation. Performance of reliable dynamic simulations of tube-rupture scenarios requires suitable experience, expertise and significantly higher effort than steady-state evaluations. This article discusses a number of heat-exchanger tube-rupture scenarios, including: the requirements for scenario evaluation; tube-rupture flow estimation; selection and sizing of relief devices and associated piping; and guidelines for identification of situations where a dynamic evaluation is appropriate.

In addition, several dynamic-simulation case-study summaries are presented, illustrating the utility of this method in the proper selection and sizing of relief systems. Special emphasis is given to liquid-filled systems, which see very rapid pressure-rise rates upon tube rupture. These cases show that dynamic evaluation can lead to better relief-device selection and sizing, as well as improved materials selection for various conditions, including some that do not require dynamic evaluation under American Petroleum Institute (API; Washington, D.C.; www.api.org) guidelines.

TABLE 1. SUMMARY OF TUBE-RUPTURE SCENARIO DYNAMIC EVALUATION CASES

HP Fluid/ LP Fluid		Natural gas/ Propane evaporator	Natural gas/ Propane condenser	Natural gas/ LP steam [8]	Hydrotreater effluent/ Stripper bottoms [6]	Natural-gas condensate / Liquid propane	Ethylene / Liquid propylene [7]	Ethylene / Liquid methanol [7]
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Design pressure (HP/LP)	barg	89 / 17	89 / 17	149 / 5.5	183 / 128	89 / 17	111 / 18.9	111 / 17.2
Operating pressure (HP/LP)	barg	69 / 1	67 / 8	113 / 3.5	158 / 19	43 / 7.2	101 / 11.9	101 / 36
Operating temperature (HP/LP)	°C	–16 to –20 / –24	2 to 10 / 18	3 to 80 / 147	275 to 310 / 230 to 290	–20 / 18	–26 to 11 / 25	11 to 15 / 64
Blocked-in pressure-rise rate	bars/s	0.16	0.92	5	74	67	28	64
Set pressure, P_{set}	barg	17	17	5.5	23/24.1	17	16.2	11.8
Relief device		PSV	PSV	PSV	PSV (3)	Rupture disk	PSV	PSV
Peak pressure, P_{max} P_{max}/P_{set}	barg	18.4 8.2%	18.2 7%	6 9%	37.7 64%	17.05 0.3%	20.5 26%	16 36%
Peak rupture flow	kg/s	3.7	3.6		17.1	5.7	13.4	7
Peak relief flow	kg/s	4.6	7.8	12.5	338.9	165.2	Not reported	Not reported

Note: Cases 4 through 7 refer to exchangers that are liquid-filled on the LP side

Evaluation criteria

Process-hazard analyses for shell-and-tube heat exchangers call for evaluation of tube-rupture scenarios if the difference in maximum allowable working pressure (MAWP) between the low-pressure (LP) and high-pressure (HP) sides is greater than that covered by the 10/13 (or 2/3 rule, as may be applicable). This is based on ASME Boiler and Pressure Vessel Code Section VIII, Div.1 [*1*], which requires a system to be hydro-tested at 130% of its MAWP.

This code requirement eliminates the need to evaluate a tube-rupture scenario, as the LP side is protected if its design pressure is no less than 10/13 of the HP side's design pressure. API-521 6th Ed. [*2*] notes that "Pressure relief for tube rupture is not required where the low-pressure exchanger side (including upstream and downstream systems) does not exceed the criteria noted above. The tube-rupture scenario can be mitigated by increasing the design pressure of the low-pressure exchanger side (including upstream and downstream systems), and/or assuring that an open flow path can pass the tube-rupture flow without exceeding the stipulated pressure, and/or providing pressure relief."

This option is often used to eliminate a tube-rupture scenario evaluation. However, for an exchanger with a large pressure difference between the HP and LP sides, uprating the LP side design pressure can be expensive, and a tube-rupture scenario evaluation is necessary. The required activities in a tube-rupture scenario evaluation are detailed in the following sections.

Tube-rupture flow estimation

API 520, Part 1 [*3*] provides the necessary guidelines and equations for single- and two-phase flow estimation. For two-phase flow, API-521 [*2*] recommends the following: "A two-phase flow method should be used in determining the flowrate through the failure for flashing liquids or two-phase fluids. The flow models developed by DIERS (the Design Institute for Emergency Relief Systems) and others can be adapted for this purpose. In cases where the fluid flashes at the low-pressure side of the heat exchanger, two-phase flow methods based on the homogenous equilibrium model (HEM), such as those proposed by DIERS, may be used for the flow through the tube to the break."

Darby's work in this area [*4*] also presents a good summary of these steady-state sizing methods, including the homogenous direct-integration (HDI) method.

Relief-device selection

In systems where the shellside-tubeside pressure difference is high, the pressure rise on the LP side can be very rapid. In those cases, relief valves provided to protect the LP side from overpressure may not respond quickly enough to protect the system. Such a scenario may call for the installation of a rupture disk.

Many companies have developed their own practices for identifying scenarios that require protection with rupture disks. Some companies prefer that the rupture disk is mounted directly on the exchanger — not on the inlet or outlet piping — because the disk might not react fast enough with the intervening pipe. This is not always practical to implement, since other factors must be considered, such as layout constraints or free-draining requirements for two-phase or liquid-relief lines. Thus, it is recommended that rupture disks be installed as close as possible to, if not directly on, the heat exchanger.

Liquid-filled systems, especially those filled with an incompressible liquid, such as water on the LP side, can experience a very rapid high-pressure spike upon tube rupture. Even a rupture disk may not be able to respond. Multiple disks at different locations on the exchanger itself may be required. Depending on the toxicity, flammability and reactivity of the fluids, consideration of tube-rupture-relief contingency may be advisable, even if the 10/13 rule is followed. The acoustic pressure wave that occurs

RECOMMENDATIONS ON DYNAMIC MODELING FROM API-521 [*1*]

"A one-dimensional dynamic model can be used where the approach is to simulate the pressure profile and pressure transients developed in the exchanger from the time of the rupture. These methods generally include the dynamic model of the tube-rupture relief scenario and the response time of the relief device, the accuracy of which is critical in calculating the accuracy of pressures generated. The opening time for the device used should be verified by the manufacturer and should also be compatible with the requirements of the system.

This type of analysis is recommended, in addition to the steady-state approach, where there is a wide difference in design pressure between the two exchanger sides [for example, 7,000 kPa (~1,000 psi) or more], especially where the low pressure side is liquid-full and the high-pressure side contains a gas or a fluid that flashes across the rupture. Modeling has shown that under these circumstances, transient conditions can produce overpressure above the test pressure, even when protected by a PRD (pressure-relief device). In these cases, additional protection measures should be considered."

in the case of incompressible-liquid-filled systems results in a waterhammer-type effect that cannot be simulated with the dynamic simulation tools commonly used for analysis of these scenarios. Sometimes a rupture pin is also considered, allowing faster open times than rupture disks. Typical opening times for relief devices are 50–100 milliseconds (ms) for spring-loaded pressure safety valves (PSVs) and around 1–10 ms for graphite rupture disks [*5*].

The capacity of a relief device handling high pressure-rise rates can be estimated using Equation (1), taking into account the pressure relief device's (PRD) opening capacity (*OC*), set pressure (*SP*), allowable overpressure (*AOP*) and relief-valve opening time (*T*).

$$OC = SP \times AOP/T \quad (1)$$

For example, for a PSV with a set pressure of 5.5 bars, with 10% overpressure allowed, and an opening time of 100 ms (0.1 s), OC = 5.5 bars × 0.1/0.1 s = 5.5 bars/s.

The blocked-in pressure-rise rate (where no credit is taken for any flow out of the exchanger) calculated in dynamic runs can be compared with the PRD opening capacity to determine the suitability of the selected type of relief device. If the PRD's opening capacity is lower than the blocked-in pressure-rise rate, the device may not be able to open sufficiently in time to capture the pressure rise.

Relief-device sizing

The steady-state calculation procedures described previously are applicable to tube-rupture flow estimation. However, sizing of the relief device itself and its inlet and outlet lines requires relief-flow estimation. The API-521 [*2*] guideline states that for steady-state relief device sizing, "PRD size should be based on the gas and/or liquid flow passing through the rupture."

The volumetric flowrate of the LP fluid equivalent to the volumetric flowrate of the HP fluid passing through the rupture location should be used when the fluid properties at the relief location are significantly different from those at the rupture location, or when the relief device is located at some distance from the exchanger. Alternately, API-521's recommendations with regard to dynamic modeling are shown in the box above.

In summary, API-521 recommends that for exchangers with differential pressures of less than 70 bars, relief-device sizing should use the tube-rupture flow estimate. For exchangers with differential pressures greater than 70 bars, use a dynamic simulation of the system to estimate relief flows and relief-device sizing.

Other situations where a dynamic evaluation is sometimes considered are the following:

- Exchangers with liquid-filled shells
- Sizing of relief piping, because steady-state methods can lead to oversized relief piping, especially for short, sharp-peak relief flows, as pipe holdup effects are not considered
- Long shells with baffles on a tight pitch
- For existing units where the overpressure protection was mounted on the relief piping
- For existing units with high differential pressures where a relief valve was used

Examples

Several tube-rupture dynamic-simulation studies are presented in the following sections. Cases 1 through 5 are recent tube-rupture studies that utilize commercial dynamic-simulation software. In these cases, the heat exchanger's LP side is split into several volume segments to facilitate the observation of the physical phenomena occurring during the rupture event. The details of this approach are discussed in Ref. *6*. Cases 6 and 7, as reported by Ennis and others [*7*], are also discussed here for comparison with these results for liquid-filled tube-rupture cases. Table 1 gives a summary of the cases.

Case 1: Natural-gas propane chiller. Natural gas is cooled in a chiller to reduce the hydrocarbon dewpoint, where liquid propane evaporates at 1 barg and –24°C on the shellside. The natural gas is on the tubeside at 68 barg pressure and temperatures around –16 to –20°C. The exchanger in this example is specified as type AKL based on Tubular Exchanger Manufacturers Association (TEMA; Tarrytown, N.Y.; www.tema.org) standards. TEMA exchanger-type codes, such as AKL, provide a shorthand for basic designs and manufacturing methods of heat exchangers. For more information on TEMA standards and codes, see Specifying Shell-and-Tube Heat Exchangers, *Chem. Eng.*, May 2013, pp. 47–53. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a slow pressure-rise rate of 0.16 bars/s in the shell, as the pressure rises from 1 barg operating pressure to 17 barg relief pressure in 100 s. A spring-operated safety valve is adequate to protect the LP side of the exchanger for this scenario.

