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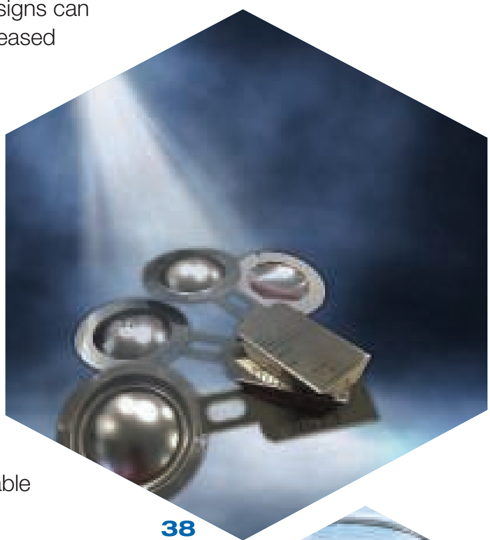
June 2016 Volume 123 | no. 6

Cover Story

In the News



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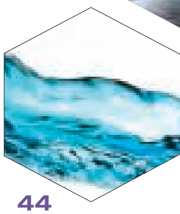

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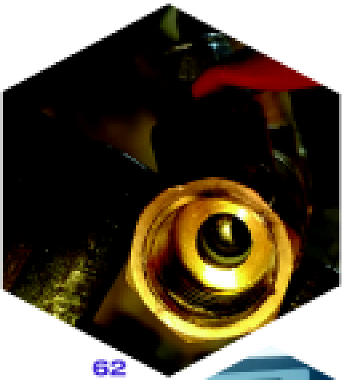

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Nicholas Chopey Scholarship awarded

Chemical Engineering has been a leading source for technology and news for the chemical process industries (CPI) since the launch of our magazine in 1902. Additionally, we seek to bring recognition to, and to help advance, the chemical engineering profession. With that in mind, *Chemical Engineering* established the annual Chopey Scholarship for Chemical Engineering Excellence in late 2007. The award is named after Nicholas P. Chopey, the magazine's former Editor-in-Chief, who devoted over 47 years of his professional career to making valuable contributions to *Chemical Engineering*.

The 2016 award winner

Congratulations to this year's scholarship recipient, Meghan O'Leary, who is a third-year student of chemical engineering at the State University of New York (SUNY) at Buffalo. She is a member of the Tau Beta Pi Engineering Honor Society, as well as of the University's Honor College and is on the Dean's List. She was also the recipient of the 2015 Grace W. Capen Academic Award for Outstanding Academic Achievement and of the 2015 Sophomore Organic Chemistry Award for Scholastic Excellence. In addition to her academic achievements, O'Leary is active in the university's Cross Country and Track Club. She is interested in continuing her education and pursuing an M.S. degree in chemical engineering.

About the scholarship

The scholarship is awarded to current third-year students who are enrolled in a fulltime undergraduate course of study in chemical engineering at one of the following four-year colleges or universities, which include Chopey's alma mater and those of our editorial staff: University of Buffalo, University of Kansas, Columbia University, University of Virginia, Rutgers University and the University of Oklahoma.

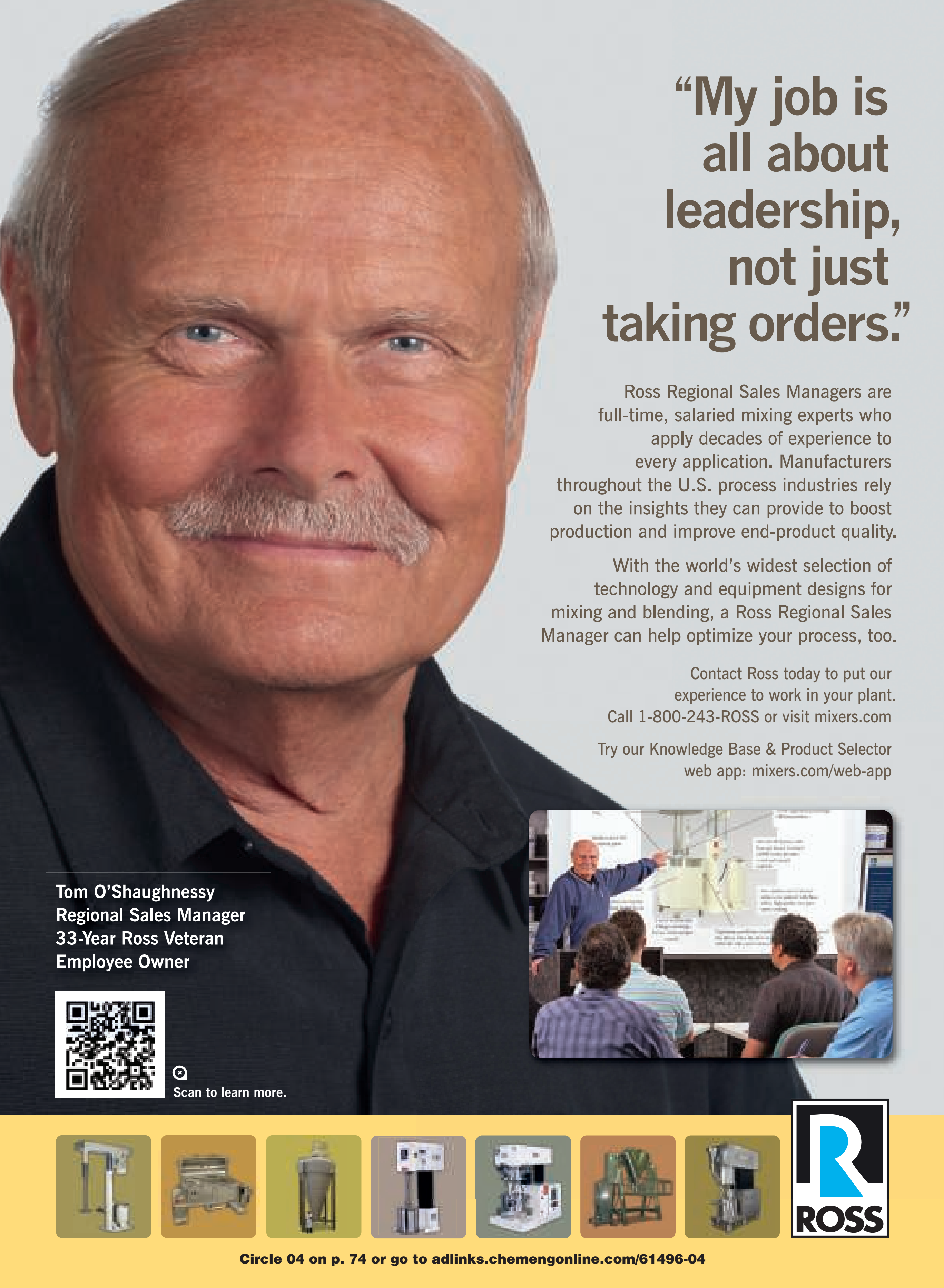
The scholarship is a one-time award. The program utilizes standard Scholarship America recipient selection procedures, including the consideration of past academic performance and future potential, leadership and participation in school and community activities, work experience, and statement of career and educational goals.

More information about the award, including how to apply and how to contribute a donation, can be found at www.chemengonline.com/npcscholarship.

In this issue

This month's issue covers a wide variety of topics. Our Cover Story sheds light on rupture disc performance and the technologies used in these safety devices. We have an Engineering Practice article that takes the reader through a series of practical troubleshooting experiences, as well as articles on vortex breakers and Prandtl numbers. The Feature Report looks in depth at electropositive filter media. Our Newsfronts cover the latest developments in the glass industry, and in heat exchanger design. And as always, the latest technology news can be found in our Chementator section. We hope you enjoy reading. ■

Dorothy Lozowski, Editor in Chief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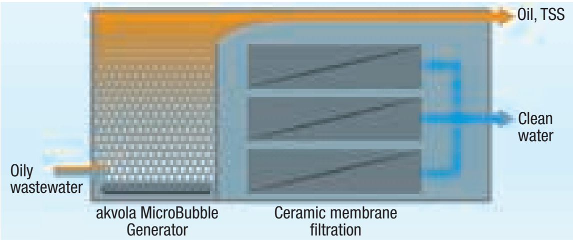
Commercial launch for a hybrid wastewater-treatment process

Edited by:
Gerald Ondrey



A hybrid process that combines micro-flotation and flat-sheet ceramic-membrane filtration to remove oil and suspended solids from difficult-to-treat industrial wastewater has been commercialized by akvola Technologies (Berlin, Germany; www.akvola.com). The system can treat water with high oil loads (up to 3 wt.%) with up to 99% removal efficiency, and at a fraction of the costs of alternative technologies, says Lucas León, founder and CFO.

In the akvoFloat process (diagram), wastewater is continually fed to the microflotation zone, where the akvola MicroBubble Generator induces fine (50–100 µm) gas bubbles. The small bubbles have a large surface-to-volume ratio, and agglomerate with suspended solids, oil, grease, algae and organic flocs to form a float layer, which is skimmed from the tank. The water then passes through the membrane module, which contains dead-end-operated, flat-sheet ceramic membranes. The akvoFloat systems are engineered to achieve stable operation at very high fluxes — generally five times higher than that of polymeric membranes, says León.

Operation at higher flux enables a reduction in the membrane area required, which translates into lower investment costs, explains León. Operating the membrane dead-end also reduces energy costs, because the pressure drop (transmembrane pressure of 0.2 bar) is 7–10 times lower than that used in crossflow membrane systems, he says. Finally, the MicroBubble Generator consumes 5–10 times less energy than conventional dissolved air flotation (DAF) systems.

The process was first demonstrated in a 400-m^3/h pilot plant that treated scrubber water at a metallurgical-coke plant of ThyssenKrupp in Duisburg, Germany. The company is now focussing on treating oily industrial wastewaters, such as that generated in the metalworking, petroleum-refining and steel industries. In the first quarter of 2016, akvola Technologies has received six orders for its akvoFloat units, the first of which (2.5 m^3/h) has been operating since March at a wastewater treatment facility in Austria. The company is also working on the engineering of larger scale projects (250 m^3/h) with two EPC (engineering, procurement, construction) companies for two different applications, says León.

Sun and rain generate electricity in this solar cell

An all-weather solar cell that generates electricity by both sunlight and rain has been developed by researchers led by professor Qunwei Tang from the Institute of Material Science and Engineering at Ocean University of China (Qingdao; http://eweb.ouc.edu.cn) and professor Peizhi Yang from Yunnan Normal University (Kunming, China; www.csc.edu.cn).

The researchers developed a highly efficient dye-sensitized solar cell and coated the cell with an extremely thin film of graphene. Graphene conducts electricity and has a large number of electrons that can move freely across the entire graphene layer (delocalized electrons). In aqueous solution, graphene can bind positively charged ions with its electrons, a property used to remove lead ions and organic dyes from solutions.

This property inspired the researchers to use graphene electrodes to obtain power from the impact of raindrops. The raindrops contain salts that dissociate into positively and negatively charged ions. The positively charged ions, including sodium, calcium and ammonium ions, can bind to the graphene surface. At the point of contact between the raindrop and the graphene, the water acquires additional positive ions and the graphene acquires additional delocalized electrons. This forms a “pseudocapacitor” made of a double-layer of electrons and positive ions. This produces a voltage and current.

Tang says the all-weather solar cell will make it possible to generate electricity also in acid-rain-prone areas and on islands and reefs. It can also be used in marine navigation, he says.

COOLING-TOWER MOTOR

A new electric motor for driving cooling-tower fans features a design that prevents current from flowing through the shaft bearings, allowing longer lifetime and less maintenance. The TEAO motor, made by Marathon Motors Corp. (Wausau, Wis.; www.marathonelectric.com) also has the highest ingress protection (IP) rating for small airborne particles of any fan motor currently available and can be mounted with the shaft at any angle, the company says. It is suitable for use in all HVAC (heating, ventilation and air conditioning) applications and for cooling towers in the power generation and other industries, notes Chris Voll, distribution product manager at Marathon. The motor is available in a range of sizes from 3 to 250 hp.

ELECTRODE SLURRY

A continuous process for making electrode slurry for lithium-ion batteries has been developed by Bühler AG (Uzwil, Switzerland; www.) and Chinese battery producer Lishen, enabling this critical material to be manufactured on a larger scale to meet the increasing demand for electric-powered vehicles. The new process uses a twin-screw extruder to make the slurry, which formerly had to be made batch-wise. The new process enables a “much more consistent quality to be achieved, takes up 60% less space and reduces energy consumption by 60%,” compared to batch production, says Bühler.

Lishen awarded Bühler its first large-scale order for four production lines valued at nearly CHF10 million (about $10.2 million). The investment represents a production capacity of about

(Continues on p. 8)

Note: For more information, circle the 56-digit number on p. 74, or use the website designation.

150,000 electric vehicle batteries per year (or 20-million/yr batteries for e-bikes).

ZERO-POWER COOLING

A newly introduced coolant material can reduce temperatures rapidly from room temperature to below freezing with the addition of water. The material enables the possibility of industrial cooling systems that consume little to no electric power and do not require the compression of refrigerant materials, such as chlorofluorocarbons (CFCs), according to developer Frosty Cold LLC (Overland Park, Kan.; www.frostycoldtech.com).

Using a patented blend of solid fertilizers, the product undergoes an endothermic reaction when exposed to any type of water, and cools by 50°F or more in just 10–20 seconds, depending on the mix ratio of the powder to water, explains John Bergida, the founder and president of Frosty Cold.

The non-oxidizing, endothermic salt has numerous features that allow it to be used in a broad range of cooling applications. After cooling, the water can be evaporated and the powder reused for hundreds of cycles, Bergida says. The instantly activated material is flexible, even when frozen, and is non-toxic, Bergida says. At the end of its life, it can be used as a fertilizer.

Frosty Cold developed a proprietary manufacturing process for the material and has set it up at a California manufacturing plant. In addition to consumer, medical and cold-chain applications, such as ice packs, beverage coolers and shipping pads, the company is also pursuing industrial cooling applications. These include zero-power cooling, continuous refrigeration, air conditioning, cooling-tower heat removal, machine chillers and more.

DIGITAL MECHANICS

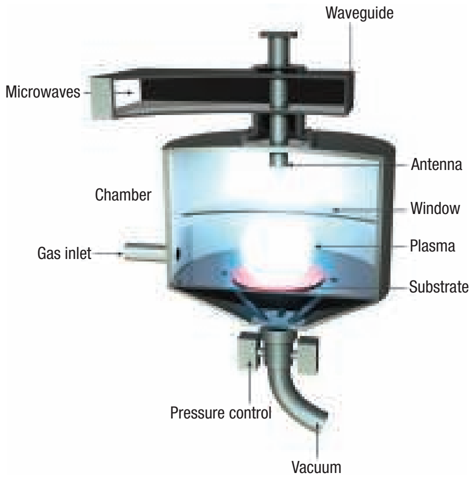
At the Hannover trade fair, Siemens AG (Munich, Ger-

(Continues on p. 10)

Diamond-based electrodes allow handling of difficult-to-treat wastewaters

A scaled-up version of an electrochemical cell with boron-doped diamond electrodes has been introduced, and the system treats wastewaters containing difficult-to-oxidize dissolved pollutants. Known as Diamox, the electrochemical oxidation cell was developed by Element Six (www.e6.com), a designer and manufacturer of synthetic diamond materials and products. The unit mineralizes the dissolved contaminants in the water and, via oxidation by electrochemically generated hydroxyl radicals, releases them as CO_2. The company's next-generation version increases the oxidation capacity by five times compared to its original device, making it more suitable for industrially relevant scales — up to 2 kg of chemical oxygen demand (COD) per hour.

Using a microwave plasma-enhanced chemical vapor deposition (CVD) process (diagram), the company synthesizes its solid, free-standing bulk diamond materials by manipulating conditions at the substrate surface such that carbon forms diamond preferentially over graphite. The CVD process allows Element Six to control the purity and introduce boron atoms to the diamond as dopants. "The addition of boron in a ratio of about 1 atom of boron per 500 atoms of diamond allows the material to become a metal-like conductor," explains Tim Mollart, applications engineer at Element Six. This results in an electrode that can perform electrolysis, but still retain the properties of diamond, including chemical inertness and erosion resistance, Mollart continues.



The inertness of the diamond surface is critical to the material's operation in wastewater treatment. The current passing through the electrode generates hydroxyl radicals from water at the electrode surface, and since the radicals do not react with the inert diamond, they exist long enough to oxidize dissolved pollutant molecules in wastewater.

The Diamox water-treatment system is best applied to industrial wastewaters containing phenolic compounds, mercaptans, dyes, aldehydes and wastewater from pharmaceutical manufacturing, Mollart says. Element Six is actively working with water-treatment technology providers to develop modular electrochemical advanced oxidation water-treatment systems.

A direct route for making polycarbonate from CO_2 and diols

A direct copolymerization of carbon dioxide and diols has been achieved by Keiichi Tomishige and Masazumi Tamura at Tohoku University (Sendai; www.che.tohoku.ac.jp) and Hiroshi Sugimoto at Tokyo University of Science (both Japan; www.sut.ac.jp). The synthesis takes place with a metal-oxide catalyst using 2-cyanopyridine as a promotor, and produces alternating co-oligomers with yields and selectivities of up to 99%.

For example, a polycarbonate with molecular weight of 1,070 and dispersity (a measure of the polymer's heterogeneity) of 1.33 is obtained with 97% yield after reacting 1,4-butandiol in an autoclave with CO_2 at 5 MPa and a relatively mild temperature of 403K after 8 h.

The catalyst, which is obtained by calcination, does not leach into the reaction solution, and maintains its activity after recovery from a reaction. The catalyst system is applicable for a wide variety of diols, including linear C4–C10 α,ω-diols, producing corresponding co-oligomers with yields of 94–99% and higher. These compounds cannot be made by conventional routes, such as the copolymerization of CO_2 and cyclic ethers and ring-opening polymerization of cyclic carbonates.

The chemists believe this new route is simpler and more environmentally friendly than alternative methods, which require expensive or hazardous reagents, such as phosgene, carbon monoxide and epoxides. It also opens the door for utilizing CO_2 as a feedstock.

Making motors intelligent

At the Hannover trade fair (April 24–29; Hannover, Germany), ABB (Zurich, Switzerland; www.abb.com) introduced a new sensing solution for monitoring low-voltage motors. Smart sensors attached directly to the motor supply information regarding operating and condition parameters via wireless transmission. The innovative sensor technology offers plant operators not only huge potential savings on maintenance and repair, but will also make it easy to utilize the Internet of Things, Services and People (IoTSP) for millions of motors, says ABB. IoTSP is ABB's concept for enabling its users to take advantage of the opportunities of digitalization. With the new solution, small and mid-sized companies can also benefit from the advantages offered by the IoTSP.

The smart sensor provides information on operating and condition parameters, such as vibration, temperature or overload, and calculates power consumption. The data are analyzed by a software program, and provided to the plant operator in the form of graphics for maintenance planning, thereby enabling downtime reductions of up to 70%, says ABB. At the same time, the lifetime of the motors can be extended by up to 30% and energy consumption reduced by as much as 10%, so that the investment in this form of condition monitoring pays for itself in less than a year, says the company.

The sensors can be installed at the factory or retrofitted on any already operating low-voltage motors within minutes. Cybersecurity is guaranteed because the smart sensors wirelessly transmit the data via encryption protocols to a secure, cloud-based server, where they are analyzed using special algorithms.

The photocatalytic reduction of CO_2 into CO

Conversion of carbon dioxide into useful carbon sources, such as carbon monoxide, formic acid and formaldehyde, is attracting considerable interest as a way to recycle and utilize CO_2. A step in this direction is the direct photocatalytic reduction of CO_2 into CO using water as a source of electrons. Researchers in the group of Kentaro Teramura at Kyoto University (Kyoto, Japan; www.moleng.kyoto-u.ac.jp/~moleng_04/teramura/index.html) have developed a catalyst system that uses a silver-loaded Ga_2O_3 photocatalyst with a $ZnGa_2O_4$ layer. The Ag serves as a co-catalyst to enhance CO evolution, while the $ZnGa_2O_4$ inhibits the generation of H_2.

Now, the researchers have doubled the conversion efficiency by adding a rare-earth compound, such as ytterbium-based oxide, to their basic catalyst system. The reaction is performed at room temperature in a flow reactor with an internal ultraviolet (UV; wavelength less than 265 nm) light sources. The laboratory-scale system (30 mL/min) generated 100 µmol/h of CO with 80–90% selectivity. The researchers now plan to enhance the CO selectivity and modify the catalyst system to enable operation at longer wavelengths so that solar radiation can be used.

many; www.siemens.com) introduced its digital measurement technology for gears — Flender Gearlog. This new technology entails the capture of values relating to rotational speed, torque, temperature and, in the future, also vibration by special sensors. The system adds up these readings in parallel with machine capacity utilization. The measurement results are logged, saved and digitally depicted in compressed form. Operators are able to visualize the results at any time or read them out in the form of a dataset. The measurements enable conclusions to be drawn about the applied load and loading capacity of gears when used in specific applications. The full transparency of operating data means it can be used to identify possible sources of damage, capacity reserves and overloading in the measured gear.

Flender Gearlog comprises software, a hardware component and sensor equipment coordinated in line with the gear. Special algorithms are used to compress the time signals and depict wide-ranging information relating to operating data on a digital basis. If threshold values are exceeded, Flender Gearlog also records time signals, allowing any detected overloads, for instance, to be additionally analyzed. All the data necessary for this are already available locally, and in the future, will also in the cloud.

The measurements can be performed on all available Flender gears, both catalog and non-standard types, for instance for the mining, cement or oil-and-gas industry, for wind turbines and cranes. The Hannover fair marked the beginning of a one-year pilot phase for the product, says Siemens.

HS-FCC DEBUT

In late April, Technip (Paris, France; www.technip) was awarded an engineering, procurement and construction (EPC) contract by Daelim Industrial Co. to provide

(Continues on p. 11)

Imitating cactus plants to improve membrane performance

Regulation of water content in polymeric membranes is important in several applications, including proton-exchange fuel cell membranes. Normally, this is achieved either by external regulation or by operating the cells at higher temperatures.

Now a team from CSIRO (Melbourne, Australia; www.csiro.au) and Hanyang University (Seoul, South Korea; www.hanyang.ac.kr), led by the university's professor Young Moo Lee, has developed an alternative solution that does not rely on external regulation of water supply or high temperatures. The team proposed a new concept for regulating membrane hydration in low-humidity or non-humidified environments without modifying the morphology of an ion-exchange membrane, analogous to the water-retention mechanisms of the cactus plant (such as *Ferocactus schwarzii*). The team explains that the cactus retains water by opening and closing an array of stomatal openings, which respond to environmental conditions. The stomata are open at night, and closed in daytime in hot and arid conditions.

In the team's concept, water content in hydrocarbon polymer membranes is regulated through nanometer-scale cracks in a hydrophobic surface coating. These cracks function as nano-scale valves to retard water desorption and to maintain ion conductivity in the membrane on dehumidification. According to the team, hydrocarbon fuel-cell membranes with surface nanocrack coatings operated at intermediate temperatures exhibit improved electrochemical performance, and coated reverse-electrodialysis membranes show enhanced ionic selectivity with low bulk resistance.

Lee says that one of the main barriers to the widespread use of fuel cells in electric vehicles is water and heat management in fuel cell systems. He says the team's work addresses this hurdle, and brings us a step closer to wider use of fuel-cell-powered vehicles. The work could also help in other existing technologies that require hydrated membranes, including devices used in water treatment and gas separators.

Collaboration commercializing technology for reusing complex catalysts

The manufacture of pharmaceuticals and many fine chemicals requires costly, toxic catalysts with metal atoms bonded to complex organic ligands that catalyze the creation of chiral centers. Current processes often use homogeneous (dissolved) chiral catalysts and batch processing, an approach that requires extra steps to separate catalyst from products, a process that often destroys the catalyst or makes catalyst recycling difficult.

Now, GreenCentre Canada (Kingston, Ont.; www.greencentrecanada.com), a not-for-profit organization that commercializes technologies developed in academic laboratories, and Chiral Technologies (West Chester, Pa.; www.chiraltech.com), a company specializing in enantioselective separation of racemic mixtures, are jointly commercializing a technology from the University of Alberta and TEC Edmonton (Edmonton, Alta.; www.ualberta.ca, www.tecedmonton.com) that allows continuous use of these catalysts in flow reactors without leaching of the catalyst into the product stream. The technology enables dramatically better recyclability.

In this invention, the chiral catalyst can be physically attached to solid supports to allow heterogeneous catalysis in flow systems, or if preferred, in batch.

Research by Alberta chemistry professor Steve Bergens resulted in a method to covalently link complex metal-ligand catalysts to a polymer matrix, thus immobilizing them. "The idea of immobilizing these catalysts is not new, but previous efforts were not robust enough to handle continuous flow or many reuses in batch," explains Andrew Pasternak, commercial director at GreenCentre Canada. "Bergens devised a very ingenious way to achieve robust immobilization without disrupting the catalyst activity of the metal-ligand complexes."

After further development of Bergens' original research, Chiral Technologies was approached to develop and market flow columns incorporating the technology that can be integrated into existing synthesis systems and can dramatically improve catalyst recyclability while maintaining high activity.

The collaborative partners are planning to offer flow columns containing several commonly used chiral metal-based catalyst systems for real-world pharmaceutical synthetic processes, Pasternak states.

This handheld chemical analyzer connects to smartphones

A new smartphone-operated portable chemical analyzer provides a platform for chemical leak detection and other industrial applications, according to developer MyDx Inc. (San Diego, Calif.; www.cdxlife.com). The company designed the handheld analyzer for consumers, but the technology platform has origins in the space program and could be used in industry.

The initial rollout of the MyDx product is aimed at the medical marijuana industry, where it will be used by growers and users to quickly test levels of cannabinoids (including THC) and other compounds in cannabis plants. The company plans to follow its cannabis product with other sensors, using the same platform for detecting chemicals in water and air samples, including CO, NH_3, NO_2 and others.

The analyzer is equipped with conducting polymer receptors that are chemically functionalized to bind to specific target molecules. Binding induces expansion or contraction of the polymer, thereby changing resistance in associated electrical circuitry. Resistance changes correspond to levels of the target molecule.