Figure 2 shows the exchanger shellside segmentation considered for the simulations. Figure 3 shows the temperature, pressure and flow transients for the run. In this run, the rupture was considered at the extreme left of the exchanger in segment V1. The gas cools as it expands

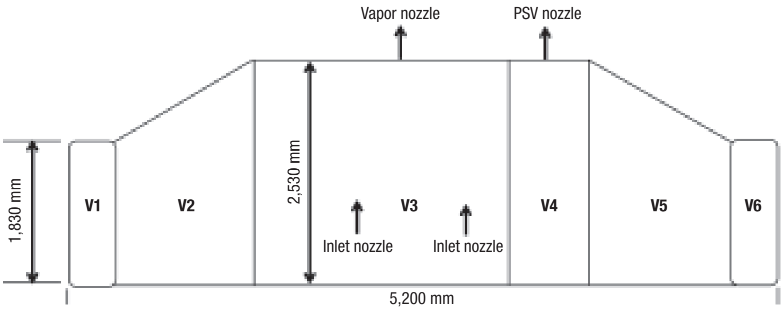

FIGURE 2. This schematic shows an exchanger shellside segmented into several volumes to facilitate the observation of the physical phenomena occurring during the rupture event. In this case, HP gas flows from left to right, the propane liquid level in the shellside is 1,800 mm and the tubes are not shown

on the LP side upon flowing across the tube rupture, resulting in its temperature dropping to –67°C immediately after rupture, and subsequently increasing as the shellside pressure rises. While the fluid temperature in the shellside is estimated to drop to a minimum of –48°C near the rupture location, direct impingement of the rupture fluids on the intact adjacent tubes, shell and tubesheet is possible. Conservative design practices led to a selection of the minimum design metal temperature (MDMT) for the exchanger based on the minimum rupture fluid temperature. These calculations did not consider the thermal inertia of the metal mass in the system, inclusion of which can allow a higher MDMT selection.

Case 2: Natural-gas-cooled refrigerant condenser. A propane-refrigerant-based natural-gas dewpointing plant utilizes the cooled, dewpointed gas to condense refrigerant discharging from compressors. Refrigerant at 5–8 barg condenses on the shellside, whereas HP natural gas at 67 barg flows on the tubeside of the exchanger, which is TEMA type BEM. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a relatively slow pressure-rise rate of 0.92 bars/s in the vapor-filled shellside, as the pressure rises from 8 barg operating pressure to 17 barg relief pressure in 9.8 s (Figure 4).

A spring-operated safety valve is adequate to protect the LP side of the exchanger. The dynamic simulation indicated that a PSV size based on the tube-rupture flow is inadequate to limit the pressure rise to be within the required 10% overpressure. The PSV size was increased, and while this leads to an increased peak relief above the tube-rupture flow, the peak pressure rise can now be contained to the prescribed limit.

Case 3: Natural-gas heating with LP steam. This study's work [*8*] focused on HP natural gas on the tubeside of an exchanger heated with condensing LP steam on the shellside in a TEMA-type BEM exchanger. The natural gas is at 113 barg pressure and the temperature ranges from 3.2 to 80°C. The LP steam is at 3.5 barg and 147°C. The set pressure on the relief device protecting the LP side is 5.5 barg.

Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a shellside pressure-rise rate of 5 bars/s, increasing from 3.5 barg operating pressure to 5.5 barg relief pressure in 0.4 s. Upon relief valve opening, the pressure-rise rate drops to 0.27 bars/s. It was determined that this pressure-rise rate is acceptable for the installation of a spring-loaded relief valve. The study also indicated that the PSV set pressure should be set lower than the exchanger design pressure, as the pressure near the tubesheet can be higher than at the PSV inlet due to inlet line losses.

Case 4: Hydrotreater effluent stripper-bottoms exchanger. A hydrotreater effluent stream is cooled against the stripper bottoms stream of the unit in a shell-and-tube heat exchanger. The exchanger comprises two shells in series, with the HP hydrotreater effluent on the tubeside at 158 barg and temperatures of 275–310°C. The stripper bottoms pressure on the shellside is 17–19 barg and the temperature is 230–290°C. The shellside design pressure was originally selected as 128 barg, based on the 10/13 rule. Dynamic evaluations for single and multiple tube-rupture scenarios were executed [*6*]. On tube rupture, a very rapid pressure rise in the liquid-filled shell was estimated at 74 bars/s, with pressure rising from 18.9 barg operating pressure to 23 barg relief-valve set pressure in just 55 ms. Peak pressure rise in the shell protected with one, two or three spring-loaded relief valves was estimated. The dynamic runs indicated that the peak pressure rise can be limited to 37.7 barg, 50.1 barg and 81.4 barg using three, two, and one PSVs, respectively. Thus, a significant margin for shell design-pressure reduction is available below the originally selected design pressure of 128 barg. The study showed that despite the rapid pressure-rise rate, PSVs with a set pressure selected well below the design pressure to capture the pressure rise can, in fact, be used to lower the LP design pressure.

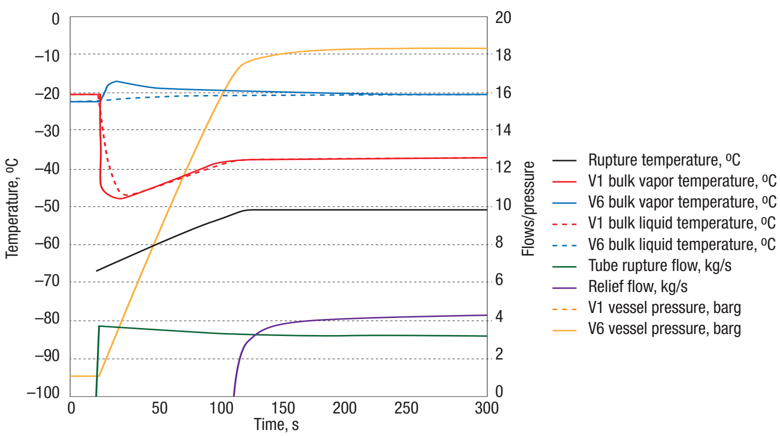

FIGURE 3. Case 1's tube-rupture event occurs 18 s into the run, while relief flow starts at 118 s into the run. Note that the temperature rises in segment V6 due to pure compression without exposure to cold rupture fluids

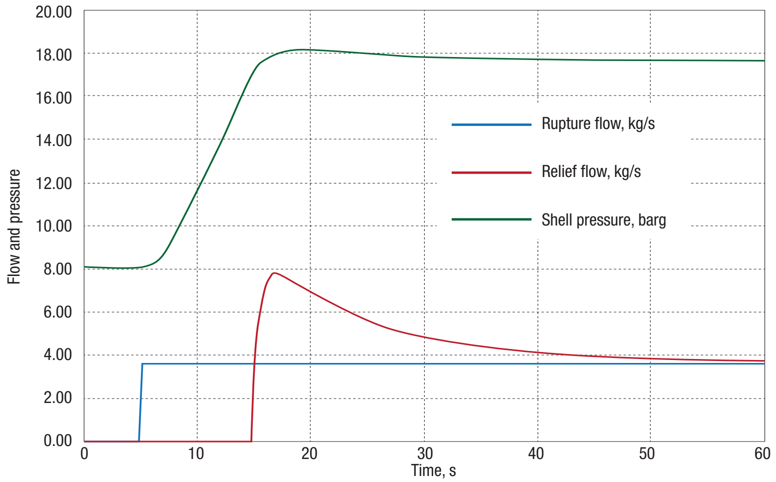

FIGURE 4. For Case 2, this transient diagram shows the exchanger LP shellside pressure rise on tube rupture, rupture flows and relief flows, for a PSV set pressure of 17 barg

Case 5: Liquid propane cooled by natural-gas condensate. A propane-refrigerant-based natural-gas dewpointing plant uses natural-gas condensate to sub-cool liquid refrigerant. Liquid propane at around 5–8 barg pressure is on the tubeside, and HP natural-gas condensate at 43 barg flows on the shellside of the exchanger, which is TEMA type AEL. The condensate state is two-phase, vapor-liquid in and out of the exchanger. Dynamic evaluation of a single-tube, full-bore rupture in this exchanger indicated a fast pressure-rise rate of 65 bars/s in the liquid-filled tubeside. The pressure rises from an operating pressure of 7.2 barg to 17 barg relief pressure in 0.15 s.

A rupture disk was selected as the relief device. Dynamic simulation of this scenario was carried out, and shows that the peak relief flow on disk rupture in liquid-filled systems can be an order of magnitude higher than the associated tube-rupture flow driving the event, as shown in Figure 5. The dynamic model was used for sizing the rupture disk's inlet and outlet lines based on the transient relief flows, with the criteria that the LP side must stay below the allowable design overpressure.

Accurate modeling of this system involving two-phase choked flow in pipes is a challenge, even with the advanced dynamic simulations packages available commercially. A commercial simulation model, which uses a momentum conservation equation based on Darcy's law, was used in this study to model the rupture disk's inlet and outlet lines. The exchanger tubeside was modeled using three volume segments, one each for the channels, and one to account for the volume of the intact tubes. Figure 6 shows the simulation process flow diagram (PFD) used for the transient analysis.

Cases 6 and 7: Liquid-filled exchangers in an ethylene plant. Ennis [*5*] presented dynamic simulation results for two liquid-filled exchangers, the first with liquid propylene, and the second with methanol on the LP side. Table 1 provides further system details. For both exchangers, the HP-LP pressure differential is >70 bars. The study used models that solve one-dimensional partial differential equations for the conservation of mass and momentum for the liquid-filled riser to the PSV attached to the exchangers. This method is a more rigorous approach for two-phase pipe flow than available in some dynamic-simulation software packages.

The blocked-in pressure rise calculated was 28 bars/s for the propylene-filled system, and 64 bars/s for the methanol-filled system. PSVs were proposed as the relief device for both cases. Note that as in Case 4, the PSV set pressure was significantly below the LP design pressure, allowing pressure to rise to above 10% of the PSV set pressure.