The device works by inserting a disposable, sample-containing cartridge, where small air pumps pull vapor from the sample to the sensor surface. "The technology really is an electrical analog to the human sense of smell, where receptors detect specific molecules and the brain interprets the signal," explains Daniel Yazbeck, the former Pfizer and Panasonic scientist who now heads MyDx. The analyzer relays data to iOS- and Android-based smartphones wirelessly, where a specialized app interprets the signal. Depending on the sensor and target, the analyzer can detect down to the parts-per-million or parts-per-billion level, and results can be obtained in three minutes, Yazbeck says.

The company licensed the sensor technology from the California Institute of Technology (Pasadena, Calif.; www.caltech.edu), which developed it in conjunction with NASA's Jet Propulsion Laboratory for use as a chemical leak detector in the space shuttle program. ■

proprietary equipment for the world's first commercial High Severity Fluid Catalytic Cracking (HS-FCC) unit. The HS-FCC cracks heavy hydrocarbons into lighter olefins, such as propylene, and lighter fuels, such as gasoline. It will be constructed as part of the expansion of the existing residue conversion facilities at the S-Oil petroleum refinery in Onsan, South Korea.

The proprietary equipment provided by Technip includes an innovative downflow reactor, the key component of the HS-FCC technology. HS-FCC was developed by an alliance comprising Saudi Aramco, JX Nippon Oil & Energy Corp, King Fahd University of Petroleum and Minerals (see *Chem. Eng.* August 2013, p. 10). The technology is licensed by Technip Stone & Webster Processing Technology and Axens. This first unit was licensed by Axens.

LINEUP

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Plant Watch

Ineos to build world-scale linear alpha-olefins unit in Texas

May 17, 2016 — Ineos (Rolle, Switzerland; www.ineos.com) has announced that Ineos Oligomers has made a final investment decision build a new world-scale linear alpha-olefin (LAO) unit at Chocolate Bayou, Tex. Its capacity of 420,000 metric tons per year (m.t./yr) is 20% larger than when the project was originally announced. When it comes onstream in November 2018, Ineos Oligomers will have a global LAO capacity of around 1 million m.t./yr.

Shandong Luqing Petrochemical commissions China's first C4 Oleflex unit

May 17, 2016 — Honeywell UOP (Des Plaines, Ill.; www.uop.com) says that Shandong Luqing Petrochemical Co. has accepted the performance of China's first standalone Honeywell UOP C4 Oleflex process unit, which produces 170,000 m.t./yr of isobutylene. Located in Shandong province, the plant will support China's growing demand for fuel and petrochemicals. The C4 Oleflex process uses catalytic dehydrogenation to convert isobutane to isobutylene.

AkzoNobel expands performance coatings plant in Indonesia by 40%

May 17, 2016 — Akzo Nobel N.V. (Amsterdam, the Netherlands; www.akzonobel.com) has completed phase one of the €2.5-million expansion of its performance coatings plant in Cikarang, Indonesia. The investment will increase capacity at the facility by 40%. AkzoNobel has been in Indonesia since 1971 and is now the country's largest paints and coatings producer.

Huntsman begins production at new pigments plant in Georgia

May 17, 2016 — Huntsman Corp. (The Woodlands, Tex.; www.huntsman.com) announced the startup of operations at its brand-new color pigments facility in Augusta, Ga. Huntsman has invested more than $172 million in the plant — the first of its kind to be built in North America for more than 35 years. It has a capacity of 30,000 m.t./yr of yellow, red and black iron-oxide pigments.

Jacobs awarded engineering contract at Saudi Aramco refinery

May 17, 2016 — Jacobs Engineering Group Inc. (Pasadena, Calif.; www.jacobs.com) has received a two-year contract from Saudi Aramco Total Refining and Petrochemical Co. (SATORP) to provide general engineering services at SATORP's Jubail Industrial City II facilities in Saudi Arabia. Jacobs will provide a range of feasibility studies, conceptual designs and detailed engineering designs for a portfolio of minor capital projects.

Chemours starts up 200,000-m.t./yr titanium dioxide plant in Mexico

May 17, 2016 — The Chemours Co. (Wilmington, Del.; www.chemours.com) has begun the commercial startup of a new titanium dioxide (TiO_2) line at its Altamira plant in the Mexican state of Tamaulipas. The new line, which uses the Chemours chloride process, is expected to take several years to reach its nameplate capacity of 200,000 m.t./yr.

Asahi Glass to expand capacity for vinyl chloride monomer in Indonesia

May 13, 2016 — Asahi Glass Co. (AGC; Tokyo; www.agc.com) will further increase production capacity for vinyl chloride monomer (VCM) at P.T. Asahimas Chemical (ASC), one of its consolidated subsidiaries in Indonesia. ASC has just doubled its VCM capacity to 800,000 m.t./yr, and now a debottlenecking operation will further increase this to 900,000 m.t./yr by 2018.

GreenMantra starts production of waxes based on recycled-plastic feedstocks

May 11, 2016 — GreenMantra Technologies (Brantford, Ont., Canada; www.greenmantra.ca), a producer of high-value waxes and specialty chemicals from recycled plastic feedstocks, has completed construction of its first commercial-scale (5,000 m.t./yr) manufacturing plant. GreenMantra uses a patented catalytic process to transform hard-to-recycle polyolefin plastics, such as grocery bags, shrink wrap and bottle caps, into waxes, greases, lubricants and other specialty chemicals.

Mergers & Acquisitions

Resin manufacturers Polynt Group and Reichhold Group to merge

May 18, 2016 — A planned merger between Polynt Group (Bergamo, Italy; www.polynt.it) and Reichhold Group (Durham, N.C.; www.reichhold.com) will create a global, vertically integrated manufacturer of resins for composites and coatings, and of other specialized chemicals, including intermediates, plasticizers, additives and compounds. Subject to regulatory approval, the merger is expected to be completed in the second half of 2016.

Total buys battery manufacturer Saft to boost its renewable-energy business

May 16, 2016 — Oil and gas major Total S.A. (Paris, France; www.total.com) plans to acquire industrial battery manufacturer Saft S.A. (Paris, Fance; www.saftbatteries.com). "The combination of Saft and Total will enable Saft to become the Group's spearhead in electricity storage", says Patrick Pouyanné, chairman and CEO of Total.

Thyssenkrupp Industrial Solutions gains new business structure

May 13, 2016 — Thyssenkrupp Industrial Solutions, the engineering and construction arm of the Thyssenkrupp Group (Essen, Germany; www.thyssenkrupp.com), is modernizing its management structure to focus on customers and business fields, and speed the integration of the previously separate engineering companies Uhde, Polysius and Fördertechnik. Jens Michael Wegmann, CEO of Industrial Solutions since October 2015, says: "We are operating in a difficult environment, and we want to make our organization faster, more flexible and more efficient."

Honeywell to spin off its resins and chemicals business

May 12, 2016 — Honeywell (Morristown, N.J.; www.honeywell.com) plans to spin off its resins and chemicals business into a standalone, publicly traded company named AdvanSix Inc. This part of the business manufactures Nylon 6, ammonium sulfate, and chemical intermediates, including phenol, acetone, cyclohexanone and caprolactam, with a turnover of $1.3 billion. Completion is expected by early 2017.

Solvay sells Latin American PVC business to Unipar Carbocloro

May 10, 2016 — Solvay S.A. (Brussels, Belgium; www.solvay.com) is selling its 71% stake in Solvay Indupa (Buenos Aires, Argentina; www.solvayindupa.com) to Brazilian chemical group Unipar Carbocloro. Indupa makes PVC, sodium hydroxide and sodium hypochlorite, and is valued at $202.2 million.

Rennovia and Stora Enso join forces on bio-based processes

May 10, 2016 — Renewable materials company Stora Enso Oyj (Helsinki, Finland; www.storaenso.com) and specialty chemicals company Rennovia, Inc. (Menlo Park, Calif.; www.rennovia.com) have announced a joint development and license agreement to cooperate on developing bio-based chemicals. Rennovia uses high-throughput techniques to develop catalysts for the production of chemicals from renewable feedstocks.

GE Power to acquire HRSG business from Doosan

May 10, 2016 — GE Power (Schenectady, N.Y.; www.gepower.com) has agreed to buy the heat-recovery steam-generator (HRSG) business of Korea's Doosan Engineering & Construction for $250 million. Last November, GE Power completed the acquisition of Alstom's power and grid businesses. Demand for combined-cycle power plants, which use HRSGs, is currently very high, the company says.

Biotech company Aemetis buys cellulosic ethanol specialist

May 6, 2016 — Biotechnology company Aemetis, Inc. (Cupertino, Calif.; www.aemetis.com) has acquired Edeniq (Visalia, Calif.; www.edeniq.com), which develops technology to make ethanol from cellulose. Edeniq has 29 of its Cellunator mechanical systems in U.S. ethanol plants, and has signed several license agreements for its enzyme-assisted technology. ■

Charles Butcher

Innovation and Demand Keeps Glass Industry Afloat

Despite competition from many new players, the glassmaking sector is rebounding with new applications and smart products

IN BRIEF

The global glass industry is looking up again, in the aftermath of the recession of the past 10 years, when much of the industry for both of the main markets — flat glass and container glass — suffered quite badly. For a number of years, the market was quite uncertain for container glass for bottles and jars, as well as for the main flat-glass products — glazing in homes, commercial buildings and vehicles; wired glasses for fire resistance; patterned glass for decoration; and a range of glass for environmental control and energy conservation.

The industry rebound is being helped by a number of new demands, such as specialty glass for electronics devices as well as new innovations, such as smart windows.

The market outlook

Float glass. According to the U.S. National Glass Association (NGA; Vienna, Virginia; www.glass.org) the float-glass industry (the flat glass made by the float-glass method — see box below) experienced steep capacity reductions in North America and Western Europe where many plants had to close down, although in

MAKING GLASS

Practically all commercial glass is made mainly of silica (SiO_2) — the main constituent of sand. Sand could by itself be fused to produce glass, but this requires heating the sand to about 1,700°C. The melting temperature of sand can be lowered to about 800°C by adding sodium carbonate to produce a mixture of 75 wt.% silica and 25 wt.% sodium oxide. A glass of that composition is water soluble, however, which is undesirable. To give the glass stability, substances such as calcium oxide (lime) or magnesium oxide are added.

Most commercial glasses have a similar composition of up to 75 wt.% SiO_2, up to 15 wt.% Na_2O, up to about 10 wt.% CaO, up to about 3 wt.% MgO, and up to 3 wt.% Al_2O_3. Container glass has a very similar composition, except that flat glass contains a higher proportion of MgO.

The composition of the glass is varied to suit a particular product. The quantities of raw material are carefully dosed because consistency of composition is paramount in glass making. (Continued on page 16)

(Continued from page 14)

Making float glass

According to organizations such as the NGA and the British Glass Manufacturers' Confederation (British Glass, Sheffield, U.K.; www.britglass.org.uk), there are about 260 float plants and more than 400 float lines worldwide, with a combined output of some 800,000 metric tons of glass per week. A float plant, operating non-stop for up to 15 years, produces about 6,000 km of glass per year in thicknesses of 0.4 to 25 mm and widths up to 3 m.

The float glass process was conceived by British engineer Alastair Pilkington in the 1950s. It allows forming a perfectly flat sheet by floating molten glass on a pool of liquid metal. The glass is smoothed by gravity and surface tension, instead of being squeezed by rollers. Today practically all flat glass in the world is made using the Pilkington float process.

The glass-making process starts with the delivery of raw materials. They are all dusty materials either in the form of powder or as fine-grained material. The raw materials are heated in a furnace to produce molten glass. The molten glass floats on a molten tin bath to become a flat solid ribbon at 600°C. Tin is the most widely used metal, although lead and various low-melting-point alloys have also been used.

The glass ribbon is transferred on transport rollers into a controlled cooling tunnel that can be more than 100 m long. During this process the glass cools to room temperature.

Making bottles

Bottles, on the other hand, have been traditionally made by glass blowing and blow-molding. Today most bottles and jars are made by one of two automated processes: press-and-blow or blow-and-blow. Press-and-blow is the most commonly used method. Press-and-blow formation takes place in an individual section machine. Individual section machines have between 5 and 20 identical sections. Each carries out the glass-container forming, so that 5 to 20 containers can be produced with one machine at the same time. Press-and-blow formation begins when the molten glass reaches a temperature of about 1,200°C. A shearing blade is used to cut and shape the glass into a cylindrical shape called a "gob". The gob falls and rolls toward the molds. A metal plunger presses the gob into the blank mold where it assumes the mold's shape and is then called a "parison." The parison is moved into a final mold where it is blown into the mold to assume its final dimensions.

The blow-and-blow method is similar to press-and-blow, except that the gob is forced into the blank mold using compressed air. The parison is flipped into a final mold where it is blown again to form the interior side of the glass container.

Japan, float capacity remained practically unchanged.

In China, on the other hand, the float-glass industry experienced spectacular growth. Despite the recession, growth was quite strong in the emerging economies of Brazil, Russia, India, and in some countries of Asia and Africa, the NGA says.

According to the NGA, the big companies also found it difficult to compete with the many small players that emerged during the past 20 years. The competition from the smaller companies was mainly a consequence of the introduction of turnkey technology. The world's four largest glass makers — Asahi Glass Co. (AGC; Tokyo, Japan; www.agc.com), Guardian Industries (Auburn Hills, Mich.; www.guardian.com), Nippon Sheet Glass Co. (NSG; Tokyo; www.nsg.com) and Saint-Gobain SA (Paris, France; www.saint-gobain.com) — continued to expand their businesses globally. However, the majority of the new plants that appeared recently were built by smaller, regional manufacturers, the NGA says.

The dearth of experienced personnel has contributed to creating a challenging business environment for glass fabricators. Attracting, training and retaining employees are top concerns of many glass makers.

Bottles. The market for bottles has also suffered, as brewers put more of their beer into cans, and thousands of small companies held prices down. In China there were more than 1,000 bottle makers selling at low prices with which the big companies could not compete.

The experience of Owens-Illinois Inc. (Perrysburg, Ohio; www.o-i.com) — the world's largest maker of bottles for beer, wine and liquor — is a good illustration. The company shed about half of its capacity in China in the light of stiff local competition. It also had to cut back in Australia because more of the country's wine was exported in bulk and bottled elsewhere. It is now taking various steps, including the development of new plants to reuse more heat, lowering energy costs, increasing automation, and building small bottle plants as efficient as big ones that will be closer to customers, in order to reduce transport costs.

Fabricators say that many of the challenges that faced them in 2015 will continue, including capacity constraints, and transportation and employment issues.

However, they view the coming years with optimism. According to the NGA, glass continues to grow in popularity around the world, especially as the industry keeps coming up with better-performing products. A vice president at NSG, Stephen Weidner, says: "We will always be building with glass. There will always be business."

Innovations

Innovation has become a top priority of the glass makers, due to the challenging environment they have faced. There have been many exciting developments and innovations in the glass industry during the past years, heralding a whole new era for the industry.

Some of the most exciting developments are outlined by William C LaCourse, professor of glass science at Alfred University (Alfred, New York, N.Y.; www.alfred.edu) — the only university in the U.S. with a degree specifically in glass engineering. (Although there are other universities with courses in glass science or engineering, they are part of a materials science course).

Some of the many exciting recent developments in the glass industry are the use of computers to generate glasses by means of a mathematical representation of glass structure, and laser modification of glass structure, LaCourse says. Glass melting can now also be modeled by computer, he says.

Most recent is the development of memory devices that are able to store information.

Smart glass. Another area of development is in "smart glasses," with light-transmission properties that can be altered when voltage, light or heat is applied. The glass may change from translucent to transparent, changing from blocking some or all of light's wavelengths to letting light pass through (Figure 1).

View

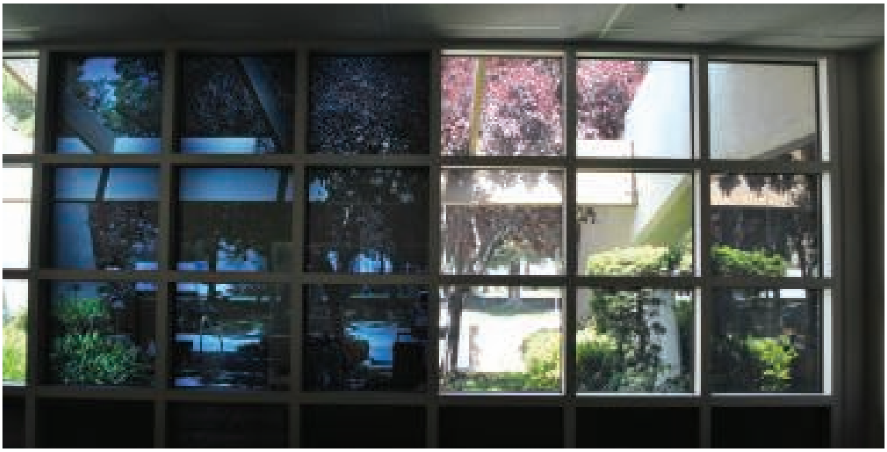

FIGURE 1. Smart glass can help save costs for heating, air conditioning or lighting by adapting to the climate

Smart glass can help adapt a building to the climate, saving costs for heating, air conditioning or lighting. Smart glass technologies include electrochromic, photochromic, thermochromic, suspended particles, micro-blind and polymer dispersed liquid crystals.

Companies offering electrochromic glasses include: SAGE Electrochromics, Inc. (Faribault, Minn.; www.sageglass.com), a wholly owned subsidiary of Saint-Gobain; View, Inc. (Milpitas, California; www.viewglass.com); and Econtrol-Glas GmbH & Co KG (Plauen, Germany; www.econtrol-glas.de).

In electrochromic windows, the glass is coated with several ultra-thin metal oxide layers. On the side facing into a home, the window has a double-sandwich of five ultra-thin layers: a separator in the middle, two electrodes (thin electrical contacts) on either side of the separator, and two transparent electrical contact layers on either side of the electrodes. Lithium ions migrate back and forth between the two electrodes through the separator. When the window is clear, the lithium ions reside in the innermost electrode (which can be made of lithium cobalt oxide, $LiCoO_2$). When a small voltage is applied (about 5 V d.c.) to the electrodes, the ions migrate through the separator to the outermost electrode. When enough of them get into that layer (which can be made of polycrystalline tungsten oxide, WO_3) they make it reflect light, turning it opaque. They remain there until the voltage is reversed, when they move back and the window be-

FIGURE 2. Schott Glass received the German Industry Innovation Award 2016 for its ultra-thin, flexible glass

comes transparent again.

The glass stops solar heat gain, blocks glare, reduces fading, and eliminates the need for window shades and awnings, while allowing building occupants to continually view the outdoors.

EControl works in a manner similar to that of a traditional solar control and thermal control glass. With EControl, the outer pane of an insulating glass is replaced by an electrochromic laminated pane. This basic construction can be combined with additional functions, such as security glazing.

Another type of smart glass technology is used in suspended particle devices (SPDs). In these devices, a thin film laminate of rod-like nanoscale particles is suspended in a liquid and placed between two pieces of glass or plastic, or attached to one layer. Normally the suspended particles are randomly positioned, blocking and absorbing light. When a voltage is applied, the particles align and allow the light to pass through. Varying the applied voltage can control the particles' orientation, thus controlling the tint of the glazing and the amount of light transmitted. SPDs can also control the amount of heat passing through, reducing the need for air conditioning or heating.

Companies offering SPD smart glass include AGC, Asahi India Glass Ltd. (Mumbai, India; www.aisglass.com), and Research Frontiers Inc. (Woodbury, N.Y.; www.smartglass.com).

Flexible glass. A few companies offer a flexible, ultra-thin glass that can bend to such an extent that you can almost wrap it around your finger without breaking it. Such glass can be used in displays to make thinner and lighter portable devices, such as smartphones and tablets. It can be used as cover glass in flexible OLED (organic light emitting diode) displays, and as substrate material for thin-film batteries. It can also be used in communications to process data up to eight times faster than was previously possible. Companies offering such glasses include Corning, Inc. (New York; www.corning.com), whose thin flexible glass is called "Willow Glass"; and Schott AG (Mainz, Germany; www.schott.com).

According to John Mauro, senior research manager at Corning, the most successful of his company's innovations is "Gorilla glass," a brand of toughened glass, now in its fifth generation, designed to be thin, light and damage-resistant. The alkali-aluminosilicate sheet glass has been used mainly as cover glass for portable electronic devices such as mobile phones, portable computer displays, and television screens. Corning recently teamed with Ford Motor Co. to use Gorilla glass for the front and rear windshields on the Ford GT sports car.

The toughened glass is made by being immersed in a molten alkaline potassium salt at a temperature of about 400°C. Here the smaller sodium ions in the glass are replaced by larger potassium ions from the salt bath. The larger ions occupy more space and thus create a surface layer of high residual compressive stress at the surface, giving the glass surface increased strength, the ability to contain flaws, and crack-resistance.

Other glass makers that have developed similar glass include Asahi Glass and Schott. Asahi Glass' toughened glass is called Dragontail glass and Schott's is called Xensation, and both are also alkali-aluminosilicate sheet glass with properties very similar to those of Gorilla glass.

Glassmaking innovations

Apart from the many innovations in glass products, there have also been important developments in the glass manufacturing methods.

Late last year, Praxair, Inc. (Danbury, Connecticut; www.praxair.com) demonstrated a thermochemical regenerator system at a glassmaking facility in Mexico. Known as Optimelt, the heat-recovery system lowers fuel consumption in oxy-fuel furnaces, which use pure oxygen instead of air as the primary combustion oxidant (for more details about Optimelt, see *Chem. Eng.*, December 2015, p. 7).

In April, Praxair signed a contract with Libbey, Inc. (Toledo, Ohio; www.libbey.com), one of the largest glassware and tableware manufacturers, to supply it with the Optimelt system. Praxair also entered into a contract with Libbey to deliver O_2 to its glass melting facility in the Netherlands through a non-cryogenic, vacuum pressure-swing adsorption (VPSA) system. Both the Optimelt system and the VPSA supply system are scheduled to start up in 2017. ■

Paul Grad


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New Ways to Deal With Old Heat-Transfer Issues

New developments in heat exchangers solve common problems and enhance performance

IN BRIEF

Chemical processors are no strangers to heat exchanger problems, such as corrosion, fouling and thermal expansion, which interfere with reliability of the units and adversely affect process uptime. Because unplanned downtime in the chemical process industries (CPI) is unacceptable, experts suggest that upgrading to newer exchanger technologies may provide solutions to common challenges, while also increasing uptime, performance and efficiency.

DeDietrich

FIGURE 1. QVF coil-type heat exchangers are made of borosilicate glass 3.3 and are single-piece units where the tube coil is fused to the shell, so that no seals are required, which eliminates the risk of cross-contamination between the service medium and the product

"Reliability of heat exchangers in terms of operational uptime and efficient heat transfer at design conditions, which can be negatively impacted by fouling or outages due to mechanical failures caused by corrosion, erosion or similar phenomena, is likely the biggest operational challenge for chemical processors concerning their heat exchangers," says Hank Shamsi, president of Gooch Thermal Systems (Lebanon, N.J.; www.goochthermal.com).

Nuno Duarte, director of global business development of process technology at Wieland Thermal Solutions (Ulm, Germany; www.weiland.com) agrees. He says that today's current economic scenario is driving companies to get more from every investment and ensure that every process is running at top level, which results in increased interest in new or different solutions. "As the need for reliability continues to grow, due to higher safety standards, increased plant complexity and tighter operating expenses, assuring a continuous operation means there is an increased demand for equipment that will be able to work for longer periods without servicing. So people are looking into new solutions that can increase the time between shutdowns."

Some of these solutions come in the form of shell-and-tube heat exchangers, which remain the workhorses of the industry, that feature new materials or designs to help provide greater uptime and efficiencies. Plate-based technologies, including welded-plate and gasketed-plate heat exchangers, and spiral units, are also being considered for use in the CPI due to the benefits different styles may provide. "In the past, processors weren't always eager to evaluate alternative solutions to their heat-transfer requirements. However, the inherent advantages of welded plate and spiral heat exchangers — thermal efficiency, lower fouling tendencies, more compact footprint and, often, lower-cost stainless or high-alloy construction, combined with enhancements in design and fabrication techniques that allow for operation at higher pressures and temperatures — are the impetus behind the increased ac-

NOV

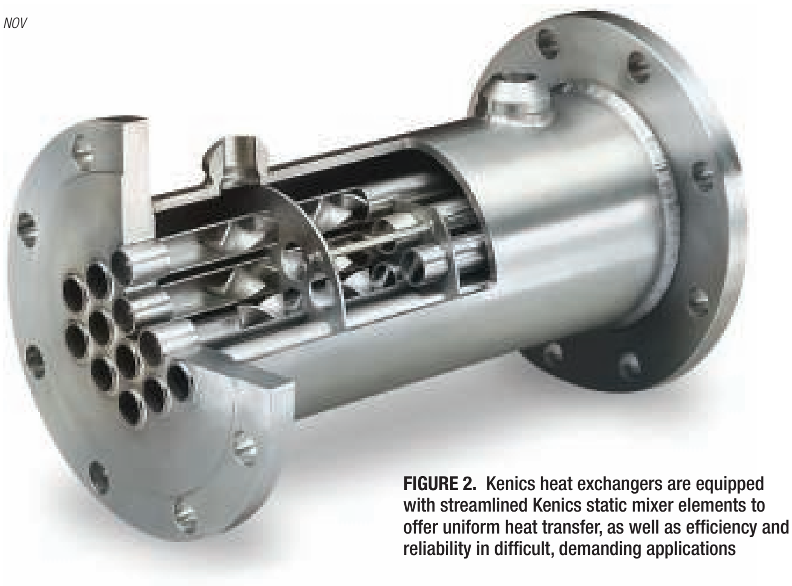

FIGURE 2. Kenics heat exchangers are equipped with streamlined Kenics static mixer elements to offer uniform heat transfer, as well as efficiency and reliability in difficult, demanding applications

ceptance of welded plate and spiral heat exchangers in more demanding applications and difficult services," adds Shamsi.

Why upgrade?

"A lot of the exchangers in service today were built over twenty-five years ago and likely used materials such as carbon steel or copper tubes and, in today's chemical processing environment, that's no longer acceptable because of corrosion concerns," explains Ron Herman, director of sales and marketing with Enerquip (Medford, Wis.; www.enerquip.com). "Some of the older units were also built without following the current standards of the Tubular Exchanger Manufacturer's Assn. (TEMA; Tarrytown, N.Y.; www.tema.org), so if there is thermal expansion in a process, safety and environmental concerns also may be an issue. Or, older units may simply be difficult to clean and maintain so maintenance doesn't occur as often as it should and that results in fouling and unplanned downtime."