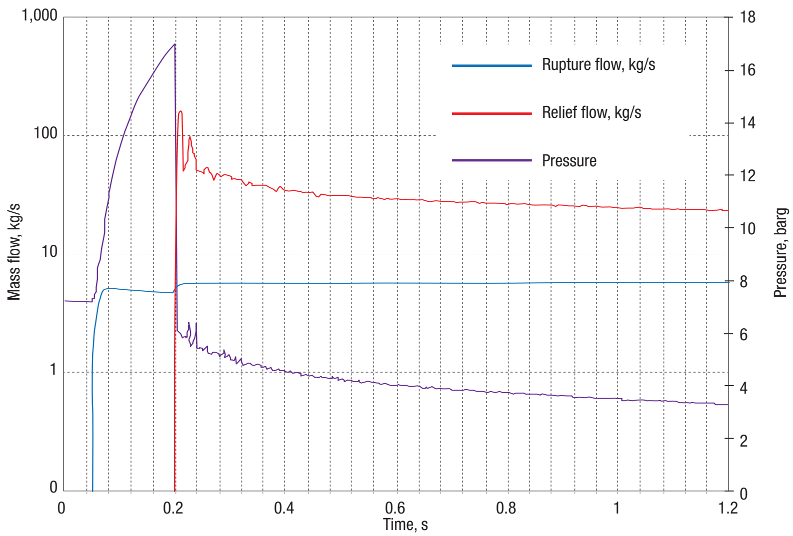

FIGURE 5. Case 5's rupture occurs 0.05 s into the run, followed by rapid pressure rise to rupture disc burst pressure of 17 barg at 0.2 s. Initial relief flow can be seen to be significantly higher than the rupture flow

Closing thoughts

The following are some conclusions that can be drawn based on the information presented in this article:

- Dynamic simulations can allow for more accurate PSV sizing for tube-rupture scenarios than steady-state methods
- Based on dynamic simulation studies, PSVs can be used to protect liquid-filled exchangers with high pressure differentials of over 70 bars
- Dynamic simulation should be considered for evaluating tube-rupture scenarios of liquid-filled systems for relief-device selection and sizing, even when exchanger differential pressures are less than 70 bars, if the exchanger LP side is not pro-

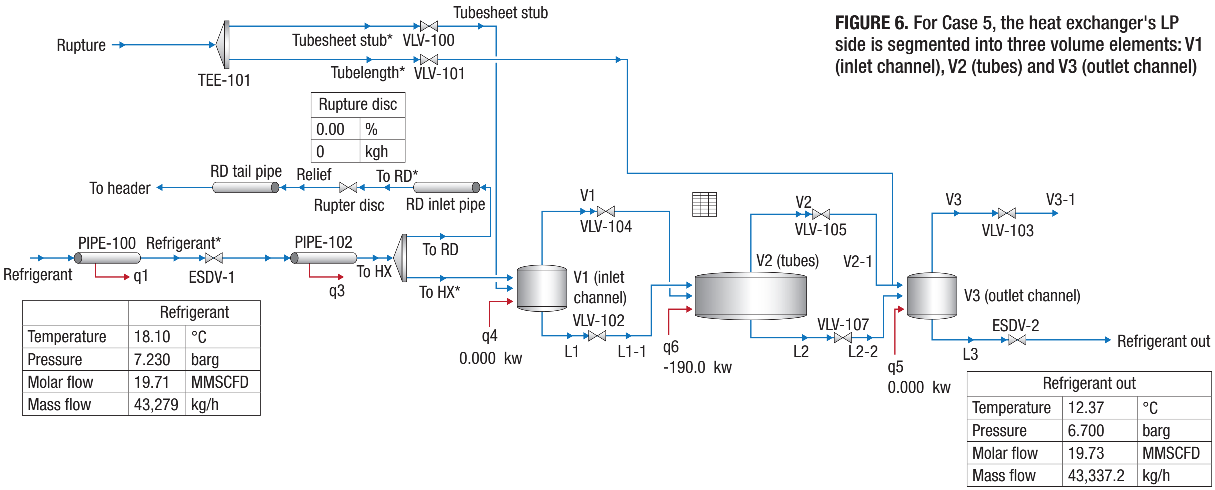

FIGURE 6. For Case 5, the heat exchanger's LP side is segmented into three volume elements: V1 (inlet channel), V2 (tubes) and V3 (outlet channel)

tected by the 10/13 rule

- Line sizing for the rupture disk's inlet and outlet should be based on the transient relief flows, with the criteria that the LP-side pressure rise is limited to the allowable design overpressure
- Dynamic simulations allow evaluations of suitable exchanger minimum metal design temperatures
- Dynamic evaluation of the heat-exchanger tube-rupture scenario is often simplified by looking at the exchanger in isolation from the larger system of which it is a part, since the assumption of instantaneous closure of inlet and outlet isolation valves and emergency shutdown valves (ESDVs) on tube rupture will give the fastest, and thus most conservative, pressure-rise estimate. Hazard analysis should, however, consider the impact of actual ESDV closure rates on the system beyond the ESDVs, especially for liquid-filled systems, which see very rapid pressure-rise rates

For further guidance, Figure 7 presents a decision chart for evaluating tube-rupture scenarios based on API-521 guidelines. Figure 7 and the cases discussed above show that dynamic evaluation can lead to better relief-device selection and sizing, and materials selection for various conditions, including some that do not require dynamic evaluation under the API guidelines. ■

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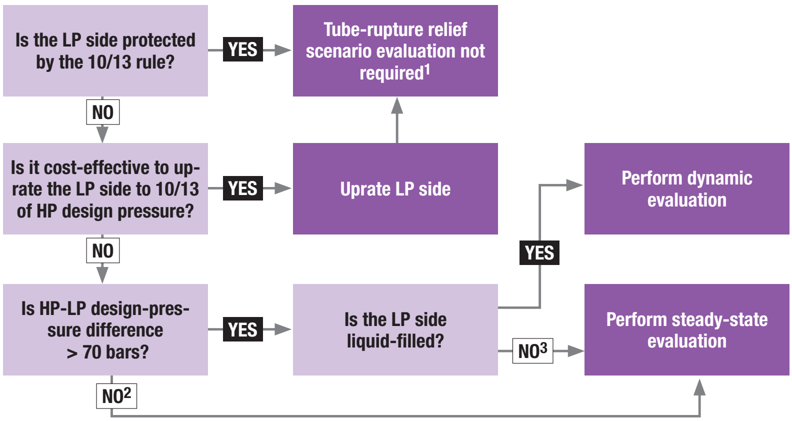

Notes:

1. Evaluation may still be required for reacting systems
2. As illustrated in Case 4, even for scenarios where the HP-LP pressure differential is <70 bars, dynamic simulation may be required if the LP side is liquid-filled. The pressure rise could still be too rapid for the PSV opening capacity. Even if a rupture disc is installed, inlet and outlet line sizing based on steady-state tube-rupture flow calculations may not be accurate
3. As illustrated by Case 2, dynamic simulation can allow for more accurate PRD sizing

FIGURE 7. Based on API-521 guidelines, this decision chart for evaluating tube-rupture scenarios can help engineers determine if steady-state or dynamic evaluation is most suitable

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Thermal Design Guidelines for Optimizing Shell-and-Tube Heat Exchangers

Ensuring optimal performance of shell-and-tube heat exchangers requires knowledge of the controlling fluid, correct exchanger geometry and configuration, as well as proper fluid placement

Satyendra Kumar Singh
Simon India Ltd.

IN BRIEF

MAXIMIZING *U*

CORRECT FLUID PLACEMENT

MAXIMIZING EMTD

MINIMIZING SHELLSIDE BYPASS

Optimizing the thermal design of a shell-and-tube heat exchanger requires minimizing the heat-transfer area for a given heat duty while remaining within the constraints of given shellside and tubeside pressure drops. The general heat-transfer equation is shown in Equation (1), where the heat-transfer rate (Q) is given in terms of the overall heat-transfer coefficient (U), the heat-transfer surface area (A) and the effective mean temperature difference, $(\Delta T)e$.

$$Q = UA(\Delta T)e \quad (1)$$

For a given Q, A can be minimized by maximizing U, $(\Delta T)e$ or both, subject to the constraints of the shellside and tubeside pressure drops. Additional design constraints may stem from other factors, such as flow-induced vibration, space limitations, and standard tube lengths and diameters as specified by the Tubular Exchangers Manufacturers Association (TEMA) [*1*].

Maximizing *U*

Although U can be increased by increasing the shellside or tubeside heat-transfer coefficient (h_s or h_t, respectively), it can be increased substantially only by increasing the heat-transfer coefficient of the controlling side, which is the side with higher thermal resistance or a lower heat-transfer coefficient. Some general guidelines for determining the controlling side in a shell-and-tube heat exchanger are given in Table 1.

The heat-transfer coefficient of either side can be increased by increasing the velocity of the fluid in that side, or by lowering the tube diameter for given process conditions, as is evident from the basic equations in the following section.

Tubeside heat-transfer coefficient. The tubeside heat-transfer coefficient (h_t) is given by Equation (2), which is a form of the Sieder-Tate equation [*3*].

$$h_t d/k_t = 0.023(Re_t)^{0.8}(Pr_t)^{1/3}(\mu_t/\mu_{wt})^{0.14} \quad (2)$$

Where:
d = Inside diameter of a tube
k_t = Thermal conductivity of the tubeside fluid
μ_t = Viscosity of the tubeside fluid
μ_{wt} = Viscosity of the tubeside fluid at the average inner tubewall temperature

The tubeside fluid's Reynolds number (Re_t) and Prandtl number (Pr_t) are defined by Equations (3) and (4), respectively.

$$Re_t = \rho_t ud/\mu_t \quad (3)$$

Where:
ρ_t = Density of the tubeside fluid
u = Velocity of the fluid in a tube

$$Pr_t = Cp_t\mu_t/k_t \quad (4)$$

Where:
Cp_t = Specific heat of the tubeside fluid at constant pressure

All of the physical properties in Equations (2), (3) and (4), with the exception of μ_{wt}, are referenced at the average of the inlet and outlet bulk temperatures. By incorporating Equations (3) and (4), Equation (2) becomes Equation (5).

$$h_t=(0.023\rho_t^{0.8}u^{0.8}Cp_t^{1/3}k_t^{2/3})/(\mu_t^{0.33}\mu_{wt}^{0.14}d^{0.2}) \quad (5)$$

Equation (5) clearly indicates that an increase in tube velocity increases the tubeside heat-transfer coefficient.

TABLE 1: GUIDELINES FOR DETERMINING THE CONTROLLING SIDE IN AN EXCHANGER [2]	
Controlling side	**Non-controlling side**
Condensing hydrocarbon	Liquid water*
Condensing hydrocarbon	Boiling water
Boiling hydrocarbon	Liquid water*
Boiling hydrocarbon	Condensing steam
Single-phase hydrocarbon	Condensing steam
Single-phase hydrocarbon	Boiling water
Single-phase hydrocarbon	Liquid water*
Gases	Liquid water*
*Includes cooling water, demineralized water, boiler feedwater and so on	

The tube velocity can be increased in the following ways:

i. Increasing the number of tube passes
ii. Reducing the shell diameter and increasing the tube length, thus reducing the number of tubes and the flow area
iii. Increasing the tube pitch while keeping the same shell diameter and increasing the tube length, thus reducing the number of tubes and the flow area; however, it is to be noted that tube pitch is generally specified as 1.25, 1.33 or 1.5 times the tube outside diameter, posing limitations to the possible increases in this parameter
iv. Reducing the tube inside diameter; however, tube diameters are standardized per TEMA standards, and therefore, variation of this parameter is also limited [1]

It is also apparent from the same equation that reduction in the tube inside diameter increases the tubeside heat-transfer coefficient, whether or not it results in an increase in velocity. That is, even if the velocity in the tube is kept constant by reducing the tube diameter and increasing the number of tubes, it leads to an increase in the tubeside heat-transfer coefficient.

The tubeside heat-transfer coefficient can be increased by: increasing the number of tube passes; reducing the shell diameter and increasing the tube length; increasing the tube pitch while keeping the same shell diameter and increasing the tube length; or reducing the tube inside diameter

From the above discussions, it can be concluded that the tubeside heat-transfer coefficient can be increased by: increasing the number of tube passes; reducing the shell diameter and increasing the tube length; increasing the tube pitch while keeping the same shell diameter and increasing the tube length; or reducing the tube inside diameter.

Shellside heat-transfer coefficient. The shellside heat-transfer coefficient (h_s) is given by Equation (6), based on Kern's method [4].

$$h_s D_e/k_s = 0.36(G_s D_e/\mu_s)^{0.55}(Cp_s \mu_s/k_s)^{1/3}(\mu_s/\mu_{ws})^{0.14} \quad (6)$$

Where:

k_s = Thermal conductivity of the shellside fluid
μ_s = Viscosity of the shellside fluid
Cp_s = Specific heat of the shellside fluid at constant pressure
μ_{ws} = Viscosity of the shellside fluid at the average outer tubewall temperature

D_e is the shellside equivalent diameter, and is four times the hydraulic radius (r_h), which is the ratio of the free area (A_f) to the wetted perimeter (L). Equations (7) and (8) define D_e and r_h, respectively.

$$D_e = 4r_h \quad (7)$$

$$r_h = A_f/L \quad (8)$$

G_s, the mass velocity of the shellside fluid, is the ratio of mass flowrate of the shellside fluid (W) to shellside crossflow area at the center of the shell (a_s).

$$G_s = W/a_s \quad (9)$$

All of the physical properties in Equation (6), except for μ_{ws}, are referenced at the average of the inlet and outlet bulk temperatures. Equation (6) is valid for Reynolds number ($G_s D_e/\mu_s$) values between 2,000 and 100,000, and for a 25% cut segmental baffle [4].

For square and rotated-square pitches, $A_f = P_t^2 - \pi d_o^2/4$, and $L = \pi d_o$, d_o being the tube outside diameter and P_t the tube pitch. Therefore, from Equations (7) and (8), D_e is given by Equation (10).

$$D_e = 4(P_t^2 - \pi d_o^2/4)/\pi d_o \quad (10)$$

The tube pitch, P_t, is the product of d_o and the pitch ratio, r, which is typically 1.25, 1.33 or 1.50.

$$P_t = rd_o \quad (11)$$

From Equations (10) and (11), D_e is given by Equation (12).

$$D_e = 4d_o(r^2 - \pi/4)/\pi \quad (12)$$

From Equations (6) and (9), h_s is given in Equation (13).

$$h_s = 0.36(W/a_s)^{0.55} D_e^{-0.45} k_s^{2/3} Cp_s^{1/3} \mu_s^{-0.08} \mu_{ws}^{-0.14} \quad (13)$$

It is implied from Equation (13) that an increase in D_e decreases h_s, and vice versa. From Equation (12), it is evident that D_e is directly proportional to d_o for square and rotated-square pitches. The same is true for triangular and rotated-triangular pitches. Thus, a decrease in tube diameter lowers the equivalent diameter, and thereby increases the shellside heat-transfer coefficient. From Equation (13), it is also evident that increasing the shellside crossflow velocity (decreasing a_s) increases h_s. Equation (14) expresses a_s in terms of P_t, the shell inside diameter (D_i), the baffle spacing (B) and the clearance between adjacent tubes (c) [4].

$$a_s = D_i Bc/P_t \quad (14)$$

The clearance between adjacent tubes is given by Equation (15).

$$c = P_t - d_o \quad (15)$$

From Equations (11), (14) and (15), a_s is given by Equation (16).

$$a_s = D_i B(1 - 1/r) \quad (16)$$

From Equation (16), it is seen that

the shellside crossflow velocity can be increased (a_S can be reduced) by lowering D_i, B or r. Thus, the shellside velocity can be increased in the following ways:

i. Reducing shell inside diameter
ii. Reducing baffle spacing
iii. Lowering pitch ratio; however, tube pitch is generally 1.25, 1.33 or 1.5 times the tube outside diameter, limiting the flexibility in lowering this parameter

Based on the above discussions, the shellside heat-transfer coefficient can be increased by lowering shell inside diameter, baffle spacing, pitch ratio or tube outside diameter.

Correct fluid placement

In order to maximize the heat-transfer coefficient, the allowable pressure drop of each fluid (hot or cold) should be utilized to the maximum — meaning that the calculated pressure drop should be as close as possible to the allowable one. This requires correct fluid placement in terms of the shellside or tubeside of the exchanger, subject to the constraints described in this section. Further, it may not always be possible to fully utilize the pressure drop of both fluids. In such a situation, the pressure drop of the controlling fluid should be fully utilized in order to maximize the overall heat-transfer coefficient.

The shellside heat-transfer coefficient can be increased by lowering shell inside diameter, baffle spacing, pitch ratio or tube outside diameter

Sometimes, maximum utilization of the pressure drop in the tubeside requires an increase in the number of tube passes, which reduces the effective mean-temperature difference (EMTD) if the shellside has one pass. In these cases, interchanging the sides of the fluids, subject to the constraints given below, may allow utilization of the pressure drops in both sides with one-one countercurrent flow (one pass on the shellside and tubeside with flows in opposite directions), resulting in the maximization of EMTD. The combined impact of U and EMTD should be seen, and the option resulting in the minimum required heat-transfer surface area should be chosen.

There may be some other constraints, such as the corrosiveness of the fluid, the fouling tendency of the fluid, design pressure, design temperature, flow-induced vibration and so on, which may dictate the placement of the fluid otherwise (differently from the viewpoint of the minimization of heat-transfer area).

Maximizing EMTD

EMTD can be maximized by selecting the proper exchanger configuration. This is particularly important in a temperature-cross situation — that is, if the hot-fluid outlet temperature is lower than the cold-fluid outlet temperature. If there is a temperature cross, EMTD is significantly reduced if there is deviation from pure countercurrent flow. In such a situation, maximizing EMTD should be the key objective. EMTD can be maximized by providing multiple shells in series or by selecting a configuration wherein shellside and tubeside flows approach pure countercurrent flow [*1*]. Thus, the following guidelines can be applied, based on TEMA heat-exchanger type standards:

i. For TEMA E shells, one tube pass with countercurrent flow yields the maximum EMTD
ii. For TEMA F shells, providing two tube passes with countercurrent flow maximizes the EMTD
iii. For TEMA G and H shells, EMTD can be maximized by providing an even number of tube passes, that is, 2, 4 or 6 passes
iv. For TEMA X shells, as the number of tube passes increases, the flow approaches pure countercurrent flow, with the shellside and tubeside fluids entering from opposite ends. This means that if the shellside fluid enters from the top, then the tubeside fluid should enter from the bottom, and vice versa. Thus, EMTD can be maximized by increasing the number of tube passes to the extent possible (constrained by tubeside allowable pressure drop) and making the two fluids enter from opposite ends
v. For TEMA J shells, pure countercurrent flow cannot be achieved, as the shellside flow is divided into two streams with opposite flow directions. Hence, the maximum achievable EMTD is less than the maximum achievable EMTD for E, F, G, H or X shells. Therefore, this type of shell is not preferred in situations where maximizing EMTD is the objective. A J shell is generally used when minimizing the pressure drop is the objective

However, sometimes other constraints may not allow a configuration with pure countercurrent flow, and force the provision of multiple shells in series. For example, if the tubeside fluid is cooling water, more than one tube pass may be required to ensure sufficient velocity to minimize fouling, but if there is a temperature cross, this can significantly reduce EMTD with one shell pass. Therefore, the use of F, G or H shells, or multiple shells in series, is desirable in such a situation to maximize EMTD. The shellside pressure drop may be too high to select the F shell configuration. In such a case, multiple E shells in series or the use of a G or H shell may be the preferred choice. Also, F, G and H shells may not be appropriate because of potential thermal leakage through longitudinal baffles (if uninsulated). If the reduction in EMTD due to thermal leakage can more than offset the EMTD gain due to pure countercurrent or near-countercurrent flow, again the preferred option is the use of multiple shells in series.

If there is no temperature-cross situation, the reduction in EMTD due to deviation from pure countercurrent flow may not be that significant. Therefore, the combined impact of U and EMTD should be seen. For example, if the tubeside is controlling, U can be increased significantly by increasing the number of tube passes. However, for E shells, this will lower EMTD due to deviation from pure countercurrent flow. So, if the increase in U more than offsets the reduction in EMTD, the number of tube passes should be increased to the maximum. Otherwise, a single tube pass should be provided to achieve the maximum EMTD.

Minimizing shellside bypass

Shellside fluids have the tendency to bypass the tube bundle if the clearances are not properly defined. Bypassing leads to poor heat transfer due to reduced EMTD, resulting in a higher heat-transfer-area requirement for the same duty. The three main types of bypass behavior are as follows:

i. Between the tube bundle and the shell
ii. Between the baffles and the shell
iii. Through the tube-field pass-partition lane, in the case of multiple tube passes, when the pass-partition lane is parallel to shellside crossflow

Another type of bypass — through the baffle hole (between the tube and the baffle) — is not as harmful, as it does participate in heat transfer. The first type of bypass is more likely to occur with floating-head exchangers (TEMA P-, W-, S- and T-type rear heads [*1*]), and can be minimized by providing sealing strips.

The second type of bypass can be minimized by minimizing the clearance between baffles and shell, or increasing the baffle spacing or baffle cut. However, an increase in baffle spacing or cut must be done carefully, because this can lower the shellside heat-transfer coefficient. The third bypass type can be minimized by providing seal rods in the pass-partition lane. ■

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For more information on TEMA heat-exchanger types, see Specifying Shell-and-Tube Heat Exchangers, *Chem. Eng.*, May 2013, pp. 47–53

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Flare Consolidation Considerations

Consolidating multiple flares can help mitigate emissions and maintenance

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Many petroleum-refining and petrochemical facilities have experienced tremendous growth in recent years in response to increasing demand for fuels and chemical precursors. Due to environmental regulations and economic considerations, it is frequently more desirable to increase the throughput on an existing facility rather than to build a new plant. As shown in Figure 1, the total crude-oil processing capacity in the U.S. has increased steadily as the number of operable refineries declined over the years [*1,2*]. The expansion of these facilities has typically resulted in an array of independent flare systems built to meet the requirements of specific expansion projects.

Flare consolidation is one attractive solution that is based on a holistic approach to updating the existing infrastructure to meet growing demands. Integrating separate flare systems into a single flare network can be an economically and environmentally viable solution to meet challenging operational and regulatory requirements.