"There are so many improvements in today's materials and designs that it is often worthwhile to upgrade," Herman continues. "The capabilities of heat exchanger manufacturers are so much more advanced today than they were when these older exchangers were designed and put into service that we can not only replace a unit, but also greatly improve its operation and efficiency."

For example, he says Enerquip offers reverse-engineering capabilities. "If a customer provides the dimensions, parameters and process flows, we can not only run a simulation model that will duplicate the performance of a customer's current heat exchanger, but also allow us to make recommendations that will improve its performance, including upgrading the materials, planning for thermal expansion or simplifying maintenance."

Increasing reliability and safety

Many older exchangers were built using materials that could not withstand the corrosive environment sometimes found in the CPI, so they were built with a "corrosion allowance," meaning that the materials were layered and thickened to compensate for the corrosion that was expected to occur. This increased weight and size of the units. "With today's materials we don't have to overcompensate for corrosion anymore," explains Herman. "There are different blends and entirely new brands of metals that were specifically designed for corrosion resistance in the chemical industry." Not only does the use of these new materials result in a more robust, reliable heat exchanger, but it also means that the unit will be lighter in weight and provide a better return on investment. "If we are using less material, it results in a lighter heat exchanger that can be hung in framework on the second or third floor in a facility where weight might previously have been an issue. Also, the exchanger will likely last twice as long because it won't deteriorate with corrosion, so it provides a better return on investment," says Herman.

Another area that affects reliability is thermal expansion. If a hot gas is entering the shell and there's cold water in the tubes, they fight against each other. If you are using different materials in the tubing than in the shell, they may expand and contract at different rates, which is likely to cause stress on the unit, causing a possible rupture over time. "If the exchanger wasn't designed to combat thermal expansion or if someone didn't account for the thermal expansion that might occur during process upsets or high-temperature cleaning processes, there could be a safety issue," notes Herman.

He says expansion joints are one way to deal with thermal expansion. However, today's latest improvement comes in the form of a floating tube sheet-style exchanger, which features a tube sheet that is fixed in place on one end but allowed to move within the shell at the other end. "There's some spring action involved so that the unit doesn't get damaged if there's thermal expansion," explains Herman.

Improvements to alternatives

Many exchanger styles, such as plate-based and spiral technologies, would not have been considered for chemical process applications in the past. However, improvements to the design and technologies are making today's models viable and beneficial solutions.

"There has been a lot of development in the components from gaskets to welding technology to materials construction that make compact heat exchangers good for very severe applications where we may not have recommended them previously," explains Klas Abrahamsson, director, process industry with the Process Technology Division of Alfa Laval (Richmond, Va.; www.alfalaval.us). "However, because we are able to employ technologies that allow these models to withstand increased pressure and temperature requirements, they are finding use in process applications that benefit from the lighter weight and smaller footprint they provide."

For example, Alfa Laval's newest introduction, the DuroShell, is a specially engineered plate-and-shell heat exchanger that is suitable for demanding duty in high-pressure, high-temperature and corrosive applications. Designed for use up to 100 bars and at temperatures up to 842°F, the unit provides excellent thermal performance that results in maximum heat recovery using minimal heating or cooling media, which cuts fuel consumption, energy costs and the environmental impact. The small footprint and light weight also minimize installation, operating and maintenance costs and the gasket-free construction provides security against leakage, while the fully welded design allows for the high operating pressures and optimizes resistance fatigue.

Spiral heat exchangers are also employing advancements. The availability of materials in continuous-coil form, coupled with improvements in the design and fabrication machinery that allow the use of heavier plate thicknesses, have enabled manufacturers to push the boundaries of operation for today's spiral heat exchangers to pressures as high as 650 psi (45 barg), says Gooch's Shamsi.

A spiral heat exchanger offers processors certain operational advantages due to its inherent circular design, curved, single-flow channels, rectangular flow cross-section, large surface area-to-volume ratio and compact geometry. In liquid-to-liquid services, the continuously curving, single-flow passages induce high-shear rates that tend to scrub away deposits as they form, which reduces fouling and makes spiral heat exchangers suitable for handling tough fluids, such as process slurries, sludge and media with suspended solids or fibers, whether on one side or on both sides, all of which are difficult for traditional multichannel heat exchangers. In vapor-to-liquid duties, a large flow cross-section perpendicular to vapor flow, a short condensing zone, and often column-mounted execution, ensure extremely low pressure drops, making spiral heat exchangers suitable for condensing of overhead vapors from distillation columns operating under deep vacuum.

Watlow

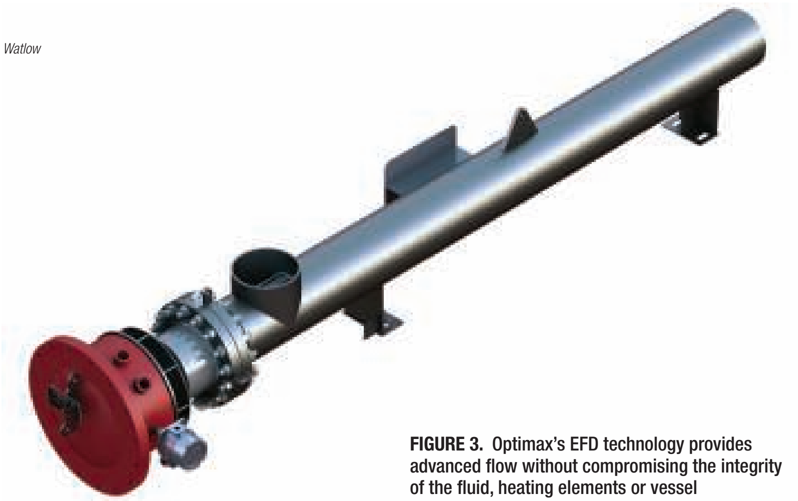

FIGURE 3. Optimax's EFD technology provides advanced flow without compromising the integrity of the fluid, heating elements or vessel

Designs for special applications

In pharmaceutical applications, users demand exchangers that eliminate any possibility of cross contamination, which requires either gasket-free construction or intermediate chambers that collect potential leaks, says Edgar Steffin, head of marketing for the QVF product line with DeDietrich Process Systems GmbH (Mainz, Germany; www.qvf.com). Avoiding contamination of the pharmaceutical product also requires the use of materials approved by the U.S. Food and Drug Admin. (FDA; Silver Spring, Md.; www.fda.gov) for contact with the product, as well.

Fine-chemicals applications also require more low-temperature process steps, notes Steffin. "For batch processes, this means huge temperature ranges during a process cycle. Increased usage of closed cooling circuits, which operate at pressures up to 6 bars (gage) are common, as well," he says. "Both these factors are difficult on materials of construction and applied sealing technology."

As an answer, his company offers QVF heat exchangers (Figure 1), which are made of inert materials with proven sealing systems or seal-free solutions. "Our QVF coil-type heat exchangers are made of borosilicate glass 3.3 and are single-piece units where the tube coil is fused to the shell, so that no seals are required, which eliminates the risk of cross-contamination between the service medium and the product. They offer heat-exchange surface areas up to 15 m^2. For higher heat-transfer rates, we offer QVF shell-and-tube heat exchangers made with highly corrosion-resistant SiC or borosilicate glass 3.3 up to 27 m^2. These are designed for the condensation and tempering of highly corrosive products up to 6 barg."

Some applications, such as those that involve fluids that are highly viscous and difficult to process (as in the the polymer, plastic and food industries), require a different heat exchanger technology altogether, says Steve Willis, sales manager for the chemical market, with National Oilwell Varco (NOV; Houston; www.nov.com/mixing). "Enhanced surface heat-exchanger technology was often the traditional method for heat transfer in these difficult applications, but we determined that by adding mixing to the problem, you can increase heat transfer and eliminate burning, scorching and uneven heat history in delicate applications like tempering chocolate, extrusion cooling of foam and cooling of adhesives for pelletizing," he says.

So, NOV offers Kenics heat exchangers (Figure 2), which are equipped with streamlined Kenics static mixer elements to offer uni-

FIGURE 4. High-efficiency heat exchanger tubes, especially on processes with media phase change, are improving heat transfer efficiencies

form heat transfer, as well as efficiency and reliability in difficult, demanding applications.

Designed for efficiency

There are some applications where efficiency is key and in many of those applications, electrical heat exchangers have been the solution. Electrical heat exchangers are typically as close to 100% efficient as is possible because any electricity that is put into the electrical heating coils goes directly to the process media. However, recent developments in design have allowed companies like Watlow to squeeze even more efficiency from this design. "We used enhanced fluid dynamics (EFD) to design a heater, the Optimax, with a higher heat flux while still maintaining the same sheath temperatures of the electrical heat exchangers that have been on the market for forty years. This provides benefits such as improved heat-transfer rates, increased efficiency, smaller footprint and lighter weight," says Mike Bange, product engineer with Watlow (St. Louis, Mo.; www.watlow.com).

Optimax's (Figure 3) EFD technology provides advanced flow without compromising the integrity of the fluid, heating elements or vessel. Fluid temperatures are further optimized though the use of optimized film temperature technology in the heating elements. Coupled together, these provide an accelerated heat-transfer rate, allowing the vessel to perform consistently at shorter lengths or smaller shell diameters.

Improvements in the tubes, as well, are increasing efficiency of exchangers, according to Wieland's Duarte. "Certainly, the high-efficiency heat-exchanger tubes, especially on processes with media phase change, are improving the efficiencies," he says (Figure 4). "Performances of the equipment have increased dramatically when compared to plain or low-fin tubes. In some cases, two exchangers can be replaced by one more efficient piece of equipment. In addition to providing these enhanced tubes to the market, our customized heat-exchanger design results in substantial capacity and energy efficiency improvements, as well." ■

Joy LePree

Sensors and Detectors

NK Technologies

Hamilton Co.

Pepperl+Fuchs

Solid-state sensor protects machinery from shocks

The AGLD Series Ground Fault Sensors (photo) keep machinery and operators safe from accidental shocks. They are designed to monitor large machines, to detect moisture ingress in water-delivery and treatment systems, and to ensure safety in heating processes. They feature a one-piece, solid-core design. The output relay will change state at any point between 5 and 100 mA, or between 80 and 950 mA, depending on the model. These sensors have a large LED display, which shows the precise trip point clearly in any light condition. A delay can be set to allow downstream protection to activate before the sensor, keeping the main circuit protection hot and equipment energized while smaller faults are cleared, says the manufacturer. Electromechanical relay output provides both normally open and normally closed contacts. These sensors are said to be compatible with most automation and control systems. — *NK Technologies, San Jose, Calif.*
www.nktechnologies.com

This family of sensors now has Bluetooth capabilities

ArcAir (photo) is the latest communication package to support this company's Arc family of process sensors. ArcAir enables economical Bluetooth 4.0 wireless connectivity in all environments, says the company. The new Bluetooth capabilities allow users to view or control Hamilton Arc sensors from a wide range of devices, including smart phones and tablets. ArcAir apps are available online for both Android and iOS platforms in three versions: ArcAir Lite (free), ArcAir Basic and ArcAir Advanced. — *Hamilton Co., Reno, Nev.*
www.hamiltoncompany.com

Floor scales are undaunted by tough industrial conditions

Hardy Floor Scales and Hardy Lift Deck Floor Scales can now be ordered in custom sizes. These process weighing scales combine best-in-class durability with the company's Process Toolbox features, including weightless calibration via the company's C2 electronic calibration process, and built-in, easy-to-use Integrated Technician (IT) circuitry diagnostics. These scales provide the latest advancements in weighing technology (including hermetically sealed load sensors that are sealed at both the gaging area and cable entry, to ensure long life). They are easy to use and install, and are designed and built to withstand harsh chemical and washdown environments. Both are available in a variety of dimensions and capacities. — *Hardy Process Solutions, San Diego, Calif.*
www.hardysolutions.com

Luminescence sensors support packaging applications

The DK50-UV Luminescence Sensors (photo) provides a reliable way to complete tasks such as error checking, sorting, measuring and positioning materials that blend into a background or are invisible. They detect fluorescent chalk marks, clear glue, tamper-proof seals and other marks that regular contrast sensors cannot detect, even on irregular backgrounds. These sensors deliver a sensing range of 600 mm in a space-saving housing that is 50% smaller than previous generation luminescence sensors, says the company. A light spot with a small focal point allows users to monitor small parts, such as O-rings, pinpoint leaks, and invisible markings down to 2.2-mm-dia. targets. These sensors are UL and cUL listed. The DK50-UV can also differentiate between multiple luminescent targets. Its graphical eight-segment LED display, which indicates luminescent signal strength, and other key parameters. It comes with an integral timer that allows slower controllers to react to sensor output. — *Pepperl+Fuchs, Twinsburg, Ohio*
www.pepperl-fuchs.us

(Continues)

Note: For more information, circle the 3-digit number on p. 74, or use the website designation.

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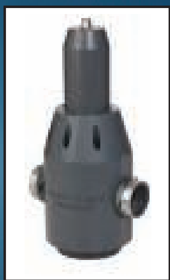

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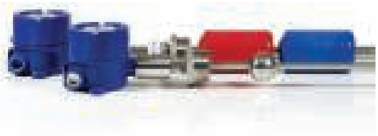


TE Connectivity

Endress+Hauser

Viscosity systems are reliable under harsh conditions

The Dynatrol CL-10DV Viscometer operates in a wide range of conditions. It provides precise measurement with fast and continuous readings for a diverse array of chemicals, including Newtonian and shear-thinning liquids. The Dynatrol viscometer uses a vibratory principle to provide continuous, online measurement of process conditions. This eliminates the need for sampling and provides exceptional accuracy, says the company. The viscosity probe is available in stainless steel and other corrosion-resistant materials. It operates in ranges up to 100,000 centipoise. It has a standard pressure rating of 1,000 psi, and a temperature rating of 300°F (higher pressure and temperature ratings are available). The microprocessor-based system has noise immunity for harsh industrial environments, and displays viscosity in standard units. — *Automation Products, Dynatrol Div., Houston*
www.dynatrolusa.com

Magnetostrictive liquid-level sensors provide reliable insight

The MPX Series magnetostrictive liquid-level sensor (photo) provides accurate, repeatable level readings in a variety of liquid-level measurement applications. The MPX-R has a large, buoyant and robust float that allows it to be used reliably in harsh environments, where fouling or buildup might otherwise be potentially troubling. The MPX-E's lighter weight design allows it to be used in applications where space is limited. The sensor is used for tank volume or level measurements and dual-level interface measurement, and the probe is available in custom lengths up to 25 ft (7.62 m). — *BinMaster, Lincoln, Neb.*
www.binmaster.com

Intrinsically safe position sensors serve many purposes

The intrinsically safe HLIR 750 Series LVDT position sensors (photo) have a 4–20-mA output signal, and are CSA listed for use in hazardous locations and applications for which an intrinsically safe sensor is required. With stainless-steel construction and a hermetically sealed sensor body, these LVDT position sensors provide reliable, contactless position measurement for critical applications in gas turbines (such as fuel-valve position feedback), vane-pitch servo controls, governor controls, and generator-shell expansion measurement. Units are also suited for the following: throttle-position sensing in engine-driven compressors in natural gas pumping stations; for height measurement for head boxes and slicers in paper mills; for edge detection and web-tension controls in plastic film plants;and for realtime position sensing for all types of valves in process plants, says the company. — *TE Connectivity, Pennsauken, N.J.*
www.macrosensors.com

Adaptable sensor assemblies are easy to clean and sterilize

The Cleanfit CPA875 and CPA871 sensor assemblies (photo) allow pH, ORP, oxygen and NIR sensors to be easily installed or removed during operation. By moving the sensor from the measuring position to a service position, these retractable assemblies allow the sensor to be cleaned, calibrated or replaced without interrupting the process. The Cleanfit CPI875 is for applications in the pharmaceutical and food-and-beverage industries, in which the sensor must be removed for cleaning, calibration or maintenance on a regular basis. The CPA875 assemblies, along with their service chambers and process adapters, are designed to drain freely and completely and allow for thorough cleaning and sterilization. The CPI871 sensor is designed for water and wastewater and chemical industries applications. The retractable assemblies permit removal and installation, while protecting the process and operaing personnel. Both sensor assemblies are available with a manual or an automatic drive. — *Endress+Hauser, Greenwood, Ind.*
www.us.endress.com

All-welded flowmeter handles air and many different gases

The Model ST100L Air/Gas In-Line Thermal Mass Flow Meters now features an all-welded, no-thread flow element connection, for improved reliability in high-pressure industrial operating environments. The flowmeter has a high pressure rating of

up to 3,000 psig, and is designed to handle a wide range of gases, including natural gas, hydrogen, helium, methane, ethane, propane, ethylene, nitrogen, carbon dioxide and many specialty gases. The ST100L Flow Meter is inherently thread-less. The elimination of threaded connections removes a potential leak path compared to standard meter compression fittings, which are threaded and can provide a conduit for hazardous gas leakage, says the company. It has no moving parts, which virtually eliminates wear, breakage and maintenance. The flowmeter measures flow with 100:1 turndown in ranges from 0.006 to 1,850 ft^3/min.— *Fluid Components International LLC, San Marcos, Calif.*
www.fluidcomponents.com

Capacitive sensors track level for all types of media

The Advanced SmartLevel Sensor (photo) combines standard capacitance-sensing technology with patented SmartLevel technology, which enables it to reliably sense solids, granulates and highly conductive acids and bases, says the company. It is housed in 316 stainless steel to withstand aggressive environments. The polyether ether ketone (PEEK) housing on the sensing nose provides protection against sticky and adhesive materials. It can withstand use in an autoclave for up to one hour, and when used with proper mounting accessories, the sensor can be used in hygienic applications. It can be easily integrated into control systems (discrete-output and IO-Link versions are available). This sensor provides excellent compensation against foam, film and material buildup that cause false triggers in competing sensors, according to the manufacturer. — *Balluff GmbH, Neuhausen, Germany*
www.balluff.com

Rugged transducer is available for position sensing

The heavy-duty LDI-127 Series Linear Variable Inductive Transducer (LVIT; photo) is a contactless position sensor that is designed for a wide array of in-plant applications, as well as industrial testing, laboratory and OEM applications. It has a compact, anodized aluminum housing (27-mm dia.; 1.05-in. dia.) that is sealed according to IP67 requirements. The LDI-127 sensors are offered in five full scale ranges, from 25 to 200 mm (1 to 8 in.). Operating from a variety of d.c. voltages, these sensors offer a choice of outputs. They include a field-programmable calibration feature, and operate reliably in temperatures from –20 to 85°C (–4 to 185°F). — *Omega, Stamford, Conn.*
www.omega.com

Sensor monitors cleaning, coating and quenching fluids

The cleaning, coating and hardening of industrial components and surfaces are critical process steps that directly impact the final product. Using inline analytical technology, the fluids used by these processes can be monitored continuously and in realtime to meet demanding process and safety objectives. The LiquiSonic sensors (photo) are installed directly into baths or pipes of any size. The sensors precisely measure the concentration of cleaning, anti-corrosive or quenching agents, allowing for immediate replenishment. This can reduce the production of off-specification batches that can result when such fluids are not replenished or replaced frequently enough. — *SensoTech, Wayne, N.J.*
www.sensotech.com

Compact Coriolis liquid flow sensor is ideal for tight spaces

The Sitrans FC430 Coriolois flowmeter (photo) is designed for both volume and mass liquid flow, and offers high-accuracy measurement with minimum pressure loss in many chemical process industries (CPI) applications. It is available for new and retrofit situations, where space is limited. The sensor's compact design is possible from the patented CompactCurve tube shape, which offers flow accuracies of ±0.1% of flowrate on both liquids and gases, says the company. User-friendly support tools provide direct access to operational, configuration and functional data. With both hazardous and sanitary approvals, this device is suitable for use during liquid custody transfer. — *Siemens Process Industries & Drives Div., Spring House, Pa.*
www.siemens.com ■

Suzanne Shelley

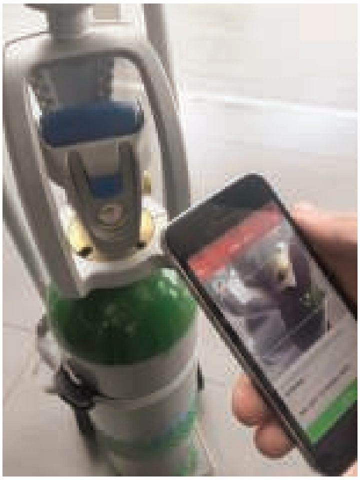
Balluff

Omega

SensoTech

Siemens Process Industries & Drives Div.

Linde Gases



MilliporeSigma

Blacoh Fluid Control

A cloud-based service for cylinder inventory

This company has introduced a new cloud-based version of its gas cylinder inventory intelligence service, Accura (photo). Each time a cylinder is moved, it is scanned and traced, and realtime location data is uploaded to the Accura platform. The service enables live information on cylinder stock levels, movement history and usage patterns, which can be accessed through a mobile application for smartphones and tablets, or via a regular web browser. Tools such as re-ordering assist and gas-consumption reports help increase productivity, especially for customers requiring an uninterrupted gas supply for process continuity. Additional benefits of the service include enhanced visibility of potentially hazardous products and cylinder expiry dates. — *Linde Gases, a division of The Linde Group, Munich, Germany*

www.linde-gas.com

Enhanced safety is among the upgrades to these pumps

The newly upgraded mRoy line of metering pumps includes new features for improved safety, improved hydraulic efficiency and easier startup and maintenance. Specific enhancements include a liquid-end bleed system, making it easier to commission a new or newly maintained pump, and threaded elements on the housing to assure there is no easy access to potential moving parts. The pumps are designed to accurately control chemical dosing while meeting API 675, CE and ATEX standards. The durable, compact design enables metering of harsh chemicals with 100-to-1 turndown capabilities and repetitive steady-state accuracy of ±1%. — *Milton Roy, Houston*

www.miltonroy.com

Faster fluid management for biopharmacuticals

Lynx CDR connectors (photo) allow efficient fluid management through sterile connection, disconnection and reconnection, providing an alternative to the more time-consuming tube-welding processes and costly manifold configurations traditionally used in upstream and downstream biopharmaceutical processing. The connectors provide six sterile connections, disconnections and reconnections from one disposable device. Previous disposable connector technologies allowed users to make only a single sterile connection per device, requiring the use of multiple devices per unit operation. According to the manufacturer, the Lynx CDR's ability to perform connections and disconnections with a wet, pressurized flow path allows for more economic fluid management than with connectors that require a dry, non-pressurized flow path. — *MilliporeSigma, Billerica, Mass.*

www.emdgroup.com

Interconnect industrial software systems of all sizes

The recently introduced Matrikon OPC Unified Architecture (OPC UA) Software Development Kit (SDK) is a fully scalable toolkit that allows users to interconnect industrial software systems, regardless of the platform, operating system or size. According to the company, the Matrikon OPC UA SDK requires the smallest amount of memory in the industry, and runs as efficiently as possible to leave sufficient computing resources for correct device functionality. The toolkit is suitable in both small embedded environments and large PC-based applications, providing the scalability to enable multiple product lines ranging from networked discrete sensors and actuators to programmable controllers. — *Honeywell Process Solutions, Houston*

www.honeywellprocess.com

New pulsation dampener design for AODD pumps

This company has launched a new pulsation dampener designed specifically for air-operated double-diaphragm (AODD) pumps. The AODDampener (photo) is constructed of 316L stainless steel with a polytetrafluoroethylene (PTFE) diaphragm, and employs an automatic air-control mechanism that utilizes the existing compressed-air source in an AODD pump system for charging. Because there is no need to adjust the dampener's charge at pump startup or when there is a change in system pressure, the AOD-

Dampener's automatic air control works with AODD systems where fluid pressures vary substantially on a regular basis. Another benefit of the dampener's automatic air control is that air is not required unless the average line pressure in the system changes. — *Blacoh Fluid Control, Riverside, Calif.*
www.blacoh.com

An ultrasonic sensor for layer detection in a variety of materials


SICK

The UD18-2 ultrasonic sensor for double layer and splice detection (photo) is able to determine whether one, two or no material layers are present between its sender and receiver. The UD18-2 can reliably detect objects regardless of material, including paper, cardboard, shiny metal, transparent plastic and more. The UD18-2 also features the functionality for up to four sensitivity levels, and the sensor can switch between sensitivity levels during operation. This allows the sensor to tackle complex applications and ensure permanent system availability. In addition, the UD18-2 features rapid commissioning thanks to plug-and-play technology, as well as variable mounting distance for flexibility during installation. The UD18-2 is also immune to dirt, dust and humidity, making it appropriate for a wide variety of applications in the packaging, paper, electronics, solar, metal and steel industries. — *Sick AG, Wildkirch, Germany*
www.sick.com

This transmitter software reduces process upsets

Micro Motion Advanced Phase Measurement (APM; photo) is a software option available on this company's Model 5700 transmitter that helps improve measurement accuracy in challenging multi-phase applications. This measurement solution provides insight into the complete flow stream, including oil, water and gas, through a local display, provid-


Emerson Process Management

ing continuous, realtime production data. The platform also provides measurement insight to reduce waste, maintain product quality, and identify process upsets in the presence of multiple phases in life sciences and chemical applications. — *Emerson Process Management, Austin, Tex.*
www.emersonprocess.com

These limit switches require no batteries

Steute Industrial Controls

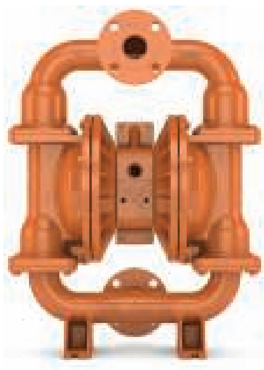
This company's line of wireless limit switches (photo) feature an internal electrodynamic energy generator — no battery is required. Displacement of the actuator generates power to send a uniquely coded signal to one or more compatible, easily-programmed receivers. If the limit switch does not receive the confirmation signal within 15 ms, it transmits a second signal. The receiver accepts up to 10 discrete signals per channel. With a transmission range of 40 m indoors and 450 m outdoors, the switches are available for operation at 915 MHz (for use in the U.S, Canada and Australia) or 868 MHz for use in Europe. A variety of actuator styles are available, including roller plunger, roller lever, rocker lever, spring rod and more. — *Steute Industrial Controls, Inc., Ridgefield, Conn.*
www.steutewireless.com

An easily expandable wireless I/O system

The new Multi-Point Wireless I/O system allows users to transfer I/O or Modbus data to and from multiple locations without the hassle of wires, Pall Life Sciences