The benefits

Generally speaking, independent flare systems could be integrated through the installation of crossover piping "jumpers" at appropriate location(s) between the main lines or headers of two existing systems. The rationale and engineering requirements for these modifications are described below.

Though many factors can affect the sizing of flare systems and relief headers, it is usually a type of utility failure, such as total or partial power failure or a loss of cooling water flow, that dictates the design basis of the disposal system. In most petroleum refineries, either partial power failure or cooling water failure is typically the controlling scenario.

Such events are generally localized to a particular area of the plant. For instance, if a chemical facility has three independent cooling-water systems, the loss of any one system should not result in releases throughout the entire facility.

Thus, the availability of a plant-wide flare system can provide increased relief capacity for such scenarios to support the expansion of processing capacity. Since safe operating limits can be set by relief- and flare-system capacities, a well-implemented flare consolidation may lead to an increase in the plant capacity through modest upgrades to debottleneck the flare systems.

Ease of maintenance

With a single large network of multiple flare systems servicing an entire facility, some of the system capacity gained may allow for any one of the multiple flares to be removed from service for maintenance without significantly impacting the operation of the facility.

With independent flares, flare maintenance would require a planned shutdown of the affected units; whereas emergency flare maintenance would require either an unplanned shutdown or turndown of a portion of the plant. In both cases, production would likely be curtailed and would thereby result in higher overall costs.

The ability to perform emergency or scheduled maintenance on the flare system with minimal impact on operations could lead to a significant increase in overall up-time for many facilities.

EPA requirements

The U.S. Environmental Protection Agency (EPA; Washington, D.C.) has released a "National Petroleum Refinery Initiative" to encourage refiners to make a commitment to emission reductions. Since 2000, 109 refineries in 32 states and comprising over 90% of the total U.S. refining capacity have agreed to comply [*3*]. As part of this initiative, a covered facility may not emit more than 500 lb of sulfur dioxide in a 24-h period during non-emergency situations, based on Emergency Planning and Community Right-to-Know Act (EPCRA) Section 304.

One option to minimize emissions

is to install a flare-gas recovery unit (FGRU) for each flare system. The consolidation of multiple flare systems into a single flare network could significantly reduce the cost of compliance as a single FGRU unit could be installed to service the entire facility (or two FGRUs could be installed to improve availability). A simplified diagram of flare debottlenecking options using this approach is shown in Figure 2. In addition, consumption rates of various utilities, such as air, steam or fuel gas to support normal flare operations, could be reduced if a cascaded or staggered flare arrangement was adopted.

OSHA's PSM standard

The consolidation of multiple flare systems into a single integrated network requires a thorough understanding of the design basis for the flare systems. There is no reasonable means of combining multiple independent systems without a concrete and well-documented design basis for the flare systems, which in turn is part of the process safety information requirement per the Process Safety Management (PSM) Standard 29 CFR 1910.119(d)(3)(i)(D) [*4*] of the U.S. Occupational Safety and Health Admin. (OSHA; Washington, D.C.).

Methodologies

All credible flare loads should be considered to ensure that the modified system can safely, economically and efficiently handle the expected loads. It is also necessary to understand the current layout of the flare system to optimize flare header connections. A thorough understanding of the current system and the proposed changes allows the designer to confirm that the modified system can operate safely and to validate that flare maintenance requirements can be met.

Identify and document

All potential loads to the flare system must be analyzed and documented. The loads can originate from a variety of sources (such as relief valves, control valves, bleeder valves, emergency shutdown [ESD] systems and so on) and can enter the flare system due to a variety of causes. To ensure that the system is adequately sized, all emergency loads (due to area fires, power failures, cooling water failures and major equipment failures) must be considered, documented, and evaluated. To properly size the FGRU and isolation seal drums for compliance with the EPA requirements, releases during routine operations and maintenance must also be accounted for and documented.

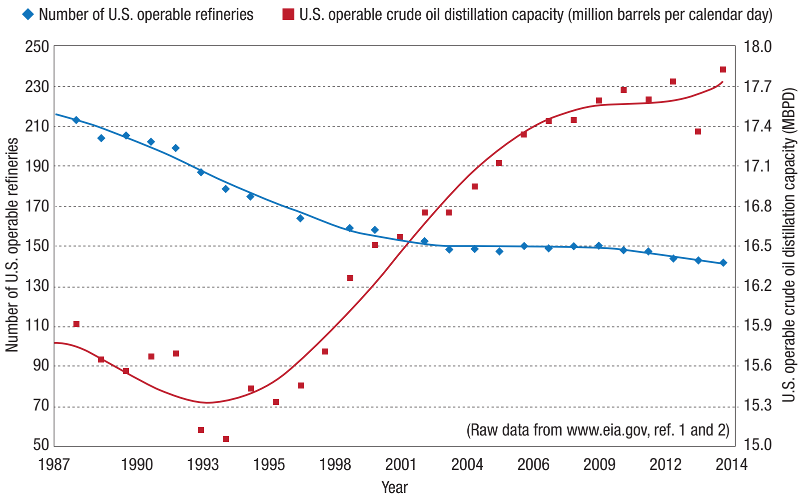

FIGURE 1. In the U.S., the total crude-oil processing capacity has increased steadily as the number of operable refienries declined over the years

Develop a model

Evaluation of the location of the existing flare headers on a plot plan or other facility map will allow for a quick overview of the system connections and aid in the design of proposed crossovers. Once the consolidated flare system has been developed, a hydraulic model of this flare network can be developed to verify that it can handle the expected loads adequately. Three types of modeling will be necessary: emergency load, non-emergency load and maintenance load.

Emergency load modeling. A standard method, such as the one outlined in American Petroleum Institute (API) Standard 521 [*5*], is applied to ensure that the system can handle the expected emergency loads. Critical items to verify include the following:

1. *Backpressure limits* — To ensure that the relief capacities for individual sources will remain adequate despite the pressures built-up in the disposal system
2. *Header velocities* — To ensure that there are no localized areas of high velocity in the flare network that could cause mechanical problems due to excessive momentum forces or acoustically induced vibrations
3. *Flare equipment sizing* — To ensure satisfactory performance of all relevant flare equipment, such as liquid knockout pots (for vapor-liquid separation), flare seals (including seal height evaluation), flare tip performance (in terms of flare radiation, noise, flame stability and so on), vaporizers and heaters and more
4. *Mechanical limits of the header* — To ensure that the flare header itself can adequately handle the expected operating requirements
5. *Liquid removal facilities* — To ensure that the integrated flare loads will not result in excessive mechanical stress due to undesirable flow patterns (such as high-velocity liquid slugs)

Non-Emergency load modeling. All releases to the flare system during normal operation or routine maintenance of the facility should be accounted for. Critical items to verify include the following:

1. *FGRU* — To ensure that the normal flare loads from all sources — such as leaking relief valves or normally open vent lines plus intermittent releases during maintenance (equipment blowdown), and operations (backpressure control valves, startup/shutdown requirements, purging) — can be handled by the FGRU. This information is used to generate the

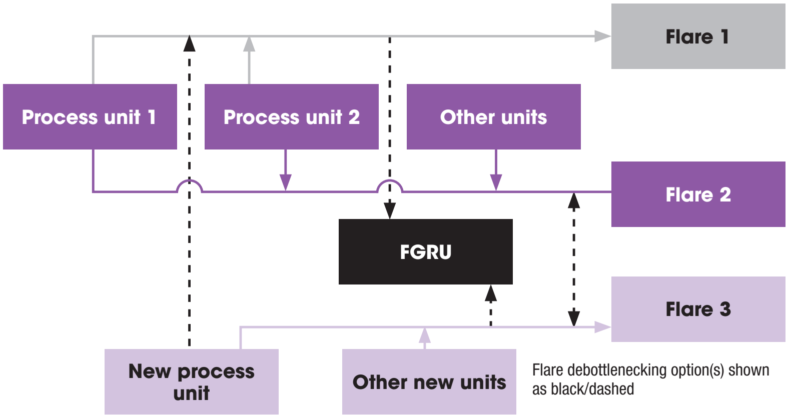

FIGURE 2. A single flare-gas recovery unit (FGRU) could be installed to service an entire facility, as shown in this simplified diagram of flare debottlenecking options

sizing parameters for the FGRU (especially the compressor).

2. *Seal drums* — To ensure that excessive or insufficient pressure will not disrupt the liquid seal in the seal drum and result in unintended release from a flare stack during normal operations. Consideration must also be given to ensure that the sealing fluid does not freeze.

3. *Liquid knockout* — While most FGRU compressors can handle limited liquid on the inlet, large liquid flow to these compressors should be avoided.

Maintenance load modeling. Evaluation of both emergency and non-emergency loads to ensure that all of the established limits would not be exceeded and that the facility could be operated safely should an individual flare (or portion of the header) be removed from service for maintenance reasons.

The results of this modeling could lead to the modification of the consolidated header design or flare operation in areas where facility upgrades are planned. The changes may include the allocation of larger diameter headers, adding mechanical supports, modifying relief devices or flare equipment, adding process safety systems, implementing operational changes, training and so on.

The flow distribution and flow pattern of the flare loads throughout the integrated flare system must be evaluated, because consolidating flares could result in areas of increased corrosion or erosion rates, temperature-induced embrittlement, mixing of chemically incompatible fluids, or a host of other operational or safety concerns.

Fluids follow the path of least resistance. Sizing a flare header that is too large could result in overloading one flare stack in a consolidated system even though the total system may have sufficient capacity. Additional modeling, such as Flare Quantitative Risk Assessment (QRA) may be required to account for the time dependency of flare loads or the statistical probability of various emergency scenarios.

Other design considerations

While the multiple benefits of flare consolidation have been described above, other design considerations could preclude its implementation. In particular, segregation of relief streams could be necessary due to incompatible functional requirements in terms of operating pressure, temperature, fluid composition, or physical properties of the relief streams. Issues such as corrosion, toxicity, reactivity, phase change, and flow pattern of the combined relief streams upon flare consolidation should be evaluated.

Concluding remarks

While flare consolidation may be driven by environmental or regulatory considerations, a properly consolidated flare could provide additional flare capacity, improve operational flexibility, and result in operational savings for the whole facility.

Multiple independent flare systems are not always practical, and there may be more than one option to eliminate the need for flare consolidation. However, performing flare maintenance only during unit shutdowns or turnarounds, installing a dedicated FGRU for each flare, and other options each have their own limitations or drawbacks.

When implemented properly, a flare consolidation program could be an economically attractive solution that allows facilities to maximize the utilization of their disposal systems while maintaining compliance to regulatory requirements of the EPA and OSHA. Sound engineering is required to ensure that environmental impacts and maintenance concerns are not mitigated at the expense of facility safety. ■

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Bulk Solids: Optimizing Screw Conveyors

Despite their apparent simplicity, the complexity of these conveying systems demands proper design and an understanding of the underlying principles

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Screw conveyors play a major role in a wide variety of industrial operations that involve the handling of bulk solids. While their use is generally limited to relatively short conveying distances, their versatility in being able to provide reliable operation for conveying over a wide range of elevation angles from the horizontal to the vertical is well established. Despite their apparent simplicity, their mode of operation is far from simple. For this reason, it is important that conveyor designers, manufacturers and users have some understanding of the basic mechanics governing their performance. This discussion of screw conveyor fundamentals draws upon background research that is presented in Refs. 1–7.

Background

The earliest form of the screw conveyor dates back some 2200 years to the time of Archimedes who developed the helical screw conveyor, mainly for pumping water for irrigation purposes. The Archimedean screw conveyor consists of a helical screw flight that is attached to a cylindrical casing, so they rotate together. Its conveying action by, positive displacement, could only be achieved at low elevation angles that restricted its use mainly to fluids or free-flowing granular materials.

Modern screw conveyors overcome this limitation, allowing bulk materials to be conveyed over a range of elevation angles from horizontal to vertical, with a design that forces relative motion to occur between the rotating helical flight and the casing. In most cases, this is achieved by the casing being fixed and the screw rotating within the casing, as shown in Figure 1.

Practical limitations require a liberal clearance between the flight and the casing, and this has been shown to be beneficial rather than detrimental to performance. The conveyor may be gravity fed, as shown in Figure 1, and in this case, the screw flight projects beyond the casing at the lower or intake end (this projection is referred to as the choke). The screw must be immersed into the feed material at least to the level of the lower end of the casing, otherwise the conveyor will not elevate the bulk material. Better performance can be achieved by employing an efficient forced-feeding system.

One widely used screw conveyor configuration is a design in which the helical screw flight rotates in a U-shaped, trough-type casing (Figure 2). This design is limited to relatively low angles of elevation, low speeds and low fill ratios. Owing to the low bending stiffness of helical flights [7], hanger support bearings are necessary, especially for long conveying distances. This explains the need for low fill ratios to protect the bearings from contact with the bulk material.

However, support bearings are not necessary in the case of shaftless screw conveyors (Figure 3). With this design, the helical flight is supported on a plastic, wear-resistant liner attached to the inside surface of the casing. The helical flight needs to

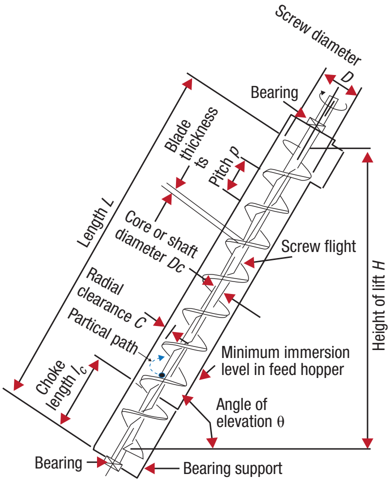

FIGURE 1. The enclosed screw conveyor with fixed casing and rotating screw is a versatile conveyor, which is widely used throughout the chemical process industries, to provide bulk-solids conveying over a wide range of elevations and speeds

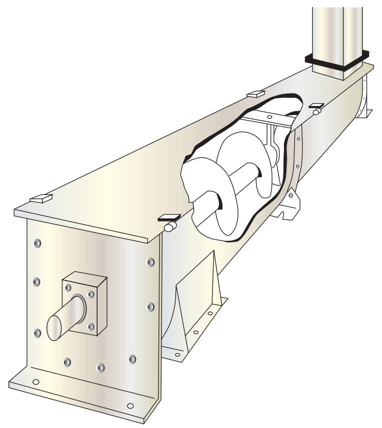

FIGURE 2. A U-shaped, trough-type screw conveyor requires support bearings, but allows for longer conveying distances and lower fill levels

FIGURE 3. The flights on a shaftless, screw-type conveyor have robust construction, which allows them to resist damage by torsional wind-up

NOMENCLATURE			
A	Cross-sectional area of material, m^2	t_s	Thickness of screw blade, m
C	Radial clearance, m	V_A	Absolute velocity, m/s
D	Screw diameter, m	V_R	Relative velocity, m/s
Dc	Core or shaft dia., m	V_L	Conveying velocity component, m/s
g	Gravitational acceleration, 9.81 m/s^2	V_{Lt}	Maximum theoretical conveying velocity, m/s
h	Variable height of material across the screw surface, m	V_S	Screw velocity, m/s
h_{av}	Average height of material on the screw surface, m	V_T	Rotational velocity component, m/s
K_v	Pressure ratio from Equation (24) = 0.4	v	$(\omega\ p)/(2\ \pi)$ = axial velocity of the screw, m/s
k_F	Stress ratio, defined in Equation (12)	α	Screw helix angle, deg
k_j	Stress ratio = 0.4	α_e	Effective screw helix angle, deg
k_s	Stress ratio, defined in Equation (13)	β	Included angle of the segment of bulk solid, deg
L	Length of screw conveyor, m	Γ	Non-dimensional screw fill capacity per pitch
N	Rotational speed of screw, rev/min	ε	Offset angle or slope angle of surface, deg
N_S	Specific speed number, dimensionless	θ	Inclination angle of conveyor, deg
N_T	Non-dimensional torque parameter	η_d	Drive efficiency
n	Vortex index	η_F	Fill ratio or fullness
P	Power, kW	η_V	Volumetric efficiency
p	Screw pitch, m	λ	Helix angle of particle path, deg
P_{hic}	Casing friction angle	λ_e	Effective helix angle of particle path, deg
P_{his}	Screw surface friction angle	μ_c	Friction coefficient for bulk material on casing surface
Q	Volumetric throughput, m^3/h	ϕ_s	Friction angle for screw surface, deg
Q_m	Mass throughput, ton/h	μ_E	Equivalent friction coefficient for trough
Q_t	Maximum theoretical volumetric throughput, m^3/h	μ_s	Friction coefficient for bulk material on screw surface
R	Inside radius of the casing, m	π	3.1416
R_e	Effective radius of screw, from Equations (9) and (21), m	ρ	Bulk density, ton/m^3
R_i	Inner radius of radius of flight, m	σ_a	Stress on screw flight surface, kPa
R_o	Outer radius of flight, m	σ_n	Normal stress of material on screw flight surface, kPa
r	Radial position, m	ϕ_c	Friction angle for screw casing, deg
T	Torque per pitch, Nm	ϕ_s	Friction angle for screw surface, deg
T_{sh}	Torque due to material contact with shaft, Nm	ω	Angular velocity, rad/s
T_{sp}	Torque per screw pitch, Nm		
T_t	Total torque for U-trough conveyor, kNm		

be of heavy cross section to resist the torsional, wind-up deformation imposed by the conveying action. The need to limit the fill ratios of U-shaped trough conveyors is necessary to prevent "throwback" and a loss in conveying efficiency.

This article provides an overview of key performance and design aspects of enclosed screw conveyors.

Enclosed screw conveyors

Referring to the enclosed screw conveyor shown in Figure 1, the conveying of bulk materials is characterized by particles moving in a helical path of the opposite hand to that of the screw. The conveying action and throughput is dependent on the 'braking effect' imposed by the casing friction. This braking effect helps to control and reduce the rotational component (or vortex motion) of the material that is imparted to the material by the inclined surface of the rotating helical screw flight.

The conveyor throughput is also influenced by the degree of fill or "fullness" of the screw. As the rotational speed of the conveyor increases, the losses due to the vortex motion decrease, up to a limiting value, making for a more efficient conveying action. However, when gravity feed into the screw intake is used (as in Figure 1), the feedrate is often insufficient to match the potential conveying capacity, and a reduction in fill ratio or "fullness" of each flight results. The overall efficiency of the conveyor can be improved by using a forced-feeding system to overcome this problem.

Conveyor throughput. Figure 4 shows a graph of throughput versus speed for a screw conveyor with a 0.165-m dia. and 0.165-m pitch helical flight conveying wheat at three angles of elevation — 30 deg, 60 deg and 90 deg. Over the lower speed range, throughput is nominally proportional to the speed, but then becomes quite non-linear and is limited with further increase in speed, sometimes reaching a maximum and then decreasing. Figure 4 also shows the maximum theoretical throughput, Q_t, for the conveyor running 100% full with the bulk material moving axially without rotation. While this is not possible in an actual conveyor (because of the influence of the friction due to the screw flight), it provides a basis for the determination of the conveying efficiency.

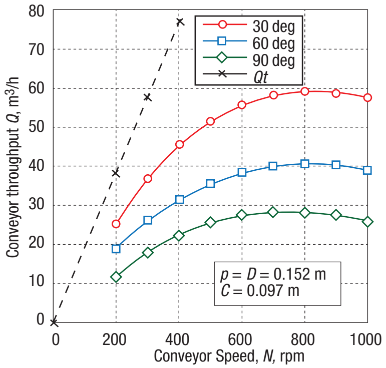

FIGURE 4. This diagram of conveyor throughput for wheat shows conveying performance as a function of rotational speed at three elevation angles

$$Q = Q_t \eta_V \quad (1)$$

Where:

$$Q_t = 60 \Gamma N D^3 \quad (2)$$

$$\Gamma = \frac{\pi}{4}\left[(1+2\frac{C}{D})^2 - (\frac{D_C}{D})^2\right]\left[\frac{p}{D} - \frac{t_S}{D}\right] \quad (3)$$

Effect of conveyor diameter — Corresponding speeds. Corresponding speeds are given by a non-dimensional, specific speed number, N_S, which is defined by Equation (4):

$$N_s = \frac{\omega^2 R_o}{g} = \frac{N^2 D}{1789} \quad (4)$$

It follows from Equation (4) that screw conveyors of large diameter attain their maximum output at lower speeds compared to conveyors of smaller diameter [*1*]. For example, for a scale of 4:1, the characteristic performance of the larger of the two conveyors would occur at half the speed of the corresponding, geometrically similar conveyor of one quarter the size.