Hugo Vogelsang Maschinenbau

ExxonMobil Chemical



Wilden Pump and Engineering

conduit, trenching or permits. The secure system deploys quickly and can be used indoors or outdoors in a variety of industries. The system can be expanded as the needs of the user's application expand. Three module types — two analog and one digital — allow users to customize their setup. The Multi-Point Wireless I/O system can be used in three different methods: I/O to I/O; I/O to Modbus serial; and Modbus serial to Modbus serial. The digital module also serves as a counter. — *ProSoft Technology, Inc., Bakersfield, Calif.*
www.psft.com

A single-use, stirred-tank bioreactor for scalable cell culture

The Allegro STR 1000 single-use, 1,000-L stirred-tank reactor (photo) provides scalable cell culture in a simple-to-install package. Installation is largely automated and requires minimal operator interaction, reducing the potential for error or damage. The cubical design and large bottom-driven impeller result in high oxygen-transfer rates and short mixing times. In addition, both disposable and reusable sensors can be integrated with the Allegro STR 1000 bioreactor for increased flexibility. — *Pall Life Sciences, Port Washington, N.Y.*
www.pall.com

Expanded throughput is available with these shredders

The new generation of the XRipper twin-shaft shredder is designed to reduce the size of coarse matter that can clog pumps, pipes and fittings. In addition to shredding more evenly, new housing geometry allows for significantly higher throughput, which can be further increased with an optional add-on feature, says the company. Designed specifically for pipelines, the XRipper model XRP (photo) has the optimal type of construction for inline installation in sewage pipelines and other confined spaces, such as ducts. The easily accessible ripper rotors and cartridge seals allow quick parts replacement. A version designed especially for channel installations, the XRC, is also available. — *Hugo Vogelsang Maschinenbau GmbH, Essen, Germany*
www.vogelsang-gmbh.com

New PE resins allow for faster film-production rates

Developed through advanced catalyst technology and process research, Exceed XP performance polymers are specifically designed to run at faster film-production rates in a variety of film applications. The polyethylene (PE) resins offer a high level of protection and preservation for a broad range of flexible packaging products, and are especially well-suited for challenging applications, such as liquid and food packaging, construction liners and agricultural films (photo), says the manufacturer. In the food-packaging sector, Exceed XP can be used in highly demanding environments with low temperatures or high volumes. — *ExxonMobil Chemical Co., Spring, Tex.*
www.exxonmobilchemical.com

An aluminum version of this AODD pump is now available

The HS430S Advanced FIT 1.5-in. high-pressure AODD pump is now available in an aluminum version (photo) that is well-suited for applications that require high head pressures, such as viscous and solid-laden slurries. The aluminum pump comes equipped with the FIT wetted path, which minimizes the number of fasteners and allows for single-socket reassembly for simpler maintenance. The pump's Simplex design allows for one liquid chamber to pump fluid while the other is used as a pressure-amplification chamber. With a two-to-one pressure ratio, the pump generates 250 psig and does not require external boosters or amplifiers to achieve this discharge pressure. — *Wilden Pump and Engineering, Grand Terrace, Calif.*
www.wildenpump.com

All-new industrial thin client for virtualized HMI systems

The BTC01 is a new standalone industrial-box thin client that is ideal for modular virtualized human-machine-interface (HMI) systems. It comes preloaded with this company's new proprietary operating system, RM Shell 4.0. The BTC01 features enhanced security, a new user interface that simplifies integration and auto-connect and connection-loss fea-

tures. The fully customizable unit can simultaneously run up to four systems, and it restricts operators to predefined web addresses. Shock and vibration resistant, the BTC01 is built on an aluminium chassis with a fanless design. All internal moving parts are eliminated, and the unit can operate safely at temperatures between –20 and 60°C. — *Pepperl+Fuchs North America, Twinsburg, Ohio*
www.pepperl-fuchs.us

These low-emission burners produce less noise

Developed with computational fluid dynamics (CFD), as well as practical combustion tests, the ACE low-emission burner (photo) produces very low NOx emissions. Its CO emissions are also very low. In typical conditions, the NOx emissions of natural-gas combustion are less than 60 mg/Nm^3 with these burners. In addition to combustion emissions, the burner's noise emissions are significantly lower than those of earlier models. ACE burners are suitable for natural gas, light and heavy oil, as well as other liquid and gaseous fuels. The ACE product family consists of several different burner capacities, currently covering the 6.5–70-MW power range. — *Oilon Oy, Lahti, Finland*
www.oilon.com

Metallic gear pumps with very few parts

The Eclipse Series of metallic gear (photo) pumps features 12 different models to handle a wide variety of chemicals, connection sizes and flow ranges for water treatment and chemical processing applications. Equipped with a patented front pull-out design that simplifies routine maintenance, the Eclipse series features the fewest number of parts compared to any other external gear pump on the market, says the manufacturer. Two different types of metallic gearing — Alloy C and 316LSS — are available for addressing higher temperatures (up to 450°F) and wider viscosity ranges for process chemicals. Each member of the Eclipse Series is magneti-

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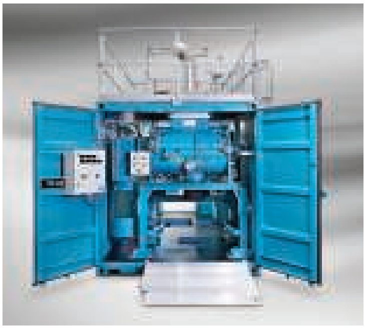

Watlow Electric Manufacturing

Sandvik Materials Technology

A&D Weighing

cally driven, with no seals to wear or replace, providing reliable handling of highly corrosive fluids in a wide range of temperatures. — *Pulsafeeder Engineered Products, Rochester, N.Y.*
www.pulsa.com

Perform wear tests onsite with this fully mobile mixer

A mobile version of this company's FKM 600 ploughshare mixer, dubbed Mixer in the Box (photo), was specially designed for users in heavy-duty industries, providing the ability to perform practical wear tests directly on their premises. Completely mobile and installed in a 40-ft standard container, the fully assembled machine has a drum volume of 600 L. Suitable for mixing heavy and coarse products, the Mixer in the Box is constructed of highly durable materials with a replaceable rubber lining to protect the cylindrical container and front plates from wear. The mixing mechanism itself has shovel armor plating made of tungsten carbide, which significantly increases service life. — *Gebr. Lödige Maschinenbau GmbH, Paderborn, Germany*
www.loedige.de

This process controller features advanced data logging

The F4T version 3.0 temperature and process controller (photo) features advanced data logging and graphical trend charts, as well as encrypted data-log records to help meet industry requirements, such as AMS 2750E and CFR 21 Part 11. Other benefits of the data-logging feature include the ability to log directly to a USB memory stick and transfer files over Ethernet. Users can create up to four trend screens and scroll through a matching color legend of parameters on the trend chart. The F4T also features a 4.3-in., capacitive color touch panel with high resolution and a graphical user interface that provides customized control. — *Watlow Electric Manufacturing Co., St. Louis, Mo.*
www.watlow.com

Weld-free coiled tubing in lengths exceeding 1,000 m

This company has developed a method enabling the production of stainless coiled tubing (photo) in lengths exceeding 1,000 m from a single 125-kg hollow with zero welds. The new production technique is a combination of sophisticated pilgering, precision drawing and other proprietary processes. Production of the coiled tubing is expected to be up and running at a facility in Werther, Germany this month, with the first 1,010-m coiled reel order to be supplied in October 2016. — *Sandvik Materials Technology, Sandviken, Sweden*
www.smt.sandvik.com

Portable balances that can be used in vapor-filled atmospheres

The EK-EP Series of intrinsically safe compact balances (photo) are approved for both U.S. and Canada for Zone 0 or Division 1 atmospheres where vapors are constantly present and could be accidently ignited. The Series' models have capacities of 300 and 3,000 g, as well as 12 kg. The portable design means that weighing can take place near the vapor source or inside fume hoods and explosion-proof enclosures. Because the balances are powered by batteries rather than electrical mains, they do not require installation by a qualified electrician. — *A&D Weighing, San Jose, Calif.*
www.andweighing.com

Use this software for steel and concrete structural designs

The recently released Engineer 16 structural-design software features over 350 updates upon previous versions, including important enhancements in concrete and steel design. For concrete designs, new workflows, a new shear-wall and frame module and improved beam and column design functionalities have been added to the software package. For steel projects, improvements have been made in the areas of composite floor members, cold-formed steel design and bi-axial steel-connection design. The software's analysis and results capabilities have also been updated to include extensions for plastic strains, additional yield criterion and triangular finite elements during meshing for membrane elements. — *SCIA nv, Herk-de-Stad, Belgium*
www.scia.net ■

Mary Page Bailey

Circle 16 on p. 74 or go to adlinks.chemengonline.com/61496-16

Facts At Your Fingertips

Key Reactions for the Petrochemical Industry

Department Editor: Scott Jenkins

A handful of compounds derived from natural gas and crude petroleum are converted into a vast array of industrial petrochemicals. Starting materials for most petrochemical intermediates include synthesis gas, ethylene, propylene, butadiene and BTX (benzene, toluene, xylenes). This one-page reference provides an overview of the chemical routes and reactions required to manufacture these fundamental petrochemicals, as well as reactions for generating some of their immediate chemical derivatives.

PETROCHEMICAL STARTING MATERIALS AND MAJOR PRODUCTS		
Petrochemical	**Potential chemical routes and required reactions**	**Reactions involved in the manufacture of immediate derivatives**
Synthesis gas (syngas, a mixture of mainly H_2 and CO)	Methane can be converted to synthesis gas by steam-methane reforming. $2CH_4 + 3H_2O \leftrightharpoons CO + CO_2 + 7H_2$ (reaction occurs at temperatures between 700 and 1,100°C with a nickel-based catalyst) The formation of syngas is strongly endothermic and requires high temperatures. Steam reforming of natural gas occurs in externally heated tubular reactors. The process uses nickel catalysts on a special support that is resistant to the harsh process conditions. Waste heat from the oven section is used to preheat gases and to produce steam. Coal, biomass or other hydrocarbons can be converted to syngas via gasification according to the following reaction: $3C$ (coal) $+ O_2 + H_2O \rightarrow H_2 + 3CO$ Syngas can also be made via partial oxidation processes, in which a sub-stoichiometric fuel-air mixture is partially combusted to yield a hydrogen-rich syngas.	Syngas is a crucial intermediate resource for the production of hydrogen, methanol and ammonia. For example, $CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O$ Fischer-Tropsch (F-T) synthesis converts syngas into hydrocarbons that can then be converted into liquid vehicle fuels, such as gasoline, diesel and jet fuel, as well as chemicals such as olefins and waxes. A general representation of the F-T reaction is the following: $(2n + 1) H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$ Product distribution for F-T chemistry includes different-sized alkanes and alkenes, and to a lesser extent, oxygenated products, such as alcohols. F-T catalysts are either based on cobalt or iron.
Ethylene (C_2H_4; $H_2C{=}CH_2$)	Ethylene is commercially produced by the steam cracking of a range of hydrocarbons, including ethane from natural gas and naphtha from crude oil. Naphtha is a name given to petroleum distillates consisting of a mixture of straight-chained and aliphatic hydrocarbons with five to nine carbons. Steam cracking is the uncatalyzed thermal decomposition of hydrocarbons at high temperatures using steam. In steam cracking, gaseous, saturated hydrocarbons are broken down into smaller, often unsaturated, hydrocarbons at temperatures from 750–900°C. The partial pressures of the hydrocarbon feeds are kept low to prevent polymerization and condensation reactions from occurring. Steam cracking is generally used to manufacture lighter olefins, such as ethylene and propylene. Steam cracker feeds can include naphtha, liquefied petroleum gas (LPG), ethane, propane and butane. Steam-cracker product distributions can be controlled by changing the composition of the feed material, the hydrocarbon-to-steam ratio, the cracking temperature and furnace residence time. Cracking reactions generally take place via free-radical mechanisms in which alkane carbon-carbon bonds break homolytically, forming alkyl radicals, which can abstract hydrogen atoms. For example, in ethane cracking, hydrogen abstraction forms ethyl radicals, which undergo a unimolecular, free-radical decomposition to form C–C double bonds. Initiation: $C_2H_6 \rightarrow \cdot CH_3 + \cdot CH_3$ Propagation: $\cdot CH_3 + C_2H_6 \rightarrow \cdot C_2H_5 + H\cdot$ $\quad \cdot C_2H_5 \rightarrow C_2H_4 + H\cdot$ Termination: $\cdot C_2H_5 + \cdot C_2H_5 \rightarrow C_2H_4 + C_2H_6$	Ethanol: $C_2H_4 + H_2O$ (steam) $\rightarrow C_2H_5OH$ Ethylene oxide (used to make ethylene glycol): C_2H_4 + air (O_2 source) $\rightarrow C_2H_4O$ (in the presence of silver catalyst) Ethylene dichloride (1,2-dichloroethane; used to make vinyl chloride): $C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2$ (ferric chloride catalyst) Polyethylene (used to make plastic resins): $C_2H_4 \rightarrow [–CH_2–CH_2–]_n$ (using Ziegler-Natta catalyst at pressures of 1,000 to 3,000 bars) Ethylbenzene (used to make styrene) $C_2H_4 + C_6H_6 \rightarrow C_6H_5CH_2CH_3$ (Lewis acids used as catalyst)
Propylene (C_3H_6; $H_3C–CH{=}CH_2$)	A) Steam cracking of naphtha (see above description) B) Propane dehydrogenation. Because of an increasing demand for propylene and a shift toward ethane cracking over naphtha cracking, a number of "on-purpose" routes to propylene have become more widely used, including propane dehydrogenation (PDH). $C_3H_8 \rightarrow C_3H_6 + H_2$ (in the presence of a Pt-Sn-based catalyst)	Propylene oxide (used to make polyether and polyols) via the hydrochlorination route: $2C_3H_6 + Cl_2 + H_2O \rightarrow 2(H_2C–CHCl–CH_2OH)$ $H_2C–CHCl–CH_2OH + {}^{-}OH \rightarrow H_3C–CH–CH_2$ \ O / Polypropylene (used to make plastic resins) $nC_3H_6 \rightarrow [–CH_2–CH–CH_2–]_n$ (Ziegler-Natta catalyst) | CH_3
Butadiene (C_4H_6; $H_2C{=}CH–CH{=}CH_2$)	A) Steam cracking of naphtha (see above description) B) Bio-based butadiene has been commercialized also (using a fermentation route)	1,3-butadiene is used for the manufacture of synthetic rubbers and latex
BTX (benzene, toluene and xylene isomers)	A) Steam-cracking of naphtha (see above description) B) Catalytic reforming of naphtha. This process uses platinum- or rhenium-based catalysts. Naphtha reforming dehydrogenates naphthenes, and dehydrogenates and aromatizes paraffins, among other reactions	Benzene is used to make ethylbenzene, and then styrene ($C_6H_5CH{=}CH_2$), as well as cyclohexane and further precursors for Nylon Toluene is used to manufacture toluene diisocyanate (an intermediate for polyurethane), as well as tri-nitrotoluene (TNT). It is also used as a component of gasoline, and as a solvent for sealants, adhesives and others *p*-xylene is used to make terephthalic acid, a precursor to polyesters. *o*-xylene is used to make phthalic anhydride

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Precipitated Calcium Carbonate from Limestone

By Intratec Solutions

Calcium carbonate ($CaCO_3$) is a mineral that occurs naturally in chalks, limestones and marbles. Its largest use is in the pulp-and-paper industry as a filler and pigment. Other calcium carbonate applications include its use in building construction, plant and crop fertilizers, food additives, water and sewage treatment, ceramics, pharmaceuticals and cosmetics.

The process

The following paragraphs describe a carbonization process for precipitated calcium carbonate (PCC) production from limestone. Figure 1 presents a simplified process flow diagram, showing the main pieces of equipment.

Calcination. Initially, the limestone from a quarry is stored in bins. Typical extracted limestone contains about 75 wt.% of $CaCO_3$. Mined limestone is crushed in a jaw crusher and calcined (burned) in a vertical-shaft lime kiln at about 1,000°C. In the kiln, the calcium carbonate present in the limestone decomposes into calcium oxide (CaO; also known as lime or quicklime) and carbon dioxide, which is captured and treated for reuse in the process.

Slaking. The CaO is fed to a stirred slaker tank, where it is hydrated (slaked) with water to form a calcium-hydroxide slurry called slaked lime or slake. Before carbonation, the impurities (silica and other oxides) originating from the limestone are separated from the slake, producing a pure slaked lime.

Carbonation. The pure slaked lime is then fed to a set of atmospheric stirred reactors, where it is diluted and subsequently reacted with the recovered carbon dioxide from the lime kiln. The carbonation reaction is regulated by the equilibrium of the solution: as calcium ions are converted to calcium carbonate and precipitated out of solution, more calcium hydroxide dissolves to equalize the concentration of calcium ions.

Drying, grinding and finishing. The slurry from the carbonators is sent to a filter press, which removes most of the water. Recovered water is recycled for reuse in the slaking step. The PCC from the filter is dried with hot air, de-agglomerated in grinders, packed and stored.

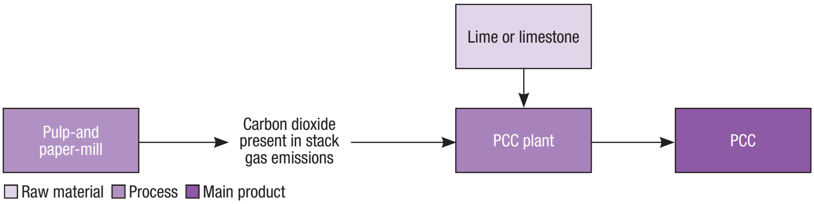

FIGURE 2. This diagram shows how a PCC plant could be a satellite plant for a pulp-and-paper mill

Economic performance

An economic evaluation of the process described was conducted based on data from the first quarter, 2014. The scope of this analysis assumes a PCC plant located near a limestone quarry.

The total capital investment required to construct a plant with the capacity to produce 50,000 metric tons per year of PCC in the U.S. is estimated at about $21 million. The capital investment presented includes fixed capital, working capital and additional capital requirements. The production costs (including costs associated with plant operation, product sales, administration, R&D activities and depreciation) are about $260/ton of PCC produced.

Process integration

When PCC plants are integrated with pulp-and-paper mills (Figure 2), they are called PCC satellite plants. These plants use the stack gas emissions from the lime kiln in the paper mill, mainly because of its higher carbon dioxide content. PCC satellite plants commonly use lime as a main raw material, rather than limestone. This integration between the two processes has a major effect on the emission profile of the pulp-and-paper mill, since greenhouse gas emissions are significantly reduced.

This column is based on "Calcium Carbonate Production from Limestone: Cost Analysis," a report published by Intratec. It can be found at: www.intratec.us/analysis/calcium-carbonate-production-cost. ■

Edited by Scott Jenkins

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

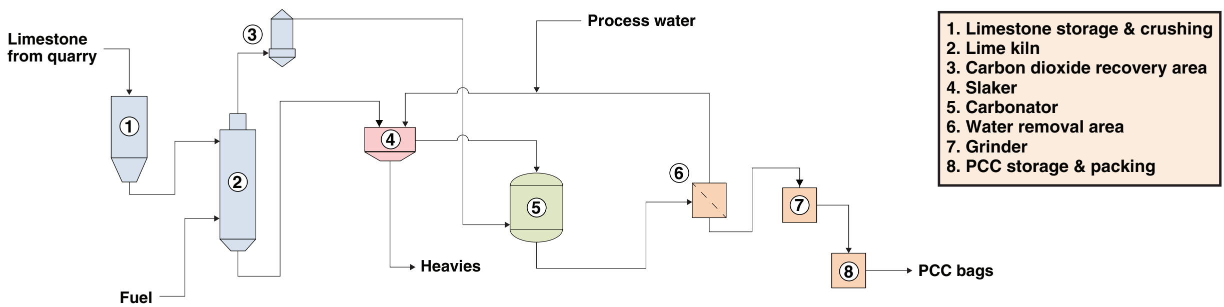

FIGURE 1. The process flow diagram shows precipitated calcium carbonate (PCC) production from limestone

Modern Rupture Discs Support Increased Plant Capacity

The use of today's high-performance rupture disc designs can help to reduce many common operating problems and support increased throughput requirements

Alan T. Wilson
Oseco

IN BRIEF

Chemical process industries (CPI) plants are typically designed to achieve specific production volumes, but as anyone who has worked in one knows, those production targets are prone to change as market factors and plant objectives evolve. Most CPI facilities are expected to increase (or decrease) production targets at some point. An increase in production targets typically involves increasing the operating pressures, temperatures or both, in order to increase the rate of process reaction and the quantity of final product manufactured at the site.

FIGURE 1. Rupture discs provide overpressure protection, so they play a vital role in CPI plant safety. High-performance rupture discs can maximize system efficiency and support increased plant capacity

When operating pressures are brought closer to the set pressure of rupture discs and relief valves, these changes can increase the frequency of nuisance failures, which can lead to pressure releases and shutdowns. Fortunately, pressure-relief technology has evolved over time, resulting in greater accuracy and higher performance for today's advanced rupture disc designs.

Rupture discs are designed to protect vessels and other capital equipment from dangerous and damaging overpressurization, by bursting open and safely relieving the overpressure condition when the line or vessel reaches a pre-determined pressure and temperature. They can provide both primary and secondary relief, and are used in combination with pressure-relief valves to prevent leakage and protect relief-valve seats from potential exposure to corrosive and sticky substances.

The burst pressure is commonly set at or below the maximum allowable working pressure (MAWP) of the vessel and the temperature at which overpressure is expected to occur. In some cases, it may be desirable to set the burst pressure well below the MAWP. An increase in operating pressures means that these devices must withstand pressures closer to the expected burst pressure. Rules governing the use of rupture discs in chemical process plants can be found in ASME BPVCVIII.1-2015, Section VIII [*1*].

Most rupture discs are manufactured from corrosion-resistant metals, using a design that is specified to meet the burst pressure and performance requirements of a given application. The user must specify the size, type, material, requested burst pressure and temperature.

The rupture disc manufacturer then manipulates the appropriate material in different ways to design and produce rupture discs that meet all of the user's specifica-

Note: The discussion provided in this article does not include every rupture disc type and situation, but is representative of most rupture discs used in chemical process industries (CPI) applications. Users should always refer to the data sheets for any specific brand and model for performance specifications.

tions. During the manufacturing process, several pieces from each lot are forced to burst as a test, to ensure that the manufactured lot meets the specifications.

Rupture discs have evolved considerably since their first use in the 1930s. Nonetheless, most of the older designs are still in use today. Compared to modern designs, older rupture disc designs have lower performance capabilities, reduced repeatability and are more difficult to accurately calibrate to a specific burst pressure.

While they may be less expensive than the newer high-performance designs, they may bring tradeoffs in performance or reliability. In many cases, a facility's particular management of change (MOC) protocol prevents upgrading to modern technology. When this happens, users often become accustomed to tolerating the poor performance of these outdated designs.

Understanding the terms that are used to describe rupture disc performance, and the technology options that are available to meet the increasing demands placed upon these important safety devices can give engineers the tools needed to support increased production objectives at the chemical process plant.

TABLE 1. MANUFACTURING DESIGN RANGE

Customer request: Burst pressure of 100 psig @72ºF Rupture discs will be marked somewhere between the minimum and maximum possible marked burst pressure				
Manufacturing design range	+10 to –5 psig	–10%	–5%	0%
Maximum possible marked burst pressure	110 psig @72ºF	100 psig @72ºF	100 psig @72ºF	100 psig @72ºF
Minimum possible marked burst pressure	95 psig @72ºF	90 psig @72ºF	95 psig @72ºF	100 psig @72ºF

TABLE 2. BURST PRESSURE TOLERANCE

Customer request: Burst pressure of 100 psig @72ºF		
Burst pressure	35 psig (≤40 psig)	100 psig (>40 psig)
Maximum acceptable burst pressure	35 + 2 = 37 psig	100+5%=105 psig
Minimum acceptable burst pressure	35 – 2 = 33 psig	100–5%=95 psig

TABLE 3. OPERATING RATIO

Rupture disc with a marked burst pressure (BP) of 100 psig @72ºF				
Operating ratio	70%	80%	90%	95%
Maximum operating pressure (If based on marked BP)	70 psig	80 psig	90 psig	95 psig
Maximum operating pressure (If based on marked BP minus burst tolerance)	66.5 psig	76.0 psig	85.5 psig	90.3 psig

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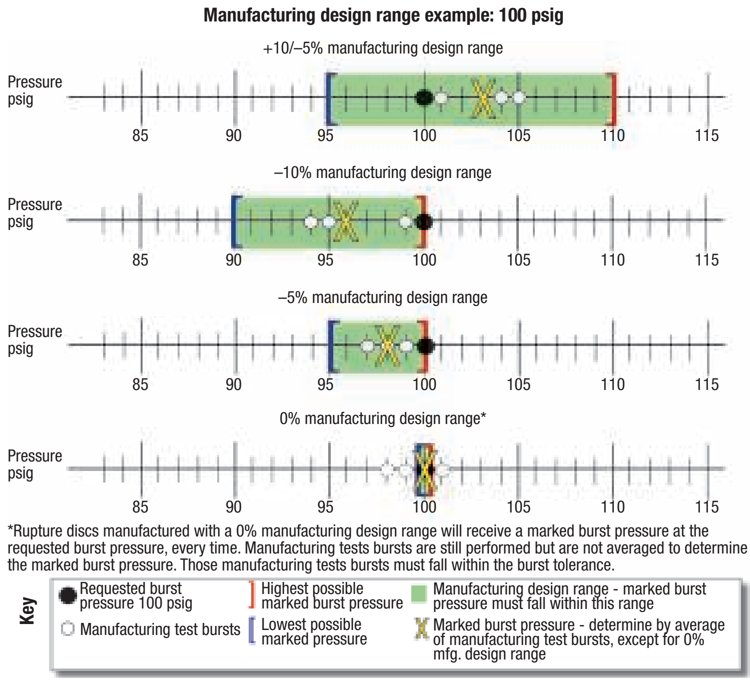


FIGURE 2. To determine the marked burst pressure, several manufacturing test bursts are run and their results averaged. The marked burst pressure on any rupture disk must fall within the parameters defined by the manufacturing design range. As shown in these examples, the marked burst pressure may be above or below the requested burst pressure, depending on the manufacturing design range available and the results of the manufacturing test bursts

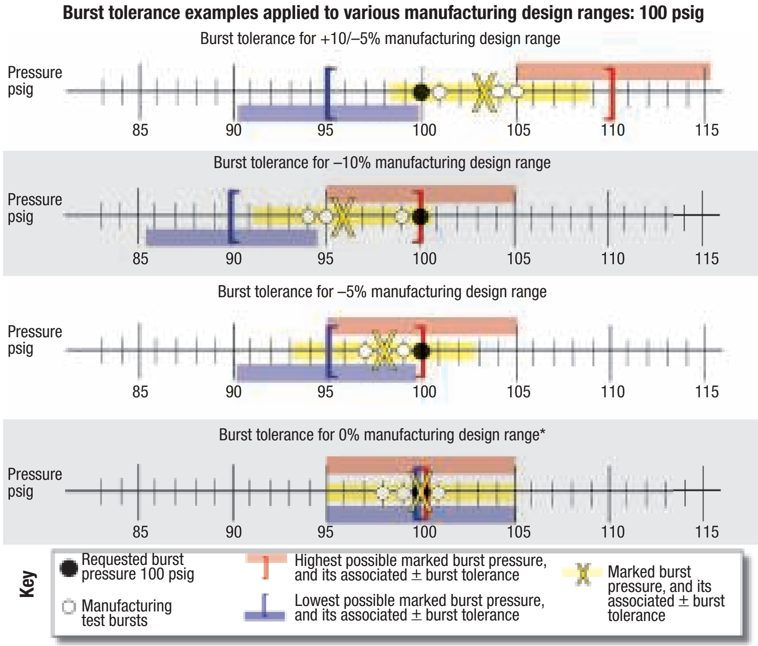


FIGURE 3. The burst tolerance is the range in which a rupture disc will burst upon activation, relative to its marked burst pressure. ASME code defines the standard burst tolerance for rupture discs as ±5% of the marked burst pressure for pressures above 40 psig. For pressures up to and including 40 psig, the standard burst tolerance is ±2 psi

Key terminology

Key rupture disc specification terms are discussed as follows:

Manufacturing design range. The manufacturing design range is an agreement between rupture disc manufacturer and user that specifies how close the marked burst pressure must be to the requested burst pressure. Specifically, ASME defines manufacturing design range as follows in the Endnote 47 of Ref. 1:

"The manufacturing design range is a range of pressure within which the marked burst pressure must fall to be acceptable for a particular requirement, as agreed upon between the rupture disk manufacturer and the user or his designated agent. The manufacturing design range must be evaluated in conjunction with the specified burst pressure to ensure that the marked burst pressure of the rupture disk will always be within applicable limits of UG-134. Users are cautioned that certain types of rupture disks have manufacturing ranges that can result in a marked burst pressure greater than the specified burst pressure."