The mass throughput of a screw conveyor, in t/h, is given by Equation (5):

$$Q_m = \rho Q = \rho Q_t \eta_V \quad (5)$$

Volumetric efficiency of an enclosed screw conveyor. The volumetric efficiency of a screw conveyor is the product of the conveying efficiency, η_{VR}, and the "fullness," η_F, as indicated in Eq. 6:

$$\eta_V = \eta_{VR} \bullet \eta_F \quad (6)$$

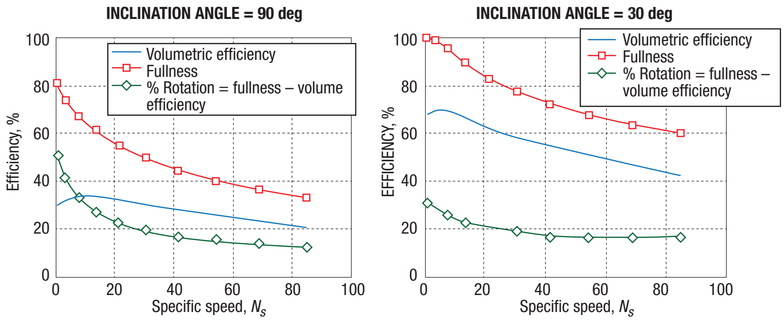

FIGURE 5. In this illustration of volumetric efficiency, "fullness" and losses due to rotation for a screw conveyor handling millet seed (p = D), one can see that efficiency decreases with an increase in inclination angle

The conveying efficiency, η_{VR}, accounts for the rotational or vortex motion, while the "fullness" is a measure of the average height, h_{av}, of material on the screw surface. This is shown in Equation (7):

$$\eta_F = \frac{h_{av}}{p} \quad (7)$$

Figure 5 shows the performance results of volumetric efficiency and fullness for an enclosed screw conveyor with gravity feed handling millet seed [*1*], for two angles of elevation (90 deg and 30 deg). The graphs are plotted against specific speed. As would be expected, η_V and η_F are significantly higher for the 30-deg angle of elevation than for the 90-deg (vertical) angle of elevation, due to more efficient gravity feeding at 30 deg. Rotational losses (defined by $\eta_F - \eta_V$) show that the losses over the range N_S = 0 to 20 are greater for the 90 deg angle of elevation than for the 30-deg angle of elevation. For $N_S > 20$, the rotational losses are approximately the same for both elevation angles. It should be noted that for the same conveying elevation height, the 30-deg conveyor needs to be, nominally, twice as long as the 90-deg (vertical) conveyor.

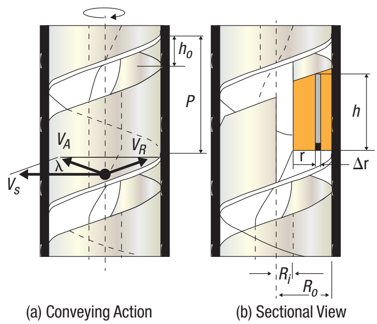

FIGURE 6. This velocity diagram for particles in contact with the screw and material profile demonstrates the mechanics of conveying action

Throughput analysis

Discussed next is the case of the vertical screw conveyor. Further discussion of this topic can be found in Refs. 3 and 4.

Conveying action within a vertical screw conveyor. Figure 6 shows the velocity diagram for a particle in contact with the screw surface at a particular location. V_S is the screw velocity due to its rotation, V_R is the relative velocity of the particle with respect to the screw surface, and V_A is the absolute velocity of the particle defined by the helix angle λ.

The velocity diagram shown in Figure 7 shows the absolute velocity resolved into two components — the "useful" conveying velocity V_L, and the "wasteful" rotational component V_T. Since the helix angle λ of the screw flight varies with the radius, being smaller at the outer periphery and larger at the shaft, the angle λ will also vary in the radial direction from the outside of the flight to the shaft. This means that the rotational velocity V_T, in theory, will vary with the radius r (Figure 6) from the shaft to the outside. The variation in V_T

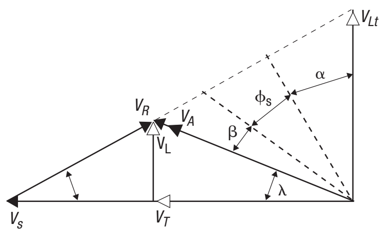

FIGURE 7. This velocity diagram depicts the "useful" conveying component V_L and "wasteful" rotational component V_T

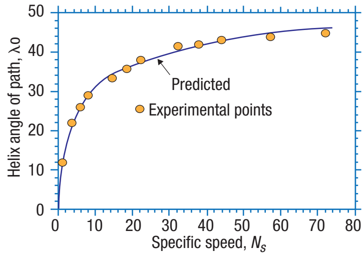

FIGURE 8. This graph shows the helix angle of the particle path at the outer periphery as a function of specific speed for a vertical screw conveyor handling millet seed ($p = D$). The figure demonstrated the benefits of increase speed in improving conveyor performance up to the limit defined by Equation (14)

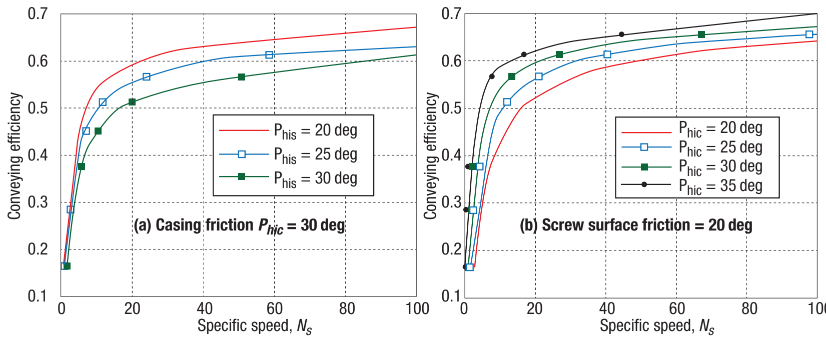

FIGURE 9A (LEFT) AND 9B (RIGHT). The effect of screw and casing surface friction shown here demonstrates the advantage of low screw friction and high casing friction

with radius describes the vortex motion in the screw and is expressed by Equation (8):

$$V_T r^n = C_V \quad \textbf{(8)}$$

In Equation (8), C_V is the vortex constant, and n is the vortex index. It has been shown by Roberts [*2, 3*] that $n \approx 0$, that is, the velocity component V_T is approximately constant and, in fact, does not vary with the increase in radius from R_i at the shaft to R_o at the outer periphery. This is because the choking action in the feed zone prevents slip back in the central region adjacent to the shaft. As a result, the height h of material on the screw flight is approximately constant and does not vary with the radius.

Effective radius. To determine the conveying efficiency, one must first determine the variation of the path helix angle λ as a function of the radius and rotational speed of the conveyor. The analysis may be simplified by lumping the rotational mass and resultant forces at the effective radius R_e defined by Equation (9):

$$R_e = \frac{2}{3}\left[\frac{R_o^3 - R_i^3}{R_o^2 - R_i^2}\right] \quad \textbf{(9)}$$

The helix angle of the screw flight α_e corresponding to R_e is defined by Equation (10):

$$\alpha_e = \tan^{-1}\left[\left(\frac{p}{\pi D}\right)\left(\frac{R_o}{R_e}\right)\right] \quad \textbf{(10)}$$

Helix angles of the particle path. The relationship between the helix angle λ of the particle path and the speed of rotation of the conveyor has been studied by Roberts [*1–3*].

It may be shown that the relationship between the specific rotational speed N_S and the helix angle λ_e defining the effective absolute path is given by Equation (11):

$$N_S = \frac{R_o}{R_e}\left[1 + \frac{\tan\lambda_e}{\tan\alpha_e}\right]^2 \left[\frac{k_F \sin(\alpha_e + \phi_s)}{{}_c\cos(\alpha_e + \phi_S + \lambda_e)} - k_S\right] \quad \textbf{(11)}$$

Where:

$$k_F = (1 - \;{}_c k_S) \le k_F \le 1.0 \quad \textbf{(12)}$$

and:

$$k_S = 2k_j \frac{p}{D}\left[\frac{1}{1 - \frac{R_i^2}{R_o^2}}\right]\eta_F \quad \textbf{(13)}$$

N_S is the specific speed defined by Equation (4). The coefficients k_F and k_S in Equations (12) and (13) take into account the bulk solid stress fields within the screw space and depend on the internal friction of the bulk solid. The angle λ_e increases with increase in speed of rotation approaching, asymptotically, a limiting value defined by the helix angle of the screw and the friction angle of the bulk solid in contact with the screw surface. That is:

$$N_S \to \infty,\ \lambda_e \to 90^o - (\alpha_e + \phi_S) \quad \textbf{(14)}$$

The helix angle λ_o at the outer periphery adjacent to the inside surface of the casing is obtained from Equation (15):

$$\tan\lambda_0 = \tan\alpha_0\left[\frac{R_o}{R_e}\left(1 + \frac{\tan\lambda_e}{\tan\alpha_e}\right) - 1\right] \quad \textbf{(15)}$$

Figure 8 shows the predicted and measured helix angle λ_o at the outer periphery of a vertical screw conveyor conveying millet seed [*3*]. The results show the significant increase in path helix angle λ_o as the speed increases, approaching asymptotically the limiting value defined by Equation (14).

Conveying efficiency. The actual conveying velocity V_{Le} at the effective radius when expressed as a ratio of the maximum theoretical conveying velocity V_{Lt}, provides a measure of the conveying efficiency allowing for losses resulting from the rotational or vortex motion. It may be shown that:

$$\eta_{VR} = \frac{V_{Le}}{V_{Lt}} = \frac{\tan\lambda_e}{\tan\alpha_e + \tan\lambda_e} \quad \textbf{(16)}$$

Influence of screw and casing friction. The performance of screw conveyors is significantly influenced by the friction generated between the bulk material and the screw and casing surfaces. Figure 9a compares the conveying efficiencies η_{VR} for a vertical screw conveyor for three friction screw surface angles — ϕ_S = 20 deg, 25 deg and 30 deg — for the casing friction angle ϕ_C = 30 deg. Figure 9b shows the influence of four casing friction angles — ϕ_C = 20 deg, 25 deg, 30 deg and 35 deg — for the screw surface friction angle ϕ_S = 20 deg. The results clearly show the advantages of low screw surface friction and high casing friction. Once the casing surface friction exceeds the internal friction of the bulk material, failure and rela-

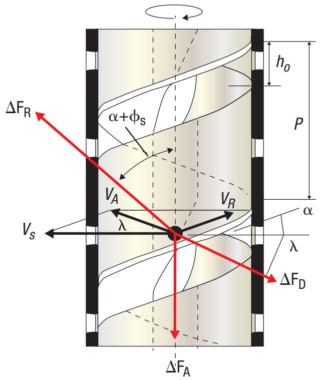

FIGURE 10. Shown here are the forces acting on bulk particles in contact with screw surface

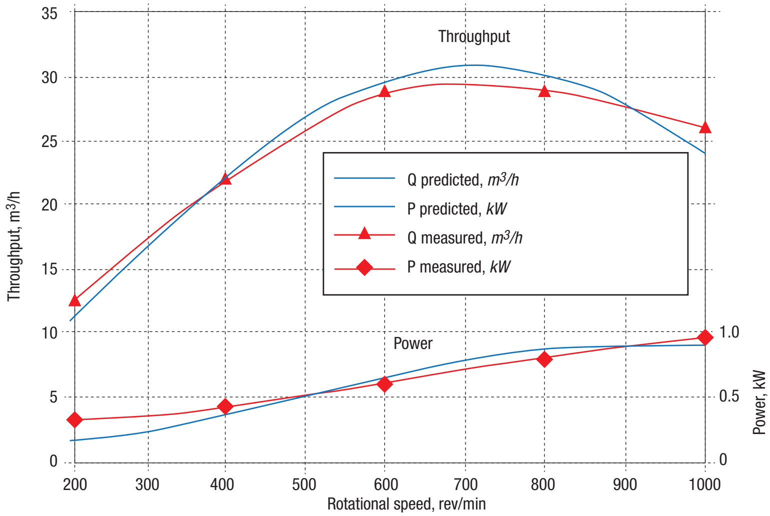

FIGURE 11. Shown here are the predicted and actual performance curves for a screw conveyor handling wheat (D = 150 mm; Dc = 50 mm; p = 150 mm; L = 2.44m; θ = 90 deg; ϕ_s = 20 deg; ϕ_c = 25 deg; kj = 0.45; ρ = 900 kg/m^3)

tive motion will be governed by internal friction and not by surface or boundary friction.