Rupture disc manufacturers typically acquire and stock a limited selection of material types and thicknesses. Early rupture disc designs had limited means of adjusting the burst pressure — other than by selecting a different material thickness. As a result, rupture disc manufacturers often were not able to achieve the exact requested burst pressure. For this reason, the manufacturing design range must be agreed upon and specified.

The way that manufacturing design range is expressed depends on the rupture disc brand, model and in some cases, designated burst pressure. Rupture discs may be specified with manufacturing design ranges of –10%, –5%, or 0% of the requested burst pressure, or in some cases, with a positive or negative pressure unit value (Table 1). A manufacturing range of –10% for a rupture disc with a requested burst pressure of 100 psig will be marked somewhere between 90 psig and 100 psig. Rupture discs ordered with a 0% manufacturing design range will be marked at the requested burst pressure. All other manufacturing design ranges will be marked at the average value of the test breaks that were done to qualify the lot.

Some older designs may not be available in the tightest ranges. For these designs, most manufacturers may offer a tighter manufacturing range for an added cost, while others may offer a zero manufacturing range as standard on premium rupture disc designs. Rupture discs with a zero manufacturing design range can help to minimize confusion, because the rupture discs will be marked with the requested burst pressure every time they are ordered. All other ranges are likely to have a slightly different marked burst pressure each time they are ordered, since they are marked with the average burst pressure of the rupture discs that were tested during the manufacture of that given lot.

Manufacturing design ranges that have a "plus" component (see the column marked +10/–5 psig in Table 1) may be marked above the requested burst pressure. If the requested burst pressure is set at the MAWP of the vessel, the rupture disc may violate ASME rules by having a marked burst pressure that is actually higher than the MAWP.

Burst pressure tolerance. As noted above, variation in materials and manufacturing processes yield slight variations in burst pressure throughout any given lot of rupture discs. ASME specifies a burst pressure tolerance of ±2 psi of the marked burst pressure for marked burst pressures up to and including 40 psi; and a burst pressure tolerance of ±5% of the marked burst pressure for marked burst pressures above 40 psi (excerpted from Ref. 1, Section UG-125). This means that a rupture disc marked at 30 psig can be expected to burst between 28 and 32 psig (±2 psi); while a rupture disc marked 100 psig can be expected to burst between 95 and 105 psig (±5%; Table 2).

Operating ratio. Manufacturers use operating ratio to define for users the maximum operating pressure that a rupture disc can withstand while expecting a reasonable service life (Table 3). It is a measure of rupture disc performance for a particular brand and model, as determined by the rupture disc manufacturer. It is not an industry-standardized definition.

Operating ratio = Maximum operating pressure/burst pressure

Some manufacturers relate it to marked burst pressures, while others may state it as a percentage of the marked burst pressure minus the burst pressure tolerance. The way the operating ratio is defined can make a difference in the maximum operating pressure. Most modern rupture disc designs — especially reverse-buckling rupture discs — have much higher operating ratios compared to older designs.

It is important to select a rupture disc with the correct operating ratio. When the operating pressure of the system approaches the burst pressure of the rup-

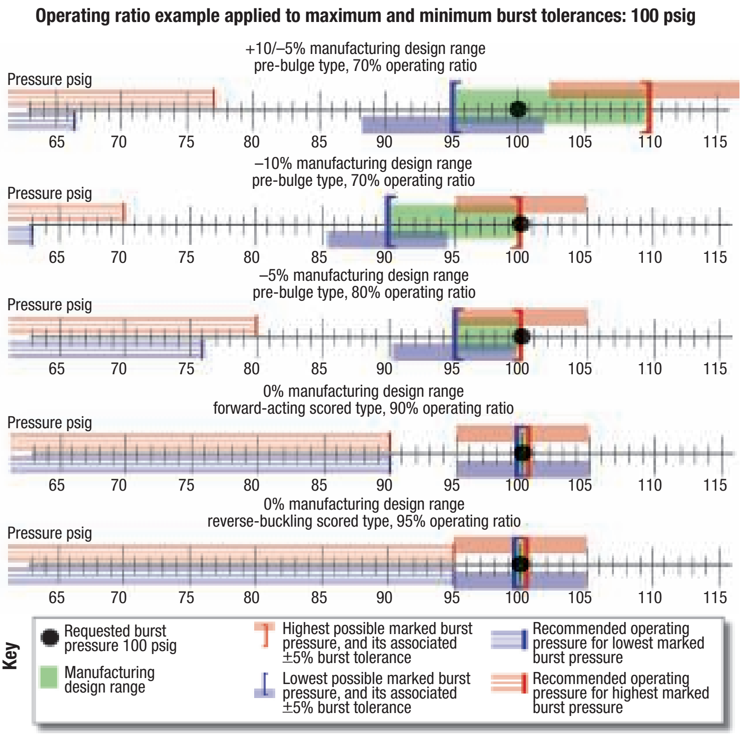


FIGURE 4. The operating ratio is calculated as a percentage of a rupture disc's marked burst pressure. It indicates how close to the marked burst pressure the rupture disc can reliably function. The maximum recommended operating pressure can be calculated by multiplying marked burst pressure by operating ratio. This is the maximum operating pressure or the highest pressure to which the rupture disc may be operated and cycled to without causing damage of fatigue to the material integrity, and is a function of the process used to manufacture the rupture disc

TABLE 4. PRE-BULGED METAL RUPTURE DISCS

Pre-bulged metal rupture discs	
Manufacturing design range	–10% or varies with burst pressure
Burst pressure tolerance (≤40 psi)	± 2 psig
Burst pressure tolerance (>40 psi)	±5% of marked burst pressure
Operating ratio	70%
Vacuum support required?	Yes — for lower burst pressures

TABLE 5. COMPOSITE RUPTURE DISCS

Manufacturing design range	–10%, –5%, 0%
Burst-pressure tolerance (≤40 psi)	±2 psig
Burst-pressure tolerance (>40 psi)	±5% of marked burst pressure
Operating ratio	80%
Vacuum support required?	Yes

TABLE 6. FORWARD-ACTING SCORED RUPTURE DISCS

Manufacturing design range	–10%, –5%, 0%
Burst-pressure tolerance (≤40 psi)	±2 psig
Burst-pressure tolerance (>40 psi)	±5% of marked burst pressure
Operating ratio	80–90%
Vacuum support required?	No*

*Vacuum support cannot be added, but most will withstand vacuum. Check product literature.

TABLE 7. SCORED REVERSE-BUCKLING RUPTURE DISC	
Manufacturing design range	–10%, –5%, 0%
Burst-pressure tolerance (≤40 psi)	±2 psig
Burst-pressure tolerance (>40 psi)	±5% of marked burst pressure
Operating ratio	90–95%
Vacuum support required?	No

TABLE 8. INTERACTION OF PERFORMANCE FACTORS: RUPTURE DISC WITH REQUESTED BURST PRESSURE OF 100 PSI@72°F				
Operating ratio	70%	80%	90%	95%
Manufacturing design range	–5 to +9 psi	–10%	–5%	0%
Burst-pressure tolerance	±5%	±5%	±5%	±5%
Min./Max. possible marked burst pressure	95/109*	90/100	95/100	100/100
Min./Max. allowable burst pressure	90.3/114.5	85.5/105	90/105	95/105
Maximum operating pressure % of marked BP*	66.5	72.0	85.5	95.0
Max. operating pressure % of marked BP–BP tolerance**	63.2	68.4	81.0	90.3

*Marked BP could exceed MAWP of vessel if requested BP = MAWP
**Some manufacturers reference the operating ratio to marked burst pressure; others reference the marked burst pressure minus the burst pressure tolerance.

ture disc, the rupture disc material can become stressed. If this stress repeats often enough, the disc material may fatigue, and the burst pressure of the rupture disc can then become reduced as a result of compromised material strength. This can lead to nuisance failures.

Vacuum resistance. Many processes require rupture discs to operate under vacuum or backpressure. Some rupture discs are manufactured from metal as thin as 0.001 in. thick. Other designs use a polymer membrane to contain the process media and transfer the pressure load to the metal rupture disc components.

When certain types of rupture discs are exposed to vacuum or backpressure, the dome can invert or collapse while still remaining intact. The next pressure cycle will reform the dome in the downstream direction. Repeated forward/reverse cycles may result in holes, cracks and compromised material strength, leading to reduced burst pressure.

Similarly, polymer membranes can burst in the vacuum direction if they are not properly supported. Discs using a polymer membrane, or those manufactured of thin, weak material require the addition of a vacuum support to prevent damage. A vacuum support is an additional component that helps the rupture disc to resist damage by vacuum or backpressure, but opens easily with the rupture disc when the disc is overpressured in the positive direction.

The evolution of rupture disc design

The leading rupture disc designs available today are discussed below.

Pre-bulged metal rupture discs — 1930s design. The earliest rupture discs were manufactured as simple sheets of metal that were bolted between pipe flanges. This design was simple, but yielded relatively low performance when compared to modern rupture discs. These early rupture discs were also inconsistent, due to the limited grades of materials that were available, and the dimensional variation of the flanges used to hold them.

Eventually, the nascent rupture disc industry discovered the importance of installing rupture discs in precision-machined holders, to ensure accurate and repeatable burst pressures. Later, manufacturers discovered that pre-bulging the rupture discs made predicting their burst performance more accurate, and made the rupture discs more robust and easier to handle (Table 4). Pre-bulged metal rupture discs are tension-loaded, or commonly known as forward-acting, rupture discs. Forward-acting discs are pressured on the concave side of the rupture disc. The material in tension is like an inflated balloon or a loaded hammock. The burst pressure of a pre-bulged metal rupture disc is determined by its material strength and thickness. When the strength of the material is exceeded, the rupture disc bursts, relieving the overpressure condition in the pipe or vessel.

Composite rupture discs — 1950s design. Composite rupture discs are made of layers of components that serve different functions. The top layer is essentially a pre-bulged metal rupture disc that has a series of holes and slits that are punched or cut with a laser. These holes and slits weaken the disc, and add a means for further adjustment of burst pressure and much lower burst pressures than pre-bulged discs are able to reach. Because this mechanism allows manufacturers to match the requested burst pressure more accurately, this type of disc is usually available with a tighter manufacturing design range.

The middle layer is usually a fluoropolymer seal that is protected from scratches and abrasion by slit fluoropolymer layers. This seal contains the process media and transfers the pressure load to the metal top.

The bottom layer (closest to the process fluid) is usually a metal vacuum support that supports the liner when vacuum is present, but opens easily when the rupture disc bursts. There are other components and configurations available for this family of disc, but this configuration is the most common (Table 5).

Scored forward acting rupture discs — 1970s to present. Scoring a pre-bulged metal rupture disc with precision tooling and specialized presses creates an even greater level of control over the burst pressure. Scored, forward-acting rupture discs usually have a cross-shaped score on the dome of the disc. This allows the disc to open with four distinct petals, without fragmenting. Some manufacturers offer 0% manufacturing range as standard. Others offer –5% or –10% (Table 6). These discs also have operating ratios as high as 90%.

Scored reverse-buckling rupture discs — 1970s to present. Reverse-buckling rupture discs are pressured on the convex side of the disc. This puts the dome in compression until the structure buckles. The disc does not experience permanent deformation until right at the point where the dome buckles. This makes reverse-buckling rupture discs ideal for applications that must operate close to the burst pressure, or are subject to cyclic loads. Modern reverse-buckling rupture discs are scored to create a non-fragmenting opening after the disc buckles. Burst pressure is adjusted by material thickness, dome height and sometimes by a dimple added to the dome. Most reverse-buckling rupture discs resist full vacuum (Table 7) without added support.

Putting it all together

When determining the maximum operating pressure for a reasonable service life, we must consider all of the performance parameters together. Table 8 shows the net result of several interacting factors. Note that the maximum operating pressure is nearly 43% higher for the highest performance rupture discs when compared to the lowest performance discs.

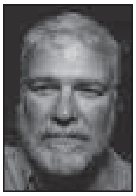
Premium scored rupture discs can cost more than lower-performance rupture discs, but as Table 8 shows, they can be operated reliably at much higher operating pressures. The increased cost of the rupture disc is often recovered through higher production rates and reduced downtime due to premature failures. ■

Edited by Suzanne Shelley

Reference

1. ASME, "2015 ASME Boiler and Pressure Vessel Code," ASME BPVC VIII.1-2015, Section VIII.

Author



Alan Wilson is senior field engineer for Oseco, a manufacturer of rupture discs and other safety pressure relief devices (1701 W. Tacoma, Broken Arrow, OK 74012; Phone: 918-258-5626; Email: awilson@oseco.com). He holds a B.S. degree in mechanical design technology from Oklahoma State University, and an MBA from Oklahoma City University. Wilson has been with Oseco for 27 years, serving as an engineering expert in research and development, rupture disc analysis and ASME code. Wilson has earned several patents for his contributions to the Oseco portfolio, and sits on two ASME committees. He has helped to design, build and teach training seminar programs for the proper use, installation and specification of rupture discs in onsite learning events for chemical processing plants and others in the field. Wilson was also on the first team to coordinate with television's Mythbusters program, when they featured Oseco rupture discs in the first of seven episodes, using them to measure explosion intensity.

An Up-Close Look at Electropositive Filtration

Electropositive filters take advantage of surface-charge effects to filter nanometer-sized particles. Provided here is an overview of how they work and where they can be used

Fred Tepper and Leo Kaledin
Argonide Corp.

IN BRIEF

Effective water management is a major issue in a growing number of geographic regions, and the chemical process industries (CPI) are implementing strategies for water reuse at an increasing rate. Filtration is a key technology area for realizing water treatment objectives. Removing small particles in the sub-micron size range, such as naturally occurring and manufactured nanoparticles, sub-micron-sized colloidal particles, microorganisms and soluble organic materials, presents difficult challenges for filtration equipment. These small particles can be significant sources of fouling for membrane micro- and ultra-filtration in several applications, including desalination, water treatment for reuse, removal of contaminants from waste streams, filtration of dyes, pharmaceutical plant wastes and others.

Modifying the surface charge of filter media offers a potentially useful and effective strategy for retaining higher levels of particles in this small size range. By manipulating the surface charge of filter media, particles can be retained at higher rates and at lower head pressures than would be possible with conventional filtration membranes. This article discusses the properties and use of electropositive filter media and describes examples where such media improve performance.

Filtration mechanisms

There are two recognized mechanisms whereby micropollutants are retained by liquid filters; namely, sieve-retention and adsorption. The sieving mechanism is perhaps the most common manifestation of conventional filtration, where the filter retains the particles because they are too large to enter or pass through the filter's mesh or pore. Even in situations where there are particle- and pore-size distributions, as long as the smallest particle is larger than the largest pore, the filtration is absolute, provided that both the filter medium and filtered particles are rigid non-compressible bodies. However, only in that circumstance may the filter be characterized as being absolute. In different situations, the removal of the same microorganism, for example, by the same filter might not take place, as when the organism decreases in size as a result of its suspension in a vehicle of high ionic strength. In any case, absoluteness is not a filter property [*1*]. Membranes are widely used in and accepted by industry as capable of 0.2 and 0.22 µm absolute removal of particulates and bacteria. However, these membranes have been observed to pass latex spheres 0.5 µm and larger in diameter [*2*].

While sieving depends on physical blockage of particles, adsorption depends on the surface characteristics of the filter media itself. For this mechanism, surface charge becomes very important. Contaminant particles and a porous filter medium can interact via short-range van der Waals forces and via electrical double-layer interactions, which may be attractive or repulsive depending on the surface charge of the contaminant particle and that of the pore surface. Since most contaminants encountered in nature are electronegative, this suggests that in order to increase retention of smaller particles, the filter medium should have a positive zeta potential [*3*].

Electropositive filters

The property of electronegativity can be defined as a measure of the tendency of an atom or a chemical functional group to attract electrons (electron density) toward itself. In the context of a chemical bond, elements that are highly electronegative will attract electron density toward their atomic nuclei, giving them a slight negative charge, while leaving less electronegative atoms, to which they are bound, with a slightly positive charge.

In the context of filtration, the overall surface charge (the combination of the electronegativity behavior of larger groups of atoms) becomes important. Small particles typically have an overall negative charge. Electropositive filters (EPFs) take advantage of this fact by introducing an overall positive charge to the filter media, in the form of a surface coating (Figure 1). EPFs can be visualized as aggregated or structured forms of flocculants. Flocculants, including alumina, are charged particles that will cause colloidal particles to aggregate.

EPF advantages and limitations

The primary advantage of EPFs is that they are effective at filtering colloidal and nanometer-sized particles at low head pressures. Those EPFs that are fibrous-based depth filters were initially designed for purifying drinking water, where operating pressures are less than 60 psi. Most membrane systems require operating pressures that are much higher — in the range of hundreds of psi.

A second advantage is that EPFs allow the elimination of water waste because there is no concentrated stream, as would be present in reverse osmosis (RO) filtration or as would be the case of using cross-flow ultraporous membranes.

Third, EPFs achieve high filtration efficiency. Their efficiencies are equivalent to ultraporous membranes. EPFs are so efficient because the electropositive charge created by their chemistry results in adhesive forces on the surfaces of the many pores that a particle must travel on its tortuous path through the depth media. Particles in aqueous media at pHs between 4 and 10 are virtually all electronegative. Certain aluminized EPFs have such a high charge that the combined electrostatic and electrokinetic fields they create extend up to 4 µm away from the surface of the media inside the pore [*4, 5*], overlapping the pore network and attracting the particle to the surface.

Fourth, EPFs have high dirt-holding capacity. In order to work at high efficiency, membranes, because they are surface filters, must have occluded particles swept away by cross-flow (using water), or must be washed out periodically. In contrast, EPFs retain dirt in their depths or amid sorbent grains of aluminized diatomaceous earth (DE; to be discussed more later) that are introduced into the EPF media.

A final advantage of EPFs is that they are capable of filtering certain soluble contaminants directly or by incorporating secondary sorbents. Examples include removing polychlorinated biphenyls (PCBs) by filtration with EPFs. Although the mechanism is not fully understood, it is believed to be the result of solvated contaminant molecules that are readily polarized, exposing a negative face to the electropositive field. Alternatively, a sorbent particle, such as powdered activated carbon (PAC), can be added to adsorb Cl_2. The advantage is that the high surface area of the PAC, as compared to granular carbon, results in high kinetic adsorption in thin layers.

Operationally, EPFs can offer other advantages, such as lowering capital expenditure (capex) compared to membrane systems when used as a prefilter for RO. In a University of Wyoming (Laramie, Wy.; www.uwyo.edu) study [*6*], substantial increases in RO membrane life were demonstrated when an EPF was inserted downstream of an ultraporous membrane that had been previously been inserted to protect the RO. Presumably, the EPF collected ultrafine particles that passed through the ultraporous filter. The study also demonstrated improvements in RO filter lifetimes if the backwash fluid was first filtered through an EPF.

The limitations of EPFs include that they are not regenerable, because the particles are retained and enmeshed

TABLE 1. COMMERCIALLY AVAILABLE ELECTROPOSITIVE FILTERS			
Media	Pore size, μm	Thickness, mm	Basis weight, g/m^2
AlOOH nanoalumina (“nanoAl”) fibers	2.0	0.8	220
NanoAl + powdered activated carbon	2.0	0.8	220
Type A media	1.1	3.8	1,280
Type A2 media	5.0	5.0	1,140
Type B media	0.6	2.6	1,430
Type C media	0.8	4.1	1,770
Type B charged composite 0.2-μm membrane	0.2	0.4a	100
Type B charged 0.1-μm membrane	0.1	0.14	60

within the depths of the media rather than on the surface, as is the case with membranes. In addition, EPFs have pH range limits (depending on which electropositive media). Finally, salt in solution may affect charge in certain EPFs, disrupting the EPFs' ability to function as intended.

Suggested applications

Electropositive filters separate a wide range of particle sizes and are diverse in composition. Those made of non-woven material and incorporated into pleated cartridges have a low pressure drop, yet are able to achieve removal efficiency equivalent to ultraporous membranes.

Because EPFs are not regenerable, they are limited, particularly for filtering heavily loaded streams, such as municipal waste. Their best use is as a polisher downstream of prefilters that would reduce the load of micron-sized particles. Suggested applications include prefiltration of streams to protect RO or seawater RO equipment, either acting alone or in concert with membranes or other media. Also, EPFs would be suited to filtration of contaminants from chemical and pharmaceutical plant waste streams, filtration of soluble and insoluble dyes, as a polisher downstream of microporous membranes and removal of microbial pathogens with minimal or no chemical treatment. Another use of EPFs is as a carrier of ultrafine sorbents, such as PAC, or nanosorbents, for development of highly dynamic adsorption media. While aluminized filters (discussed later) are primarily intended to purify aqueous fluids, they can also be used to purify other polar solvents.

Manipulating surface charge

Until the late 1960s, all commercially available EPF filter sheets were derived from a mixture of cellulose-asbestos fibers, or asbestos-based filter precoat mixtures, and were used for final polishing and sterilization. These filter media were developed in Germany by the Seitz brothers early in 1890 by chemically treating asbestos powders and asbestos fibers and mixing them with other fibrous substances (for example, cellulose). The unique filtration properties of asbestos depended on its electropositive surface charge. In the late 1960s, asbestos was beginning to be recognized as a potential health hazard, and the U.S. Food and Drug Administration (FDA) issued regulations in 1975 in response to increasing concerns over the use of asbestos-based filter media in the pharmaceutical industry.

An evaluation of asbestos had given strong indication that the unique filtration properties of asbestos depended on its electropositive surface charge. Wnek [*7*], using the electrokinetic perspectives of colloidal chemistry, proposed that asbestos owed its unique filtration characteristics to the strong positive surface charge that it possessed at neutral and lower pH. He further proposed an operative filtration mechanism for such positively charged filter media that consisted of electrokinetic capture (via attractive double layer interaction) and adsorption of negatively charged particles, which in turn resulted in modification of the surface charge on the media from positive to negative.

Companies worked to find replacements for asbestos-based filters. In the early 1980s, Cuno Inc. (Meriden, Conn.; www.cuno.com) developed and introduced a line of membrane filters, known as Zetapor media. The media was produced by the application of a coating and a charge-modifying agent to the surface of the filter media. These additions were designed to enhance the removal of bacteria. Cuno applied for and was subsequently issued patents for its Zetapor filters to Ostreicher (U.S. Patent 4,473,474).

Pall Corp. (Port Washington, N.Y.; www.pall.com) developed and began to market its own charge-modified membranes in 1982, known as co-cast Posidyne membranes (U.S. Patent 4,340,479). Significant success was achieved in removing both viruses and bacterial endotoxins by use of the charge-modified filter medium, and it appeared that such enhanced performance could also be achieved with a charge-modified polymeric membrane. The new nylon membrane charge-modified filter media were based on the unique morphology and surface chemistry of nylon (U.S. Patent 4,473,474) and the very specialized requirements of the pharmaceutical industry (low organic extractions) and the semiconductor industry (low-ionic extractions).

EPFs and zeta potential

Table 1 shows several types of commercially available electropositive filters. In virtually all cases, the filter is constructed into cartridges using non-woven filter media that carries a charge agent that can be organic (carboxyl and amine), cationic polyelectrolytes, or inorganic (aluminum

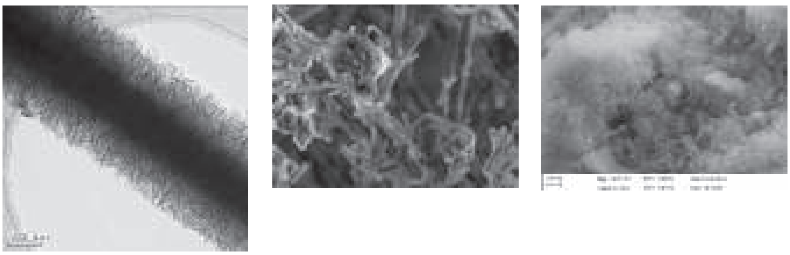


FIGURE 1. These micrographs show nanometer-scale features on electropositive filters (left); adsorbent particles incorporated into electropositive filter media (center); and aluminized particles of diatomaceous earth used as a sorbent (right)

oxy-hydroxide). The inherent charge gives such filters their primary benefit, being able to filter sub-micron particles out of aqueous solutions, some with an efficiency equivalent to ultraporous membranes, but at a fraction of the head pressure required of membranes.

Zeta potential, ζ, is a measure of the inherent charge that attracts and retains contaminants. Figure 2 compares zeta potential values of the above-described EPF media as a function of pH. It is important to note that only four media have zeta potential values greater than 25 mV in a very wide pH range from pH 3.0 to pH 9.5. In general, a value of 25 mV (positive or negative) can be taken as the arbitrary value that separates low-charged surfaces from highly charged surfaces [*8*].

Aluminum hydroxide coatings

Diatomaceous earth (DE) is a high-surface-area siliceous sorbent that has been extensively used as a filter media and as mechanical filter aid in water purification. DE consists of the skeletal remains of diatoms, and is composed primarily of silica. This very fine powder is calcined to form larger particles so as to reduce pressure drop. Precoats of DE are used as a filter aid in filter systems to collect particles as small as several microns.

In current use, DE particles are accumulated on a septum as a precoat and separation of suspended solids is accomplished by size exclusion. After first depositing a precoat, additional DE is injected into the body fluid and serves as a filter aid. After reaching pressure drop limitations, the spent bed is backwashed and replaced with a new precoat. This technique is instrumental in meeting U.S. Environmental Protection Agency (EPA) guidelines for removing *Cryptosporidium* cysts in many municipal water treatment plants. Nevertheless, the precoat method has many disadvantages, one of which is that particles (such as bacteria and virus) that are smaller than the pore size of the DE bed will permeate the bed and contaminate the water.

In 1936, Cummings described the treatment of DE to produce an electropositive, insoluble aluminum hydroxide coating (U.S. Patent 2,036,258). Such treated DE, when used as a filter aid, acted as a flocculant for colloidal contaminants. Lukasik and others [*9*] and Truesdail and others [*10*] describe a coating formed on the surface of DE and sands via the reaction shown in Equation (1):

$$AlCl_3 + 3NH_4(OH) \longrightarrow Al(OH)_3 + 3NH_4Cl \quad (1)$$

However, in the cases referenced here, the amount of aluminum compounds formed on the support material was less than 10% of the final filter aid [*9*]. A reason for the low amount of aluminum oxide-hydroxide coatings is the use of inorganic or organic (or both) salts that inhibit growth of the resulting coatings. As a result, the zeta potential had been changed from highly electronegative (approxi-

TABLE 2. FILTER CHARACTERISTICS AND VIRUS RETENTION OF OTHER DEPTH MEDIA VS TWO LAYERS NANOAL AND NANOAL-PAC						
Media	**Pore size, µm**	**Thick-ness, mm**	**Basis weight, g/m²**	**Challenge water**		**MS2 removal, LRV[b]**
				pH	TDS[a] g/L	
NanoAl	2.0	1.6c	440c	7.0	0	6.0
				8.5	0	5.5
				7	30	4.8
				8.5	30	4.1
NanoAl -PAC	2.0	1.6c	440c	7	0	>6.5
				8.5	0	>6.4
				7	30	>6.6
				8.5	30	>6.4
Type A1	3.6	1.2[c]	210[c]	7	0	2.1
				9.5	0	0.4
				7	30	0.02
Type A2	5.0	5.0	1,140	7	0	0.7
				8.5	0	0.1
				7	30	0.1
Type A3	1.1	3.8	1,280	7	0	>6.5
				8.5	0	1.2
				7	30	0.2
Type B	0.6	2.6	1,430	7	0	>6.6
				9.5	0	5.2
				7	30	0.3
Type C	1.3	4.1	1,480	7	0	5.1
				9.5	0	0.1

Notes: a) Total dissolved solids; b) logarithm removal value; c) two layers

mately –70 mV) to electroneutral for coated DE [*9*].

Introducing nanoscale features

Nanotechnology has been extensively embraced in membrane filters, where pore sizes have extended from microporous (0.08–2 µm) to ultraporous (0.005–2 µm) and down to nanoporous membranes. Nanotechnology has been employed with membranes that are planar or hollow fiber and of varied compositions, including with compositional and porosity variations across the membrane wall. The advent of nanoscale engineering in the late 2000s offered a new avenue for introducing surface-charge characteristics to membranes and to non-woven EPFs.

For example, in 2003 and 2014, two water-filtration technologies were introduced for removing microorganisms based on coating of siliceous support materials, such as microglass [*11*] and DE [*12*], with nanometer-sized alumina (nanoAl; monocrystalline aluminum oxide hydroxide, also known as AlOOH or $Al_2O_3{\cdot}H_2O$) layers. In this type of EPF, the high surface area of siliceous support material (DE or microglass) serves as a catalyst in the course of the aluminum-alkaline water reaction. The reaction is unique because only two substances are involved (aluminum and water), resulting in pristine nanoAl boehmite coating of the support material according to Equation (2):

$$2Al\ (solid) + 4H_2O\ (liquid) \longrightarrow Al_2O_3{\cdot}H_2O\ (solid) + 3H_2\ (gas) \qquad \textbf{(2)}$$

The coating formed by Equation (2) is crystallographically different from that formed by Equation (1). In Figure 1, conventional transmission electron microscopy shows an amorphous-appearing coating, that was determined to be 1.2 nm thick, deposited on the high-surface-area (50 m^2/g) disordered DE structure. It was ultimately deduced by X-ray powder diffraction data, supplemented by microscopy, and infrared spectroscopy to characterize it as the synthetic nanoAl surface described in Equation (2). The nanoAl, with a thickness of approximately 1.2 nm, is electroadhesively deposited onto siliceous support material with specific surface area of about 50 m^2/g.

Figure 1 (left) is a transmission electron micrograph showing nanoAl fibers, the active electropositive ingredient in this type of non-woven filter media. The nanofibers (that appear as a fuzz) are only 2 nm in diameter and are dispersed and attached to a 0.6-µm diameter microglass fiber. The composite is then combined with polymer fibers and formed into a nonwoven media by wet processing. The water filter's pore size is approximately 2 µm and

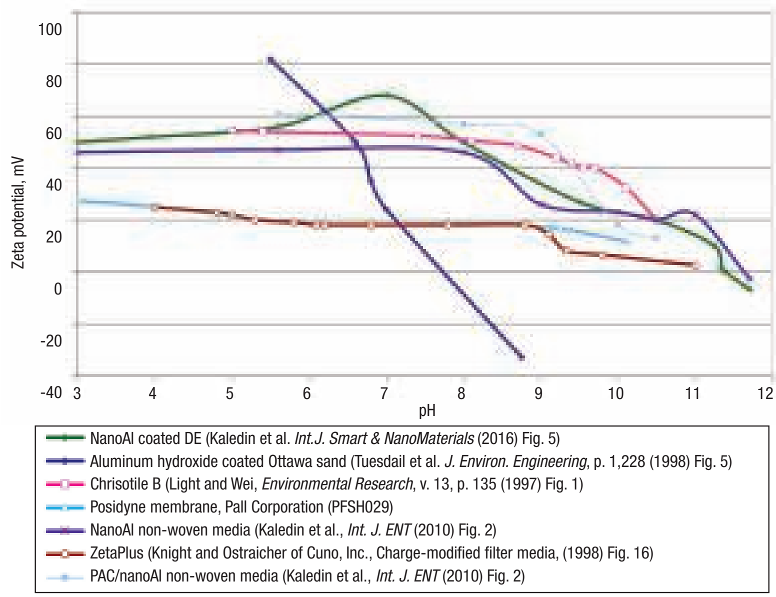


FIGURE 2. Zeta potential values, such as those shown here for commercially available EPFs, vary under different pH conditions

SILT DENSITY INDEX

Silt density index (SDI) is a sensitive method for determining the ability of a filter to remove colloidal particles. SDI is used extensively as a criterion in minimizing fouling of reverse osmosis membranes. The lower the SDI value, the cleaner the stream. EPFs can be used to pretreat water before it enters RO membranes. Pretreatment with EPF reduced nanoparticle fouling of microfiltration (MF) membrane by about 2% (with pretreatment), as compared to 80% (with no pretreatment) [*6*].

Manufacturers of RO membranes recommend that the stream be prefiltered so that it has an SDI factor less than 3.0. Typically "1-μm absolute" [*14*] filters have an SDI of about 4 to 5. Manufacturers of hollow fiber membrane filters claim SDIs in the range of 1.75 to 2.25. SDI measurements of effluents from the media with nanoscale alumina features media range from 0.5 to 1.0. Turbidity as well as SDI tests have confirmed that the extent of shedding of nanoscale particles from the nano-alumina-type filters into effluent streams is minimal.

the media thickness is 0.8 mm.

The high surface area of the nanoscale alumina fibers, plus their high zeta potential, produce strong electrostatic and electrokinetic fields that influence the flow of particles as far as 1 μm away from the surface of the media. Zeta potential is a measure of the magnitude of the electrostatic attraction or repulsion between particles. The field therefore overlaps the flow channels of the 2-μm-pore-size media. Since the particle flows through a tortuous path of approximately 400 pores across the media, there is a high probability of particle capture.

Since the electropositive nanoAl fibers are dispersed and fixed in place via electroadhesive forces, particles have easy access to the charged surface. Powdered activated carbon (Figure 1, center) or nanoparticles such as nano-silica can be retained in the nanoAl structure. The pore size of the non-woven media is 2 μm, yet the filter can remove suspended solids as small as viruses (typically 20–30 nm in diameter) and does so at high flowrates and at salinity values up to 3.4 M of NaCl (near saturation at 300,000 ppm) and at pH values in the range from 4 to 10.

Filtering bacteria and viruses

The removal of bacteria and viruses from water in CPI applications is important for several reasons. Aside from being potentially pathogenic contaminants, microbes are also foulants in HVAC (heating, ventilation and air conditioning) and other systems. Bacteria can also play a role in corrosion (*Thiobacillus ferrooxidans* is known to feed on iron and cause corrosion, for example). Microbes also have a tendency to attach to surfaces and form biofilms, which may not be affected by disinfecting efforts, such as the use of free chlorine, even at concentrations of several ppm [*13*].

EPFs can offer a means of effectively removing bacteria and viruses

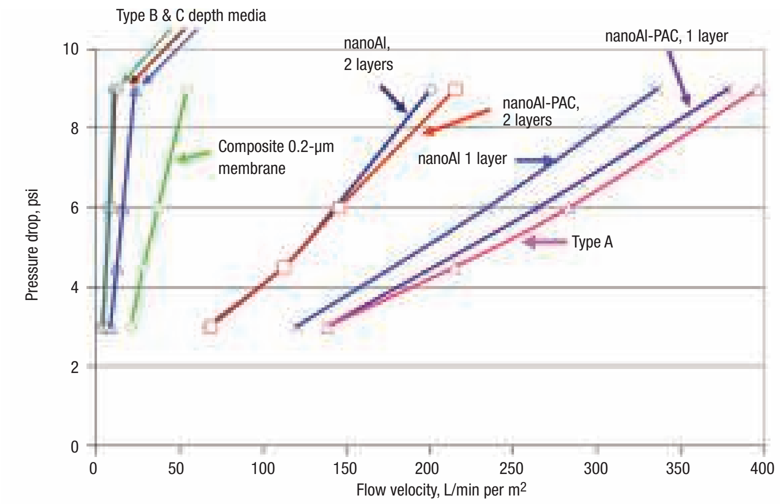


FIGURE 3. Data on the flowrates of some of the electropositive filters listed in Table 1 are shown in this graph

from water (Table 2). For example, bacteria and viruses can be retained by nanoalumina media at neutral pH. The filter retains 26-nm-sized MS2 virus (a bacteriophage) particles with high efficiency at flowrates of 1 gal/min per ft^2.

Adsorbents and EPFs

The inclusion of adsorbent materials can enhance the performance of EPFs. Adsorbents can be introduced into filter media during the manufacture of the mulch (material that will become the nonwoven filter) and then dried to produce paper media. It is pleated to form cartridges. PAC can be added for chlorine or organic adsorption and is most often used for applications involving drinking water. Other sorbent materials, such as amorphous titanium silicate, may be added for lead removal, or silver zeolite can be added as an antimicrobial agent. The aluminized DE is a reaction of aluminum powder with DE, which is dried to form a sorbent.

Electropositive adsorbents have an inherent charge that retains electronegatively charged particles. Since most bacteria and most other contaminants encountered in nature are electronegatively charged in water, such sorbents can filter suspended solids. A notable exception is the fr bacteriophage (one of the few particles that are electropositive in the acceptable pH range for drinking water — it is electropositive at pH less than about 8.9–9.0).

The use of EPFs for filtration offers the possibility of removing soluble materials, such as heavy metals, endocrine disrupters, pesticides, algae toxins and PCBs from water because such filters can support sorbent materials. In the case of nanoAl-coated EPFs, the filtration mechanism is believed to be the result of the electrostatic field inherent in the nano-alumina, which causes polarization of those compounds that have high dipole moments.

Powdered activated carbon (8-µm average particle size) embodied into non-woven nanoAl has proven to be very successful in drinking water applications.

The media shown in Figure 1, center, consisting of nanoAl that contains ultrafine (8-µm) PAC particles, has also been characterized for its ability to retain metal and particles. Its retention of colloidal and suspended solids, including bacteria and virus, were found to be equivalent to the non-PAC filter.

EPF media offers a unique way to facilitate the use of new nano sorbents by embodying them into new structures that could result in high dynamic adsorption media, much as was achieved with PAC in nano-Al. Experimental procedures used by the authors for development of novel media involve the preparation of non-woven handsheets, 12 × 12 in., embodying the test sorbent. Discs (25-mm dia. × 1-mm thick) are punched out and mounted in 25-mm-dia. filter holders (Pall Syringe filter, VWR part #28144-109), each of which can hold up to three discs. The mounted filters can be tested individually or by stacking them in series. Significant adsorption and hydrodynamic data can be derived on the use of novel sorbents embodied in thin layer structures.

DE can be coated with AlOOH to produce an electropositive filter media (known as DEAL). Quantities of DEAL can be mixed with test sorbents. This scheme is particularly advantageous where the sorbent particles are sub-micron in size. Distributing it over a coarser DEAL particle bed allows better access to the fluid stream and less pressure drop.

Pleating and flowrate

Filtration often involves tradeoffs between filtration efficiency and flowrate. Engineers must determine the optimal performance for both depending on the requirements of a particular application. One of the key factors determining the design and form of filters is the ability to achieve increased effective filtration area that will facilitate scaling and speeding up of a filtration process [*15*]. The primary motivation for developing pleated membrane cartridges is the need for increased filter area to lower applied differential pressures. Pleating also has an added benefit in that less plant space needs to be allocated for filter installations.

For nonwoven filters, the thickness of the filter also plays a role in whether it can be pleated or not. Figure 3 shows flowrate data for several electropositive depth media including some of those listed in Table1. ■

Edited by Scott Jenkins

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Rapid Prediction of Prandtl Number of Compressed Air

Two methods are presented and compared for quickly calculating this important, yet neglected parameter

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NOMENCLATURE

A	Tuned coefficient	*N*	Number of the points
ANN	Artificial neural network	*O*	Predicted value
B	Tuned coefficient	*P*	Pressure, kPa (abs)
B_P	Back-propagation	Pr	Prandtl number
b_m	Bias term	RNN	Recurrent neural networks
C	Tuned coefficient	r_m	The linear combiner output
D	Tuned coefficient.	SOM	Self-organizing maps
F	Activation function	*T*	Target value
f	Function	*T*	Temperature, K
FF	Feed-forward	*x*	Input signal of neuron
LM	Levenberg-Marquardt	*y*	Data point
M	matrix row index for m × n matrix	y_m	The neuron's output signal.
N	matrix column index for m × n matrix	w_{mn}	Synaptic weight

Over the last few decades, a considerable effort has been directed to toward the evaluation of thermo-physical and transport properties of air for a wide range of temperatures. However, relatively limited attention has been given to investigation of the compressed air Prandtl number at elevated pressures.

In this article, two new approaches for the accurate prediction of Prandtl number (Pr) of compressed air are presented. The first approach is based on developing a simple-to-use polynomial correlation for predicting Pr of compressed air as a function of temperature and pressure. The second approach is based on the feed-forward back-propagation (FF-BP) artificial neural network (ANN) methodology, wherein the results demonstrate the ability of the presented ANN method to predict accurate Pr values of air at elevated pressures. A comparison of the two approaches indicates that the developed ANN-based model provides slightly more accurate results than the new empirical correlation.

Introduction

The development of methods for evaluation of air properties was the subject of a number of earlier investigations, which were employed to conduct property evaluation calculations at specific temperature regions of interest in a certain range of scientific and technological applications, such as metrology, calibration and for air conditioning. These scientific fields of application and the corresponding investigations have been, for the most part, limited to relatively low temperatures, although Melling and others [*1*] investigated air properties in the temperature range be-

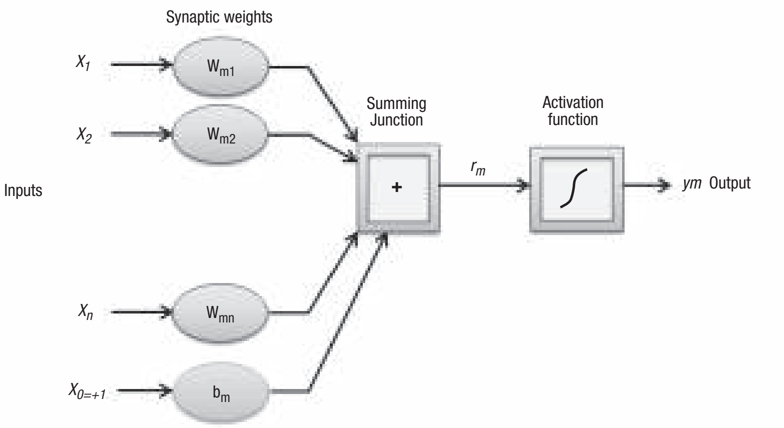

FIGURE 1. Shown here is a typical model of an artificial neuron [*12*]

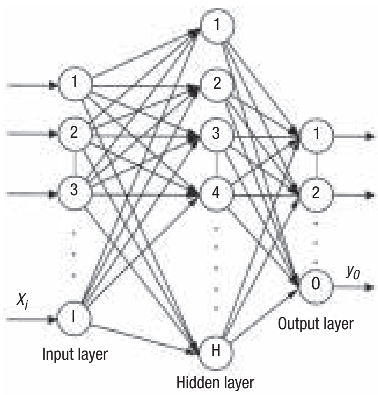

FIGURE 2. An illustration of a simple three-layer feed-forward ANN [*12*] is shown here

tween 100 and 200°C.

However, the knowledge of properties over a wide temperature and pressure range is vital for other fields, such as drying, to allow accurate prediction of heat and mass transfer phenomena during the physical processes involved.

Prandtl number. The Prandtl number is a dimensionless number approximating the ratio of momentum diffusivity (kinematic viscosity) and thermal diffusivity, as shown in Equation (1), with all nomenclature presented in the box on p. 52):

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{C_p}{k} \quad (1)$$

Unlike the Reynolds and Grashof numbers, the Prandtl number contains no length scale in its definition, so Pr is dependent only on the fluid involved and the state of the fluid. As such, Prandtl numbers are often found in property tables alongside other properties such as viscosity and thermal conductivity.

Over the years, considerable research efforts have investigated free and forced convection. However, according to the authors' knowledge, there is no simple-to-use correlation to rapidly estimate Pr of compressed air at elevated pressures. This is important because Pr is widely used in heat transfer and calculations related to convection [*2–5*].

With this in mind, two tools are presented below for predicting Pr over a wide range of temperatures and pressures. The first, an empirical correlation, can be used to quickly and easily estimate a value of Pr for air. The second method is based on a multi-layer perceptron (MLP) type of artificial neural networks (ANNs), which is shown to be able to accurately predict the Pr of air over a wide range of temperatures and pressures.

Empirical correlation

The empirical correlation presented here has been tuned using a widely accepted methodology described in the literature. The empirical data required to develop this correlation includes the reported data [6] for the Pr of air as a function of pressure and temperature (K).

Equation (2) represents the proposed governing equation in which four coefficients are used to correlate the Prandtl numbers of air as a function of temperature (expressed in Kelvin) and pressure (kPa), with the corresponding coefficients listed in Table 1.

TABLE 1. TUNED COEFFICIENTS USED IN EQUATIONS (3–6)

Coefficient	Value	Coefficient	Value
A_1	–2.60209064	A_3	3.5995496368
B_1	–4.64712011	B_3	–1.5920349698
C_1	–3.17817228	C_3	–2.224437123
D_1	2.88726660	D_3	1.8214824677
A_2	–1.145969902	A_4	–2.930937692
B_2	4.810244580	B_4	2.32398913631
C_2	4.902744144	C_4	3.17489914017
D_2	–4.240021674	D_4	–2.428258824

$$\ln(\mathrm{Pr}) = a + \frac{b}{T} + \frac{c}{T^2} + \frac{d}{T^3} \quad (2)$$

Where:

$$\mathrm{a} = A_1 + B_1 P + C_1 P^2 + D_1 P^3 \quad (3)$$

$$b = A_2 + B_2 P + C_2 P^2 + D_2 P^3 \quad (4)$$

$$\mathrm{c} = A_3 + B_3 P + C_3 P^2 + D_3 P^3 \quad (5)$$

$$\mathrm{d} = A_4 + B_4 P + C_4 P^2 + D_4 P^3 \quad (6)$$

These optimized, tuned coefficients are applicable for calculating the Pr of air for temperatures up to 1,000K and pressures up to 10,000 kPa. If more data become available in the future, the coefficients in Table 1 can be quickly retuned according to the approach outlined here. In order to obtain the values of the coefficients for the new empirical method, the following procedure has been applied:

1. The air Pr is correlated as a function of temperature for the selected pressure.
2. Step 1 is repeated for other pressures.
3. The corresponding polynomial constants, which were obtained for various Pr of air versus temperature, are then correlated.
4. The Pr of air at any temperature and pressure can then be calculated from Equation (2).

Equation (2) and its coefficients provided in Table 1 is believed to be the first simple-to-use correlation for quickly predicting Pr of air over a wide range of temperatures and pressures. Furthermore, the exponential function that was selected to develop this tool leads to well-behaved (that is, smooth and non-oscillatory) equations enabling fast and accurate predictions.

Neural-based model

Overview of ANNs. Briefly, ANNs are constructed of simple processing elements, known as neurons, in a parallel computational algorithm. The neurons are inspired by biological nervous systems. Figure 1 shows an artificial neuron. The mathematical representation of a neuron, *n*, is given by Equations (7) and (8).

$$r_m = \sum_{i=1}^{n} \left(w_{mi} x_i + b_m \right) \quad (7)$$

$$y_m = F(r_m) \quad (8)$$

Where $x_1, x_2, \ldots, x_n$ indicate the input signals; $w_{m1}, w_{m2}, \ldots, w_{mn}$ denote the synaptic weights; r_m is defined as the linear combiner output; b_m is the bias term; *f* is the activation function used; and y_m is the neuron's output signal.

ANNs are robust types of computational intelligences with the ability to express non-linear and complex relationships. This is done by using several input-output training patterns from introduced datasets to the network. A nonlinear mapping between inputs and outputs is provided intrinsically by ANNs [*7, 8*]. ANNs have primarily been used by investigators for pattern recognition, classification, and prediction [*9, 10*].

Among the wide variety of ANN types and architectures, such as recurrent neural networks (RNNs), feed-forward neural networks (FFNNs), and self-organizing maps (SOMs), most investigators use FFNNs. Most believe that FFNNs, including functional link networks (FLNs), radial basis function networks (RBFNs) and MLPs, are the most potent, versatile and trustworthy nonlinear classifier recognizers

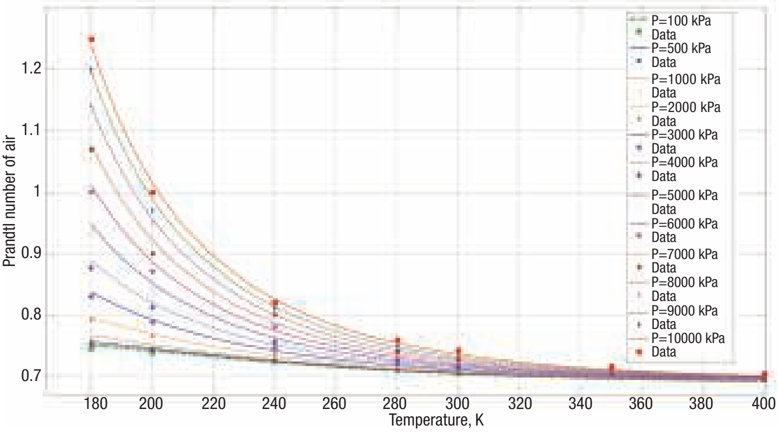

FIGURE 3. A comparison of the Air Prandtl number calculated by Equation (2) with reported data [*6*] as a function of pressure and temperature

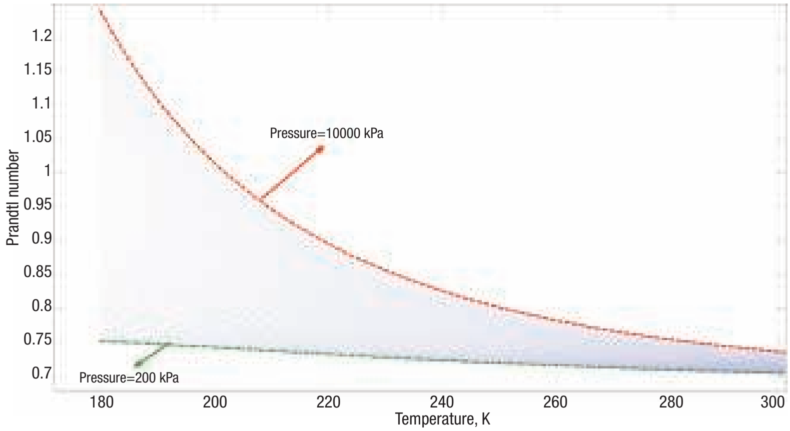

FIGURE 4. This graph shows the behavior of Pr calculated with Equation (2) as a function of pressure and temperature

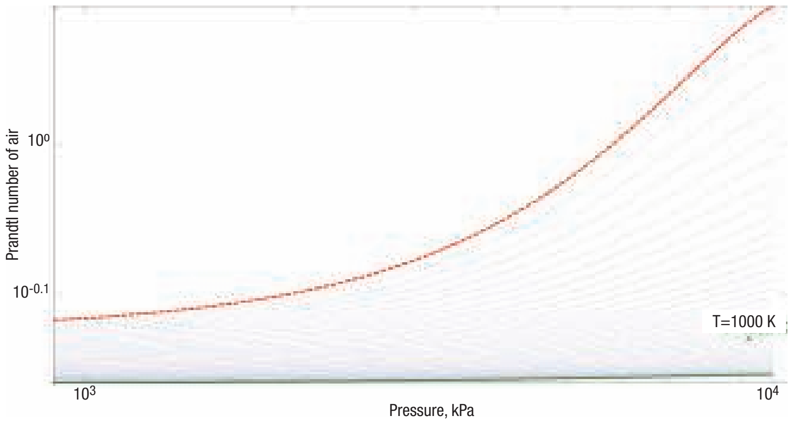

FIGURE 5. Another viewpoint of the calculations shown in Figure 4

[*11*]. Figure 2 shows a schematic diagram of a three-layered MLP neural network with *I* input branching nodes, *H* neurons in the hidden layer, and *O* output neurons.