It should be noted that the surface friction angles for cohesive bulk solids decrease with an increase in normal pressure. It is important that the surface friction angles be measured and that the appropriate friction angles corresponding to the pressures generated at the screw and casing surfaces be used in the conveyor design.

Force analysis, power and torque. The forces acting on particles in a screw conveyor are shown in Figure 10. The bulk material at the outer periphery in contact with the stationary casing exerts a force ΔF_N against the casing, mainly as a result of the centrifugal pressure. The centrifugal pressure gives rise to the normal pressure σ_n acting at the casing. A frictional drag force $\Delta F_D = \mu_C \Delta F_N$ acts in a direction opposing the absolute velocity. Here μ_C is the coefficient of friction for the bulk solid particle on the casing surface. The axial force ΔF_A arises from the weight of the bulk material acting on the screw surface plus the vertical component of the frictional resistive force due to the conveying action. ΔF_R is the resultant resistive force due to the motion of the bulk material relative to the screw surface. The relationships for the force components are given in Ref. 4.

Screw torque T_{sp}. The screw torque resulting from the bulk solid on the flight face may be determined from Equation (17):

$$T_{SP} = \frac{L}{p} \Delta F_{RA} R_e \tan(\alpha_e + \phi_S) \quad \textbf{(17)}$$

Shaft torque, T_{sh}. The normal pressure due to the bulk solid on the shaft is shown in Equation (18):

$$\sigma_n = K \rho g p \eta_F \quad \textbf{(18)}$$

K accounts for the pressure distribution around the shaft. It is assumed that K = 0.4

Torque due to the bulk solids moving relative to the shaft is provided by Equation (19):

$$T_{Sh} = 2\pi R_i^2 \sigma_n L \quad \textbf{(19)}$$

Total screw torque and power. The total torque is $T = T_{sp} + T_{sh}$. Power P is provided by Equation (20):

$$P = \frac{0.105TN}{\eta_0} \quad \textbf{(20)}$$

Case study example

The procedures for computing the throughput and power presented in this paper are examined in relation to the performance of an actual screw conveyor used to elevate wheat. The conveyor operates in the vertical position and is gravity fed. The predicted and measured results are compared in Figure 11. The agreement is considered to be quite satisfactory.

Feeding and transfers. Under gravity feed, the feeding action in the choke controls the conveyor throughput. For low-speed operation, a choke length of one screw pitch is usually sufficient. However, as the conveying speed increases, a greater choke length is necessary. The combination of the fill ratio or "fullness" η_F and conveying efficiency η_{VR} allows the volumetric efficiency $\eta_V = \eta_{VR} \cdot \eta_F$ to be obtained. Hence the throughput can then be determined.

An appropriate forced-feeding arrangement may be used to meet a specified throughput, particularly when cohesive bulk solids are to be conveyed. For example, forced feeding is utilized in the Siwertel-type ship unloader, which employs a counter rotating lower casing with feed vanes that scoop the bulk material into the screw intake. The screw conveyor capacity is controlled by the feeding device and not by the conveyor itself. To avoid blockages in the screw intake, it is essential that the conveyor speed is

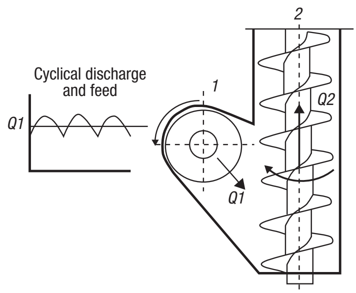

FIGURE 12. To avoid blockages at the transfer point due to flow surges during a horizontal to vertical conveyor transfer, the design capacity *Q2* of the vertical conveyor needs to be greater than *Q1,* the actual flowrate required

high enough for the fill ratio $\eta_F < 1$.

In multiple-conveyor installations where transfers are employed, it is most important that blockages be avoided. As an illustration, the transfer from a horizontal to a vertical screw conveyor as depicted in Figure 12 is considered. Two design conditions need to be considered. First, the discharge *Q1* from the horizontal conveyor will be cyclical at a frequency related to the conveyor rotational speed, as indicated. Second, the conveying efficiency of the vertical conveyor will be less than for the horizontal conveyor. To avoid blockages due to cyclical flow surges, it is recommended that the vertical conveyor be designed for a capacity, $Q2 \geq 1.2\ Q1$.

Of the various types and design of mechanical handling equipment employed in industrial operations, screw conveyors, in particular, play a major role. Nonetheless, their mode of operation, while seeming to be obvious and simple, is in fact just the opposite, quite complex. To ensure their reliability and efficient operation, conveyor designers, manufacturers and users must have some understanding of the basic mechanics governing their performance, using the concepts presented here. ■

Edited by Suzanne Shelley

Note: An additional section on U-shaped trough screw conveyors can be found in the online version of this article, at www.chemengonline.com

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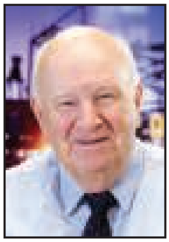

Alan W. Roberts is the founding director of TUNRA Bulk Solids Handling Research Associates (TBS) of the University of Newcastle, Australia and is currently emeritus professor there (Email: alan.roberts@newcastle.edu.au). From 1974 to 1993, Roberts was dean of the university's faculty of engineering. He was responsible for establishing the university's research and consulting group (TBS) in 1975. Over the past 40 years, this group has completed more than 3,500 projects in the field of bulk-solids handling for industrial operators worldwide. Roberts holds a B.E. (mechanical engineering with honors), a Ph.D. and honorary D.Univ. and D.Sc. degrees, and has received nearly a dozen distinguished awards from engineering institutions worldwide. In November 2010, he was awarded the Peter Nicol Russell Memorial Medal, the most prestigious award of the Institution of Engineers Australia. He has more than 50 years of research and consulting experience in bulk solids handling and has published more than 400 journal and conference papers. Since his formal retirement in 1994, he has continued to be actively involved, both hands-on and mentoring, consulting, research and student supervision.

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Equipment	702.6	704.1	686.6
Heat exchangers & tanks	649.4	652.3	620.6
Process machinery	663.0	666.9	653.2
Pipe, valves & fittings	875.4	876.4	873.9
Process instruments	411.9	411.8	411.4
Pumps & compressors	942.9	941.1	924.3
Electrical equipment	516.2	516.0	514.1
Structural supports & misc	769.9	769.1	746.3
Construction labor	322.8	324.4	317.8
Buildings	547.1	547.1	532.8
Engineering & supervision	321.2	319.8	323.4

Starting with the April 2007 Final numbers, several of the data series for labor and compressors have been converted to accommodate series IDs that were discontinued by the U.S. Bureau of Labor Statistics

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2011 = 585.7
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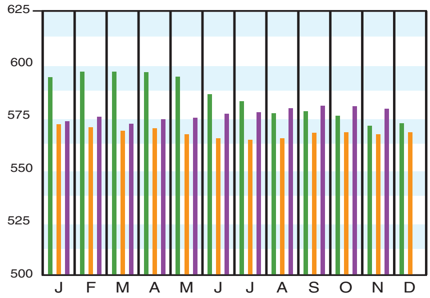

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	LATEST	PREVIOUS		YEAR AGO
CPI output index (2000 = 100)	Dec.'14 = 94.3	Nov.'14 = 93.9	Oct.'14 = 92.9	Dec.'13 = 89.5
CPI value of output, $ billions	Nov.'14 = 2,046.4	Oct.'14 = 2,057.2	Sept.'14 = 2,114.6	Nov.'13 = 2,146.3
CPI operating rate, %	Dec.'14 = 79.0	Nov.'14 = 78.7	Oct.'14 = 77.9	Dec.'13 = 75.8
Producer prices, industrial chemicals (1982 = 100)	Dec.'14 = 271.0	Nov.'14 = 283.4	Sept.'14 = 293.2	Dec.'13 = 292.0
Industrial Production in Manufacturing (2002=100)*	Dec.'14 = 102.5	Nov.'14 = 102.2	Oct.'14 = 100.9	Dec.'13 = 97.7
Hourly earnings index, chemical & allied products (1992 = 100)	Dec.'14 = 157.5	Nov.'14 = 157.6	Oct.'14 = 156.2	Dec.'13 = 158.3
Productivity index, chemicals & allied products (1992 = 100)	Dec.'14 = 109.3	Nov.'14 = 108.8	Oct.'14 = 108.1	Dec.'13 = 108.1

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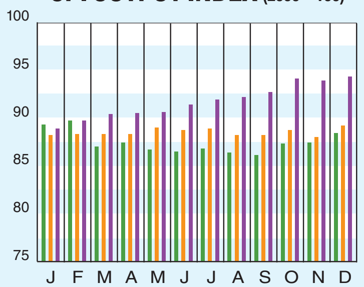

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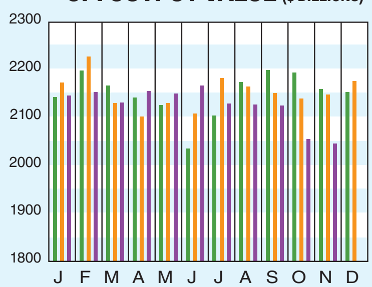

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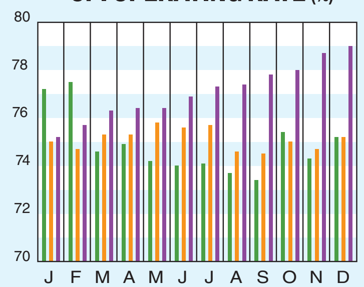

*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
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The preliminary value for the November *CE* Plant Cost Index (CEPCI; top; most recent available) shows a slight decrease from the final value for October. The small decrease for November follows a similar decline the previous month. The index value remains 2.2% above its level from a year ago at this time. Meanwhile, updated values for the Current Business Indicators from IHS Global Insight (middle) show an increase for CPI output, but a decrease for CPI value of output. Producer prices for industrial chemicals were down in December 2014.

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