A proper learning algorithm must be employed to construct a MLP neural network model. Amidst available learning laws, the most practical one is known as the back propagation (BP) learning algorithm [*12*]. The procedure of the BP method is as follows: the errors following from the differences between estimations of neural network model and corresponding target values will propagate backward via the network and the values of weights and biases will be adjusted so that the error function is minimized.

In this article, the mean squared error (MSE), as defined by Equation (9), is selected as the performance criterion of the constructed network.

$$MSE = \frac{1}{N}\sum_{i=1}^{n}\left(t_i - o_i\right)^2 \qquad (9)$$

Where *N* indicates number of the points, t_i is target value, and o_i is prediction of the network.

Design of BP-ANN. With the aim of developing a neural-based model for predicting Pr of air, a feed-forward BP-ANN with single hidden layer [*8, 13*] has been employed. The BP algorithm is trained with the well-known Levenberg-Marquardt (LM) technique [*14–16*]. Hence, the values of weights and biases are updated with regard to LM optimization. The number of neurons in the input layer and output layer equals the number of dependent variables and independent variables, respectively. Based on data reported in the literature [*6*], the Pr of air is expressed as a function of pressure and temperature:

$$\Pr = f(P,T) \qquad (10)$$

The main task is to determine the optimum number of neurons in the hidden layer. As mentioned in the previous section, the objective function is MSE. With 2-H-1 form, the number of hidden neurons has been varied from 1 to 10 and the capability of each network in predicting Pr has been measured. It should be noted that the transfer function used in the hidden layer is a log-sigmoid. For the output layer, a linear transfer function is employed.

To develop the neural-based model for the application of interest, a total number of 175 data sets have been collected from Ref. 6. Before training the networks, the database was separated into three subsets randomly: training data set (70%), validation data set (15%), and test data set (15%). The network adjusts the values of biases and synaptic

weights by employing the training subset. The allocated data points for the validation are used to avoid over-fitting. The performance of the constructed network is evaluated by measuring the differences between the predictions and corresponding target values of test subset.

Model evaluation

The empirical correlation. Figure 3 compares Pr values of air calculated from Equations (2–6) as a function of pressure and temperature with the reported data [6]. It is evident from the figure that there is a good agreement between predicted values (for pressures up to 10,000 kPa and temperatures up to 1,000K and the reliable data [6]). Figures 4 and 5 show the behavior of Equation (2) from two different viewpoints. Figures 4 and 5 show that pressure itself has a major effect on the Pr of air at temperatures less than 350K but for air temperatures higher than 350K, pressure does not have a large affect on Pr.

The tool developed in this study can be of immense practical value for engineers and scientists who need a quick check on the compressed air Pr at various conditions without opting for any experimental measurements. In particular, engineers would find the approach to be user-friendly with transparent calculations involving no complex expressions.

The BP-ANN. Figure 6 shows the obtained values for MSE as an objective function versus the number of neurons in the hidden layer. As can be seen from Figure 6, the optimum number of hidden neurons is 10, where MSE is minimum. Hence the best network topology for accurate prediction of Pr as function of pressure and temperature is 2-10-1 (two input neurons, ten hidden neurons, one output neuron).

Figure 7 shows regression plots of the built BP-ANN comprising 10 hidden neurons as compared with measured data from Ref. 6. The correlation coefficient, R, is very close to unity (R = 1 means perfect correlation between the model outputs and corresponding target value).

Comparing the two methods. All reported data were regenerated by the new empirical correlation and the selected BP-ANN model with

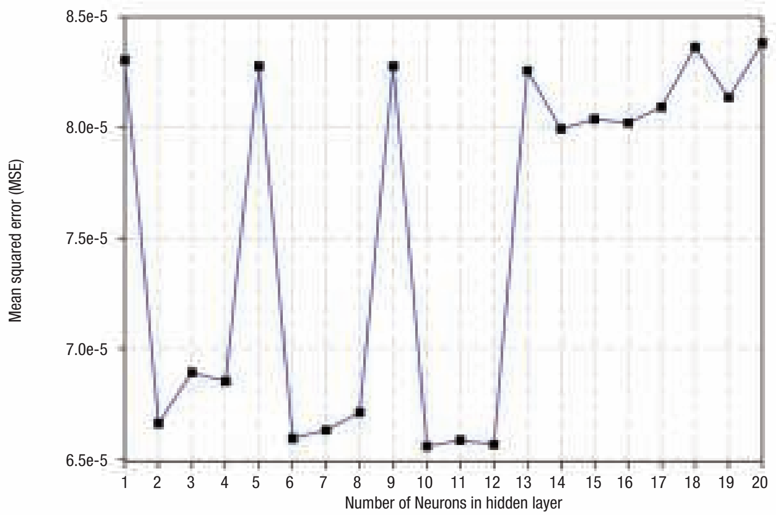

FIGURE 6. This graph shows the MSE between predictions of the constructed BP-ANNs and corresponding target values

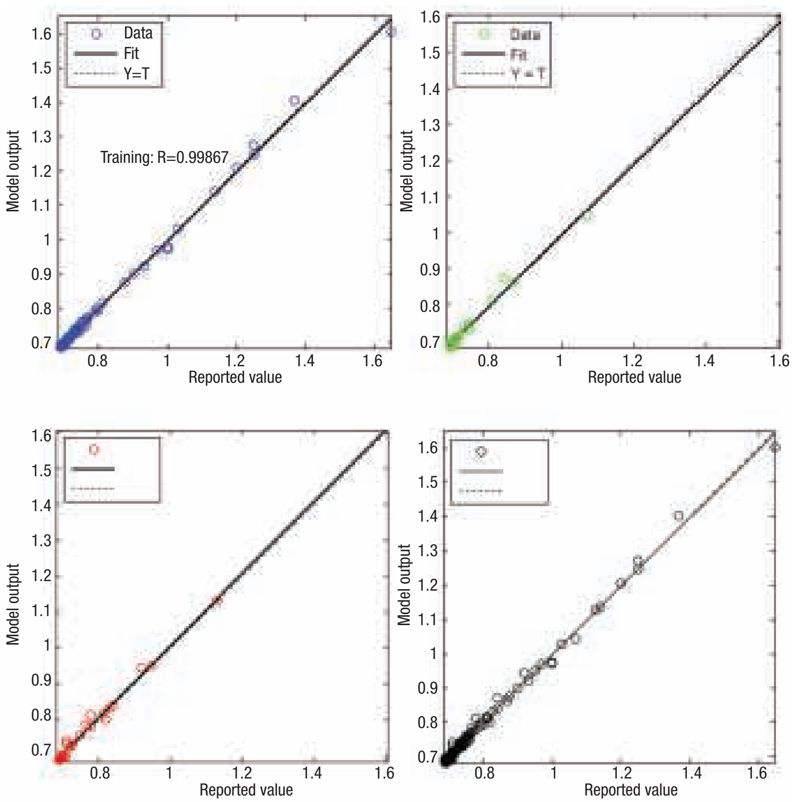

FIGURE 7. R-values for training set, test set, validation set and all the data points of the BP-ANN calculations

MSE equal to 1.11×10^{-4} and 6.56×10^{-5}, respectively. Table 2 presents the summary of accuracies with the proposed models, including the neural-based model and the mathematical expression in terms of average absolute deviation percent with reliable data [6]. One can observe that the proposed methods have average absolute deviation of around 0.64% for the empirical correlation, and 0.48% for the BP-ANN method, which are considered to be very small deviations from the

$$w_{m1} = \begin{bmatrix} 0.3216 & 4.2718 \\ 0.65214 & -11.3338 \\ -4.0507 & -1.9625 \\ 3.2956 & 1.1574 \\ -3.2416 & -0.59033 \\ 2.0465 & -1.9713 \\ 3.4723 & -1.0582 \\ 2.064 & -3.7569 \\ 0.0097574 & -4.2455 \\ 2.6965 & -4.1957 \end{bmatrix} \quad b_1 = \begin{bmatrix} 5.457 \\ -12.6913 \\ 2.0199 \\ -1.6017 \\ 1.5439 \\ -0.41678 \\ 0.64223 \\ 3.2015 \\ -3.8872 \\ 3.8679 \end{bmatrix} \quad b_2 = [3.3506]$$

$$w_{m2} = \begin{bmatrix} 2.0161 & 5.9455 & -0.33876 & -0.76768 & -0.43231 & -0.042193 & 0.03252 & -0.12619 & 0.40173 & 0.10306 \end{bmatrix}$$

calculations and measured values of Pr. However, the developed BP-ANN with 10 hidden neurons gives slightly better results than the new empirical correlation. The excellent performance of the neural network model follows from a massive interconnection of neurons.

Example calculations

As an example, a calculation of the Prandtl number of air at a pressure of 5,000 kPa and a temperature of 300K is presented.

Empirical correlation. For $P = 5{,}000$ kPa and $T = 300$K, and using the coefficients in Table 1, one finds:

From Equation (3), a = –3.26808140
From Equation (4), b = –2.09774347
From Equation (5), c = –4.80707571
From Equation (6), d = 3.132981196
Plugging these results into Equation (2) gives Pr= 0.71597

The value for Pr reported in the literature [6] is 0.721, which shows good agreement between predicted value and reported data.

BP-ANN method. To solve the same example using the BP-ANN with optimum hidden neurons requires the biases and weight values. The bias and weight terms to layers 1 and 2 (b_1, w_{m1} and b_2, w_{m2}) are given in the box above. These matricies are used as input to Matlab for calculating the value of Pr at 300K and 5,000 kPa, which gives a value of 0.718 (with MSE = 6.32×10^{-6}). This corresponds well with the literature value [6] of 0.721. ■

Edited by Gerald Ondrey

TABLE 2. COMPARISON OF PREDICTED PR WITH DATA FOR COMPRESSED AIR

Temperature, K	Pressure, kPa	Air Prandtl number			Percent absolute deviation	
		Reported data [6]	Empirical correlation	BP-ANN	Empirical correlation	BP-ANN
200	100	0.738	0.7417	0.7353	0.51	0.36
600	100	0.690	0.6943	0.6933	0.63	0.47
200	500	0.743	0.7452	0.7415	0.29	0.19
600	500	0.690	0.6944	0.6933	0.63	0.47
300	1,000	0.708	0.7059	0.7082	0.29	0.02
700	1,000	0.695	0.6982	0.6976	0.46	0.22
280	2,000	0.717	0.7141	0.7168	0.40	0.02
800	2,000	0.704	0.7019	0.7036	0.29	0.04
300	3,000	0.715	0.7103	0.7112	0.65	0.53
900	3,000	0.708	0.7046	0.7063	0.48	0.23
180	4,000	0.876	0.8880	0.8714	1.36	0.51
1,000	4,000	0.71	0.7060	0.7064	0.56	0.49
200	5,000	0.841	0.8519	0.8343	1.29	0.78
350	5,000	0.707	0.7026	0.7014	0.62	0.77
240	6,000	0.78	0.7745	0.7786	0.70	0.16
400	6,000	0.699	0.6984	0.6954	0.08	0.51
350	7,000	0.711	0.7057	0.7115	0.73	0.07
450	7,000	0.694	0.6972	0.6894	0.46	0.65
300	8,000	0.732	0.7267	0.7432	0.72	1.52
500	8,000	0.691	0.6972	0.6944	0.89	0.48
350	9,000	0.714	0.7090	0.7097	0.70	0.59
600	9,000	0.690	0.6981	0.6984	1.17	1.20
350	10,000	0.716	0.7107	0.7113	0.73	0.64
700	10,000	0.695	0.6995	0.6897	0.65	0.75
Average absolute deviation per cent (AADP)					0.64%	0.48%

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Vortex Breakers in Practice

When vortex formation limits outflow from a tank, consider a disc-type vortex breaker

Jim Gregory and Katy Lentz
Fluor

Chemical engineers have long said that, while it is easy to get liquid into a tank, it can be difficult to get liquid out. Large line sizes or high-pressure pumps can fill tanks at any desired rate. Tank drainage rates, in contrast, are strictly limited by vortex formation. High-powered pumps cannot increase the drain rate because a vortex extends into the outlet nozzle and blocks the flow. The vortex is caused by the Coriolis effect.

Coriolis forces and the resultant vortex formation are widely misunderstood because they are not well described in chemical engineering textbooks or other information sources. The Wikipedia entry for Coriolis force actually includes a Simpsons TV show episode as a reference. As a result, some explanation is in order.

Coriolis force, like centrifugal force, is sometimes referred to as a "fictitious" or "pseudo" force. This does not mean these forces are in any way unreal. It just means that they derive from changes in our frame of reference, rather than from matter and energy, which give rise to forces like gravitation and electromagnetism. Coriolis force causes a moving object to deflect in the horizontal plane when viewed in a rotating frame of reference (Figure 1).

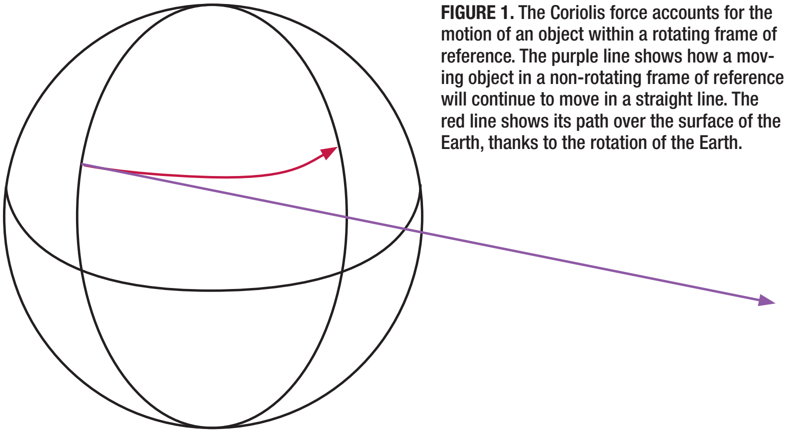

FIGURE 1. The Coriolis force accounts for the motion of an object within a rotating frame of reference. The purple line shows how a moving object in a non-rotating frame of reference will continue to move in a straight line. The red line shows its path over the surface of the Earth, thanks to the rotation of the Earth.

When liquid drains from a tank, a vertical column of liquid in the center moves down toward the outlet of the tank while the surrounding liquid moves inward horizontally to fill the void. The liquid moving horizontally is subject to Coriolis force, which causes it to rotate. The vortex speeds up because the Coriolis force continues to push the flow faster and away from the center.

Figure 2 shows how the Coriolis force always acts at right angles to the direction of flow, and never points towards the outlet nozzle. Unlike gravity, which is independent of velocity, the Coriolis force increases with velocity. The result is an "acceleration of acceleration", limited only by fluid viscosity. For water, within half a minute the whole batch is rotating at about one revolution per second.

The angular momentum of the fluid is the product of the mass of the fluid, its velocity, and its distance from the center of the tank. Due to the conservation of angular momentum, radius and velocity are inversely related. As the fluid moves inward toward the center outlet, the radius of rotation decreases and so the velocity increases, increasing the rotation rate. Soon, the cone of the vortex extends down to the outlet nozzle and blocks it (Figure 3).

In applications where drain rate is not important, vortex formation is usually not a problem. But there are many applications where the drain rate is important. In those applications, a vortex breaker is required.

Another negative outcome of operating with a vortex is gas entrain-

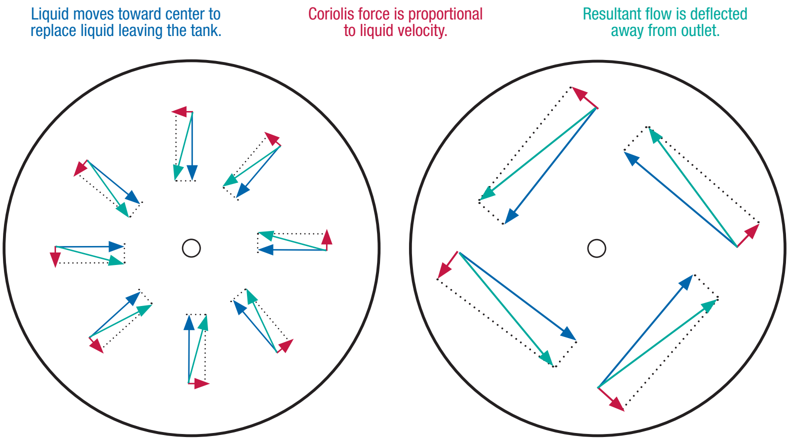

FIGURE 2: As liquid drains from a tank, the Coriolis force acts at right angles to the flow direction and so sets up a vortex motion

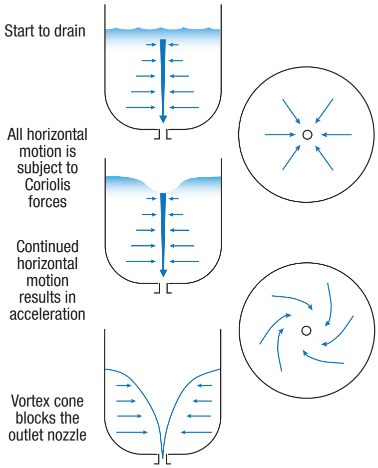

FIGURE 3: In a tank without a vortex breaker, a vortex will form and quickly grow to the point where it obstructs flow from the bottom outlet

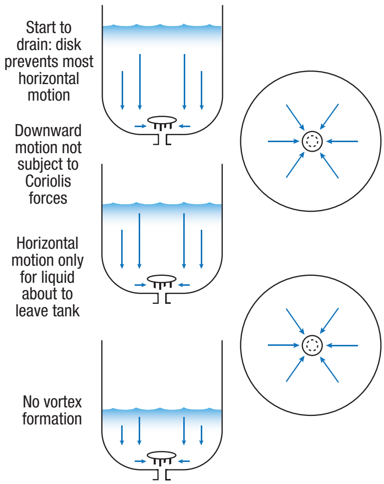

FIGURE 4. Disc-type vortex breakers work well and do not create undue flow restriction as long as they are suitably positioned

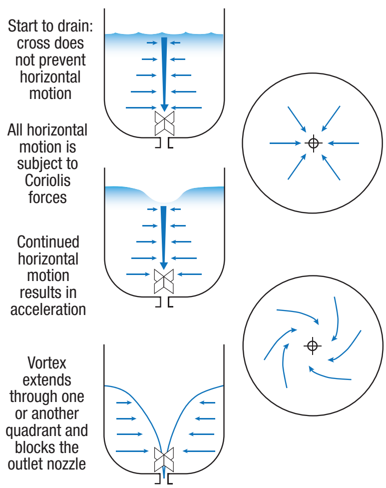

FIGURE 5. Small cross-type vortex breakers do not work in practice because they have no influence on vortex formation in the main part of the tank

ment. Gas from above the liquid can be drawn down into the vortex, reducing the capacity of the discharge pump and affecting the performance of processes downstream.

A further problem is reduced cleanability of the tank. Food and pharmaceutical manufacturers have strict requirements for flowrates in clean-in-place (CIP) applications. Typically a spray ball must supply about 3 gal/min per foot of tank circumference (40 L/min per meter) to ensure good cleaning performance. To prevent liquid holdup, which could allow dirt to accumulate, the discharge rate must be at least as large as this. In practice, tanks for CIP must be designed to prevent vortex formation.

Vortex breakers

A vortex breaker is installed to prevent the formation of a vortex when draining a tank. There are two types of vortex breakers: disc-type and cross-type.

Disc type. The disc type (Figure 4) acts as a baffle plate that impedes axial flow without interfering with radial flow. It is typically designed to be three times the diameter of the outlet nozzle and mounted approximately 1 in. (25 mm) above the nozzle. This design eliminates the center vertical column of flow above the disc and allows only horizontal flow in the area below the disc. As the liquid in the bottom of the tank moves horizontally towards the exit nozzle, the liquid above moves downward to replace it. The relatively small volume of liquid in the bottom dish that is moving toward the exit nozzle still experiences Coriolis force, but only for a short time since it is about to leave the tank.

Cross type. The second type of vortex breaker is the cross type (Figure 5). This is supposed to eliminate the formation of a vortex by providing a barrier to rotational flow. In practice, however, small cross-type vortex breakers mounted immediately above the exit nozzle do not work. A little thought shows why: the cross does not influence vortex formation since it impedes rotation only in the immediate vicinity of the outlet, not in the bulk of the tank, which is where the main rotational forces operate.

If you watch the draining of a tank without a vortex breaker you will see a vortex form. If the tank has a cross-type vortex breaker you will also see a vortex form. Looking down into a fully developed vortex shows that the cross has no effect whatsoever, with the vortex moving freely from one quadrant to another.

Given the prevalence of vortex formation when draining tanks, it is surprising that cross-type vortex breakers still sometimes appear in engineering designs. One reason may be a fear that the alternative disc-type vortex breaker will present too large a restriction and actually reduce flow out of the tank. This will not occur, however, as long as the flow area under the disc is greater than the area of the outlet nozzle.

In conclusion, the Coriolis effect causes liquid to rotate as it drains from a tank. Unrestricted, the liquid rotation creates a vortex which will block the outlet and limit the drain rate. In cases where a high drain rate is important, such as for CIP or to match discharge pump performance, a vortex breaker is required to prevent liquid holdup and air entrainment. Cross-type vortex breakers are not effective, so the disc type should be installed whenever a vortex breaker is required. ■

Edited by Charles Butcher

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Field Troubleshooting 101 and How to Get the Job Done

A major part of field work lies in troubleshooting problems: finding out why a system is not operating the way it is intended. This article provides guidelines for effective troubleshooting and contains many practical examples of their successful use

Thomas F. McGowan and
Dennis J. Coughlin
TMTS Associates

Effective troubleshooting in the field requires not only skillful engineering but also an equal dose of the right behavior. Together, these qualities represent a combination of "art and science" that will get the troubleshooting job done well and done quickly.

Field troubleshooting is not for everyone, but if you like a challenge, it may be for you. Troubleshooters are always in demand when equipment goes down or is not making product the way it should. They are brought in to solve problems that have defeated on-site personnel.

It is much like crime scene investigation on television. It's the engineering equivalent of detective work, tracking down the felons that are causing problems. When it is done effectively, everyone walks away satisfied.

A blend of science and art

A wise mentor once said that troubleshooting involved breaking the problem in half and breaking it in half again. His trade involved test trains for combustion gas analysis. Each train contained perhaps 20 ground glass joints, which were prone to leaks. Our mentor could have checked each one, with an average of 10 steps to find the leak. But using his heuristic, the math says we can find it in, at most, five steps (the leak is in joints 1–10 → 1–5 → 3–5 → 3 or 4 → 4, bingo!). The bigger the system, the greater the reduction in the number of steps needed to find a leak, or a break in a series wiring system (think Christmas lights), compared to a linear search.

FIGURE 1. Troubleshooting may require a variety of test equipment — some typical items are shown here

Having the right tools is important, too. They need not be expensive, but it helps if you have them in your gear bag ready to use. Figure 1 shows (left to right) a Pitot tube for flow measurement, a measuring tape, pipe-thread-to-barbed tubing adapters and connectors, a digital manometer, thermocouples and a field readout, a hand-held infrared temperature probe, a clamp-on ammeter and multimeter, a combination pressure/vacuum gage, a roll of electrical tape, and of course a flashlight. They will help you get the hard data you need to back up your hunches. One can also use bigger and more expensive tools, like the combustion test system shown in Figure 2, to provide fast feedback on what is going on inside the process. For those who want to learn about the wide variety of tools used by many trades, government training manuals and other source materials are available online [*1*, *2*].

The "art" side of troubleshooting includes being a good listener, being observant, taking time to think over information, taking action, opening things up to look at them, and being willing to get dirty to get the job done. The science side includes doing calculations, testing the system, and comparing the results to what was expected in the design.

The following is a litany of field problems encountered and solved in the experience of the authors by employing the guidelines suggested in this article.

Those pesky valves

Each type of valve has its own set of quirks, and many an engineer has learned to distrust all types. Here are two examples of ball valves that did not operate as expected.

Valve failure makes scrubber prequench inoperative. A brand-new solid-waste incinerator was failing particulate-matter stack tests, de-

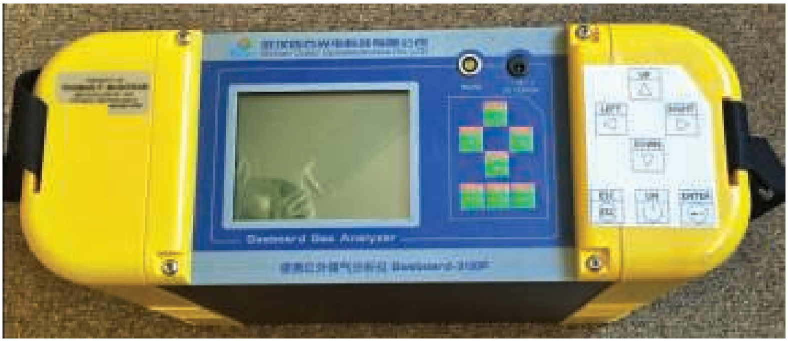

FIGURE 2. More-specialized equipment includes this portable combustion analyzer

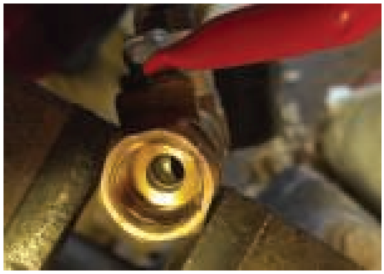

FIGURE 3. This small reduced-bore ball valve with a PTFE seat, shown here in the half-open position, is similar to the one whose broken stem caused an exhaust-gas scrubber to fail

spite being equipped with a state-of-the-art venturi scrubber and packed-tower acid-gas absorber. After three failed stack tests, we were called in to fix the problem. First step was to get the stack test data. It was horrible. Emissions exceeded the normal particulate-matter guarantee — with no air pollution control — of 0.08 grains/dry std. ft^3 (180 mg/dry std. m^3). We called the test company to ask about the M5 filter paper used in the test: what did it look like? They said it had a heavy coating of white dust. The heavy coating was no surprise, but white dust? From an incinerator? This was the first clue, since the expected color would range from brown to gray.

The white color suggested a spray-dried sub-micron salt fume from the caustic scrubber, which turns HCl into NaCl. The venturi was designed with a freshwater pre-quench to preclude sub-micron salt fume generation; the aim was to reduce the temperature to below 600°F before the gas entered the venturi throat. The venturi itself had a high flow of recirculated salt water sprayed in downstream of the pre-quench. This salt water, if vaporized, would produce the salt particles — and this was clearly happening in practice.

The venturi vendor had changed the pre-quench nozzle several times, hoping to address the issue, and finally changed the original solid-cone spray to a radial-fan spray. This was pointless, since the replacement nozzle had less time for gas/water contact and quenching than did the original. It seemed that the real problem lay elsewhere.

The piping was straightforward: fresh makeup water went to the pre-quench nozzle at a relatively steady rate to handle the adiabatic quench vaporization load (from 1,800°F down to 170°F), with feedback on flowrate provided by the level in the sump. While checking the system, we looked at the manual 1-in. quarter-turn ball valve used to fill the system with fresh water for startup (Figure 3 shows an example). We verified that the valve was closed, as it should always be during operation. Had it been open, it would have cut flow to the pre-quench via feedback from the higher sump level.

When exercised, the fill valve felt fine. While the incinerator room was hot, however, the copper pipe remained cold even though the valve was in the closed position. The only way it could be cold was if water was flowing through the "closed" valve. Indeed, the valve stem had snapped, so the fill valve was continuously adding fresh water, cutting off flow to the pre-quench and producing a spray-dried salt fume from the recycled salt water. A $15 valve swap-out solved the problem.

Stuck fuel valve creates inadvertent bypass. A second example of valve troubleshooting relates to the supply of liquid propane to two burners rated at 200 million Btu/h. The two positive-displacement pumps mounted in series produced less than the expected 250 psig output pressure. The first clue was that one pump was noisy, sounding like it was grinding rocks, while the other was comparably quiet.

The liquid propane system contained multiple quarter-turn ball valves. We made sure that those valves that could cause reverse flow and loss of pressure were all closed, and exercised them to verify their operation. All felt good except one 2-in. valve, which gave less than a solid "thunk" when closing. It did not feel quite right, and closed perhaps three degrees short of a full 90-deg swing. With these auditory and touch clues leading the way, the system was vented and the valve dismantled. A brass poppet, perhaps from a pressure control device, was found stuck inside the valve body, keeping it from full closure (Figure 4). With the foreign object extracted, the valve closed and backflow stopped. The pumps — quietly — shared the load and produced the full pressure.

Finding leaks

Leakage in and out of systems is the bane of engineers' existence, and must be minimized and eliminated. There are many ways of finding leaks, including modern ones like handheld ultrasonic leak detectors. Basic methods still hard at work, however, include soap and water solution (still required by many codes for commissioning fuel gas piping), and using your eyes, nose and ears as a guide.

Air leakage in a thermal soil-treatment plant. A client had a low production rate on a contaminated-soil treatment project in Siberia. The system had a direct-fired rotary dryer/desorber and afterburner. The first step was to get some hard data. A quick test showed 18% oxygen in the stack gas, compared to the expected value of around 7% for a tight system. Checking oxygen levels between the units pinpointed the major air leaks. Eyeballing the system found some access doors open and a shroud missing. In essence, they were heating the surrounding air rather than the process. After closing open hatches, adding some sheet metal and a bit of welding to keep out the frosty Siberian air, production went from 9 ton/h to 16–17 ton/h.

FIELD TROUBLESHOOTING REQUIRES ENGINEERING…

- Review available documents (piping and instrumentation diagrams, standard operating procedures, cut sheets)
- Review available data (tests, event logs)
- Contact vendors or use the internet to get cut sheets and parts lists
- Have the right equipment with you, and when you don't, improvise
- Break the problem into parts and isolate each issue
- Keep in mind that failure of a new component is frequently the result of its being the wrong component, or improper installation or operation
- Understand that very few of the problems encountered in process systems are truly random; if something happens more than once, there is a root cause
- Organize your work with a checklist and data sheet, and document what you have already checked out
- Change one variable at a time — isolate cause and effects from each change
- Understand the chemistry of the process as it was designed, but also of any foreign material or unexpected byproducts
- Run calculations to home in on the issues and prove or deny suspected root causes
- Get equipment model/serial number/job number nameplate data, by hand or photo
- Take good notes and always write up a trip report to close out the job

…and the right behaviors

- Actively engage the operators and maintenance personnel. Ask for their input, and be aware that all personnel have the potential to answer key questions
- Ask for help — don't let your pride get in your way
- Be persistent and unafraid to ask the "stupid" question
- Ask what happened right before any unpredicted event
- Call the original equipment designers
- Call those who installed the system
- Call those who worked previously with the system
- Routinely use senses (eyes, ears, nose and touch) in addition to your brains
- Take photos for later review
- Write up notes at the end of each day or the beginning of the next day to keep up with the data and spot errors
- Take action — don't be afraid to try things out
- Get out and around the equipment, and be willing to get dirty as you investigate
- Set aside time to think over information and discuss with others onsite
- Use the human factor to your advantage; people are a major resource of knowledge

FIGURE 4. This 1-in. long brass poppet from an unknown source became jammed inside a ball valve in liquid propane service. It stopped the valve closing fully, and so allowed backflow

Commissioning a pneumatic conveying loop. While working as a freshly minted engineer at Particulate Solid Research in New York City, one of us designed and built a pneumatic conveyor system for industrial research, made from 200 ft of Plexiglas pipe with an inside diameter of 4 in. It was instrumented with pressure taps every five feet. During commissioning, the goal was zero leakage.

The leak test method used a simple tool: a rotameter. Both ends of the conveyor pipe were capped off, and compressed air was added via a pressure regulator through the rotameter, slowly raising the pressure as leaks were found and sealed. The rotameter reading provided visual feedback on the size of the leak (for instance, an open valve, a missing pressure tap plug, or weld porosity).

Once the big leaks were found and fixed, a persistent low-level leak remained. The technicians used soap and water to check multiple Victaulic couplings used on the Plexiglas piping, the threads on pressure taps, and the valve stems — to no avail. A change in personnel and sheer persistence eventually located the felonious fitting: a Victaulic coupling in a downcomer just below a penthouse floor (Figure 5) [*3*]. The coupling's donut-like rubber gasket carried concrete chips that sliced up the rubber. With a fresh gasket, leakage fell to effectively zero. A final safety note: the compressed air approach is not acceptable for leak-testing at high pressures or large volumes, due to the amount of stored energy in these cases.

Preventing bypassing

Close cousins of leaks are bypassing problems, in which gases, liquids or solids go unexpected places inside a system. One example concerns a transportable high-temperature incinerator that processed soil contaminated with coal-tar creosote. When stack tests were run on the incinerator, two runs passed the required 99.99% lower limit for creosote destruction efficiency by a wide margin. The third test, however, showed far worse results. Interviewing the operators revealed that the failed run was "less stable" than the other two. After further consideration, the operators zeroed in on the symptom that, on that run, the draft in the kiln was not stable.

The hot solids from the 7.5 ft × 45 ft kiln exited to a rotary cooler, with the exhaust gas from the cooler being ducted to a baghouse. This exhaust should have contained only steam, air and dust. However, when the draft was momentarily unstable, CO_2 was detected in the duct as well. This confirmed that incompletely oxidized creosote vapors could bypass the oxidizer along with the CO_2. The fix was to reroute the cooler fume duct to the oxidizer inlet, thereby fully treating the fume (Figure 6).

Upstream problems

If you don't look, you don't see, and if you don't go inside, all you have is speculation. Sometimes you have to follow the process upstream to find the source of the problem.

Ionizing wet scrubber. An incinerator stack test showed particulate emissions at about 60% over

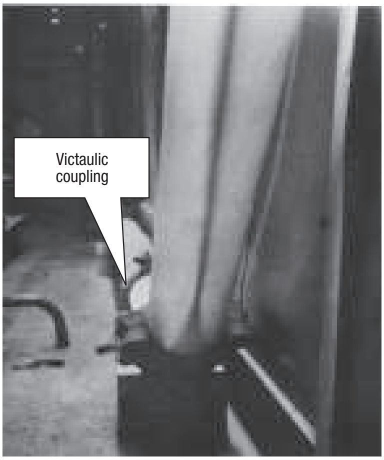

FIGURE 5. **The gasket on a Victaulic coupling on this pneumatic conveying line was cut by embedded chips of concrete, causing it to leak**

the permitted limit. Upstream was a rotary kiln and a large multi-burner oxidizer. After a pre-quench and acid gas absorber, the fume from the afterburner passed through a single-stage ionizing wet scrubber (IWS), also known as a wet electrostatic precipitator (ESP). The fume passed between grounded parallel plates, with positive charging wires between them. The charged particles would be pulled to the plates by electrostatic forces, and collected on downstream packing.

A properly set-up IWS does a very good job, removing about 84% of almost all particle types per stage. This one was not doing so. In terms of hard data, a visual examination of the M5 test filter paper showed a heavy dust coating, as expected. No news there. The high-voltage power supply showed inconsistent readings of maximum voltage, which were also lower than expected. This was the first clue, since higher voltages means better particle removal. It was time to get dirty.

Upon opening the IWS, we found thick, black, rubbery material here and there on the grounded plates. It looked much like smears of silicone rubber caulk, but with a softer, sludgier consistency. Since the plates were backwashed frequently, they should have been clean, and so the buildup was unexpected. The plate spacing was about 2 in. The buildup, which was up to ¼-in. thick, reduced the clearance between the charging wires and the grounded plates, so that short-circuits would occur at lower voltages. So we had found the cause of the low voltage and hence poor collection efficiency. But what caused the black buildup? Time to get dirty again.

Suited up, we entered the large secondary incineration chamber. We expected to see the usual white to brown refractory walls, but instead found walls that were nearly black. Walking up to the burners, we found that the large pilot burner used for startup was missing its refractory tile, whose purpose is to shape the flame and provide a point for flame attachment. Without the tile, the burner would produce a low-velocity, poorly mixed flame, atomizing the fuel but not fully burning it. Oil droplets would therefore bypass the flame and foul the IWS.

The burner tile was replaced, the

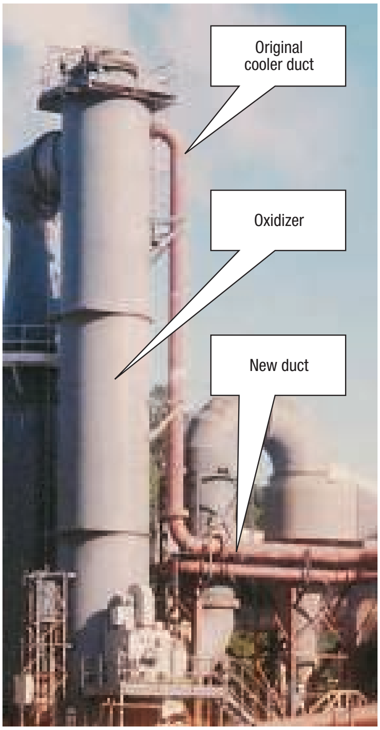

FIGURE 6. On this thermal oxidizer, under some draft conditions, incompletely treated vapors could be discharged to the stack

scrubber cleaned up, and the power supply retuned. A subsequent stack test showed particulate emissions at half the permitted limit.

A contributing issue was probably that the pilot burner was fueled with heavy No. 6 oil, whereas easier-to-burn No. 2 oil would have made more sense for cold startup. In retrospect, it would also have been a good idea to have a sight glass on the oxidizer. This would have allowed operators to see the smoking burner before it caused problems downstream.

Air-pollution-control system. A large rod bed scrubber (a variation on a venturi wet scrubber) was used to clean up combustion products downstream of a big wood-fired boiler. Unfortunately, this one was allowing more particulates than expected to escape the stack.

Suiting up (Figure 7) and looking inside revealed a buildup of particulate solids on the rod bed. We needed to head back upstream, toward the boiler, to see what might be causing the issue. The plant allowed a two-hour shutdown to gain access. A hole was cut in the steel duct, and in full harness, one of us shimmied in and slid down a 45-deg slope to check the 3,500-hp induced-draft fan. All seemed well there, but looking up into the blackness of the duct heading to the scrubber, things did not add up. There should have been three sub-ducts, separated by welded steel dividers 4-ft tall and ¼-in. thick. However, one divider had ripped loose and closed off the other two openings. As a result, almost all the flow was going into a third of the scrubber, overwhelming the water sprays and leading to buildup. There were warning signs: someone had heard a banging noise in the duct a month before, and a patch had been fitted to the high-velocity channel side due to erosion.

More missing burner tiles. An indirect-fired dryer — a three-shell, triple-pass design — had a production rate that was lower than expected. Checking burner condition is always on the list when this happens, since less heat means less driving force for drying. In addition, it is always a good idea to eyeball burners from the business end during shutdowns.

Donning safety gear and crawling along 60 ft of shell, with a tight 18-in. clearance, was made more interesting by the 9-in. flow-inducing baffles rising from below like sharks' fins and hanging from above like stalactites. Along the way, we found pieces of something — not quite metal, not quite ceramic — in the otherwise clean shell. We were rewarded at the end of the crawl, for two of the eight burners had lost their silicon-carbide tiles. Without the flame shaping and means of attaching the flame that the tiles provide, the burners had been spraying fuel oil on the inner shell, rather than burning it as planned.

Chemistry 101

Mother Nature has a wide variety of chemicals. Some are good, and some not so good.

Scrubber plugging. A client's acid-gas-absorber packing fouled and plugged, requiring twice-yearly shutdowns. We put a sample of the fouled packing in a beaker of hydrochloric acid. It fizzed and bubbled as expected, and the buildup disappeared. The buildup was a carbonate, which the acid dissolved. A simple acid wash once a year was all the scrubber needed to keep it happy.

FIGURE 7. Be willing to get dirty for confined space entry inspections

Water in your tank. A client suffered plant shutdowns soon after filling their 15,000-gal liquid-propane tank. Restart was never a problem. The seeming randomness of the shutdowns made it hard to zero in on the problem. While we were observing the offloading of propane, however, within five minutes of the truck-mounted pump starting, the plant shut down due to burner loss.

Noticing some icing on the outside of a throttling valve on one of the big burners, we did some digging into issues with propane-fired systems. It turns out that propane can contain water, the amount varying with the source of the propane, the location, and perhaps the time of year. Water has twice the density of liquid propane, so it was lying in the bottom of the tanker and passing into the storage tank when the truck pump started. The water then passed straight into the plant intake below the tank fill pipe, and from there to the burner. When the water caused the flame to flicker, the flame monitoring system cut out the burner.

The solution was more chemistry: adding alcohol to absorb the water and allow it to dissolve in the propane. Being a Sunday afternoon, alcohol supply options were slim. The quick fix was to buy two cases of an alcohol-based winter gasoline additive used to stop water from freezing in automobile fuel lines.

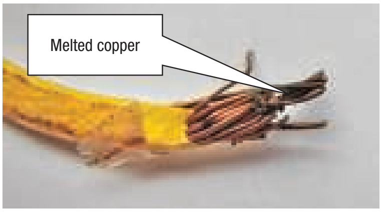

FIGURE 8. This electrical wire shows melting and arcing at the point where it was pinched inside a connection box, causing an intermittent fault

When the next tanker came in, we poured about a gallon of alcohol into the transfer hose, clamped it up, slowly opened the valves, waited, bump-started the pump once, waited, bumped it again, waited, and then pumped the load out. The plant happily hummed along. We got more alcohol in quarts from a truck stop (thanks to one of the operators who knew that it is used for truck brakes), and later a full barrel with a manual pump. With that, the problem was behind us.

Electrical issues

Power is critical to making a plant run, from the three-phase 460 V that powers motors all the way down to milliamp circuits for instrumentation. A multimeter and clamp-on ammeter come in handy when troubleshooting, but as always, people can be even more important than tools.

Pinched wire. A fuel supply pump would shut down randomly, and similarly refused to start on a random basis. The problem had gone on for a while and was growing worse, shutting down an entire plant. We worked with the electricians, who raised the motor amp trip level and changed out breakers, but with no success. The problem appeared to lie between the motor control center and the motor itself. Then the human factor took the stage. When the electrician was told we had to re-pull 500 ft of wire, his brain sprang into action. He said he knew where to look, and found a pinched wire in the cast-steel connection box on the motor. The cover had clamped the wire. A close look at Figure 8 shows where some of the copper has melted from repeated arcing. With wires trimmed back and packed in appropriately, the pump motor — and the client — were happy again.

A bad switch. Switches are a bit like valves. Normally they are dependable, but infrequently they can turn out to be malefactors.

A radioactive hazardous-waste lagoon was being solidified with a grout mixture. A diesel pump transferred the mixture to a 12-ft diameter pond mixer mounted on a 100-ton crane.

The job safety plan called for work to cease during thunderstorms. When the first storm came in, the crew came out. When they went back to work, they found that the idling diesel pump had shut itself down and would not restart. The starter was pulled and replaced, and all was well until the next storm, when the same thing happened. Yet another storm-related shutdown later, it was time to invoke a basic rule of troubleshooting: the third time a problem happens, it's time to find the root cause and fix the problem.

When we inspected the starter personally, we found that the Bendix-type starter pinion was locked up and the matching ring gear on the engine looked unhappy. The control panel looked like one on a working boat, with switches on a pulpit exposed to the elements. We removed the toggle-type start switch and turned it upside down. Water dripped out. The root cause turned out to be the fact that when it rained, this switch shorted out, and energized the starter motor. The starter got tired of running its Bendix unit into the already turning ring gear, effectively braking the engine to a stop. One marine waterproof switch later, all was well.

The wrong thermocouples. It's a good habit to specify all the thermocouples on a system to be of the same type. This reduces the chance of a Type R being installed in place of a Type K, and so on. Much mischief has occurred when the wrong type is installed: in incinerators, for example, low oxidizer temperatures and high CO emissions. For very hot equipment, refractory color provides a first approximation to cross-check with control-room readings. The best way to check out the issue, however, is to insert a field thermocouple into a nearby port and compare its readings with those of the installed instrument. When bench-checking thermocouples, one can vigorously stir the tip in a mix of chopped ice and water. If it reads within 2°F of 32°F or 1°C of 0°C, the thermocouple and its wiring are okay. Another good check for high limits is to pull the high-limit thermocouple and use a propane torch on it.

Uncooperative machinery

It's been said that machines run better when one of the authors is around, but that is not always the case, as you will see below.

Apron feeder. A rotary kiln system had a slow-moving apron feeder for metering the contaminated soil feed. It stopped feeding during a stack test, which is not a great time for a breakdown. From this point on, the worm-drive gearbox would work only when not under load. Procuring and installing a new gearbox would result in a three-day shutdown.

It's okay to open things up if they don't work anyway. With nothing to lose, we therefore had the case pulled apart. Other people who looked at it said that the big 12-in. diameter driven gear was worn out, since it had a groove cut through the outer edge of the teeth. We said otherwise; having read an article on a failed elevator drive of the same type, we knew the groove was part of the original machining, being the root of the worm drive gear. We had the big gear pulled out, knocked off the bearings, and discovered a hidden 3/8-in. square key that had sheared. After a quick trip to the local automotive machine shop that had a hydraulic press, a new key was installed and we were back up and running in four hours.

But what had caused the key to shear? The root cause that killed the gearbox was soil compacting and locking up on the sides of the apron feeder. This is an old problem in bulk solids, which in general are prone to arching and bridging if the length of the flow channel is more than about three times the width. After figuring out the cause, we loaded the belt to no more than 12-in. deep. A mirror above the feed bin, plus a light, allowed the front-end loader operators to see the soil level, and fixed the problem.

Belt conveyor. On the same rotary kiln system, contaminated soil was screened to 2 in. and passed through a dryer, before being transferred to the kiln via a belt conveyor 100 ft long. While walking the circuit during startup, we observed that feed was going into the dryer, but not coming out the other end. The cause was a stick, 2-ft long and about 1.5 in. in diameter, that had made it through the 2-in. screen. Jammed at the feed end of the belt, the stick was pinching the belt edge and backing up soil into the dryer. We alerted the operators to shut down the plant before they filled the dryer up.

This abuse had caused the conveyor belt to slack off. When retightened, it refused to track correctly, trying to run up and off the idler rollers. Several hours of work proved futile and we contemplated replacing the belt (with a two-day downtime), figuring it had been stretched beyond repair. Then the human factor saved us. When the night-shift crew came in, one of them, normally a quiet type, spoke up. He pointed out that when the belt was installed, the nuts on the belt splice faced down. They now faced up! While hard to imagine, this meant the belt had completely inverted itself when the stick pinched it at the feed point. We flipped the belt back over and it tracked perfectly. It had just worn itself into a comfortable position and resented being turned over.

Summary

When troubleshooting, keep your eyes open and be observant. Be persistent. Break the problem into parts to quickly isolate the issue. Ask for help. Listen to people. Take good notes as you go, and always, always write up that trip report to close out the job! ■

Edited by Charles Butcher

References

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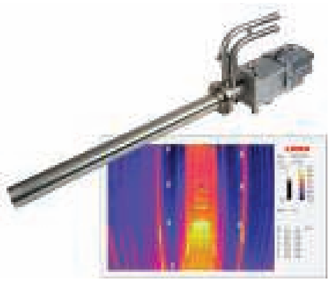

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Economic Indicators

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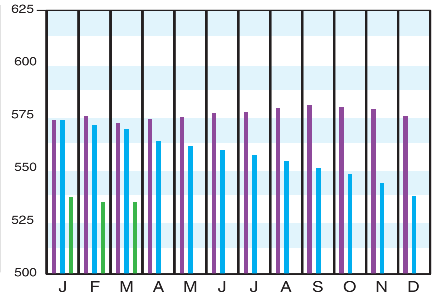
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Mar. '16 Prelim.	Feb. '16 Final	Mar.'15 Final
CE Index	533.9	533.9	568.6
Equipment	635.5	637.0	688.1
Heat exchangers & tanks	538.7	546.2	624.5
Process machinery	644.0	648.6	672.2
Pipe, valves & fittings	800.3	791.2	858.5
Process instruments	383.2	378.9	404.0
Pumps & compressors	969.7	972.2	953.5
Electrical equipment	508.3	506.7	513.5
Structural supports & misc	697.4	700.0	745.9
Construction labor	323.9	319.5	321.8
Buildings	538.5	536.9	545.3
Engineering & supervision	316.8	315.8	319.0

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

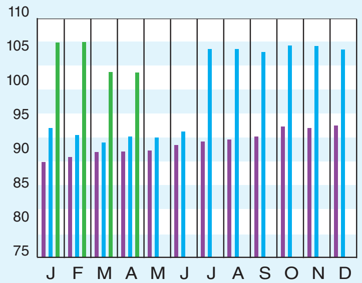
Annual Index:
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6
2013 = 567.3
2014 = 576.1
2015 = 556.8



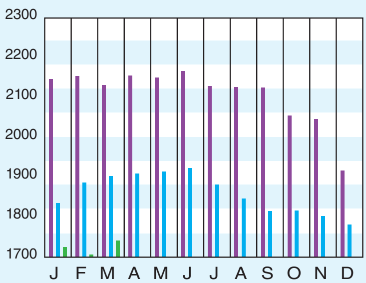
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2012 = 100)	Apr.'16 = 102.0	Mar.'16 = 102.2	Feb.'16 = 101.9	Apr.'15 = 101.3
CPI value of output, $ billions	Mar.'16 = 1,742.1	Feb.'16 = 1,704.3	Jan.'16 = 1,713.4	Mar. '15 = 1,902.6
CPI operating rate, %	Apr.'16 = 75.0	Mar.'16 = 75.2	Feb.'16 = 74.9	Apr.'15 = 75.0
Producer prices, industrial chemicals (1982 = 100)	Apr.'16 = 221.6	Mar.'16 = 219.2	Feb.'16 = 221.7	Apr.'15 = 245.5
Industrial Production in Manufacturing (2012=100)*	Apr.'16 = 103.4	Mar.'16 = 103.1	Feb.'16 = 103.4	Apr.'15 = 102.9
Hourly earnings index, chemical & allied products (1992 = 100)	Apr.'16 = 161.9	Mar.'16 = 160.1	Feb.'16 = 158.6	Apr.'15 = 158.1
Productivity index, chemicals & allied products (1992 = 100)	Apr.'16 = 102.5	Mar.'16 = 102.6	Feb.'16 = 101.9	Apr.'15 = 102.5

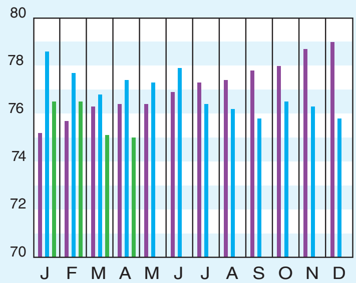
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*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.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The March 2016 preliminary value for the *CE* Plant Cost Index (CEPCI; top; the most recent available) stayed even with the value from the previous month, with the Construction Labor, Buildings and Engineering & Supervision subindices all rising, while the Equipment subindex dipped slightly. The preliminary March 2016 CEPCI value is 6.1% lower than the corresponding value from March last year. This is again a smaller year-over-year difference than in the preceding several months. Meanwhile, the latest Current Business Indicators (CBI; middle) for April 2016 showed small decreases in the CPI output index and the CPI operating rate compared to the previous month. Producer prices edged higher in April, after a series of recent decreases.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