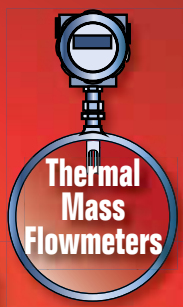
CHEMICAL ENGINEERING
February 2014
www.che.com



PAGE 44

Small-matrix, Model-less Multivariable Control

Focus on Drying and Evaporation

Solving the Pipe-Flow Calculation Maze

Two-Part Feature Report Starts on Page 32

Facts at Your Fingertips: Chemical Protective Clothing

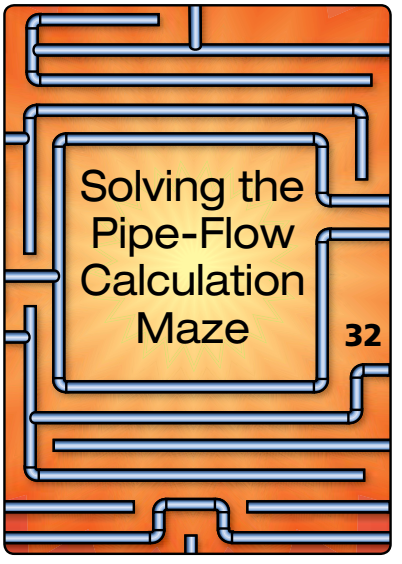
Asset Management

Mixing Technologies

Access Intelligence

CHEMICAL ENGINEERING
www.che.com

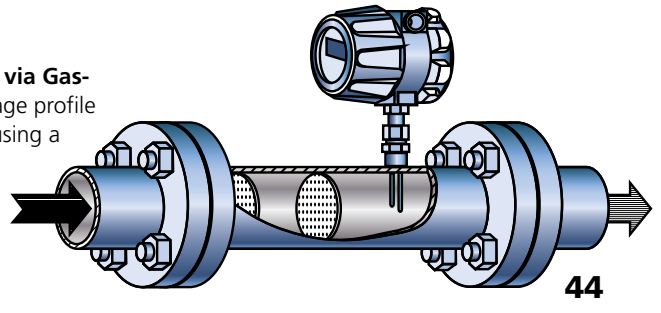
FEBRUARY 2014 VOLUME 121, NO. 2



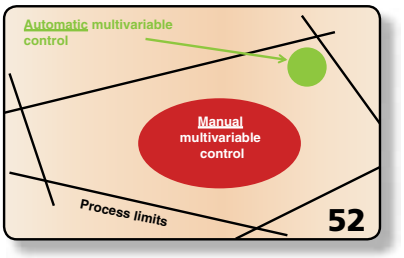
COVER STORY

NEWS

ENGINEERING



ENGINEERING



EQUIPMENT & SERVICES

COMMENTARY

DEPARTMENTS

ADVERTISERS

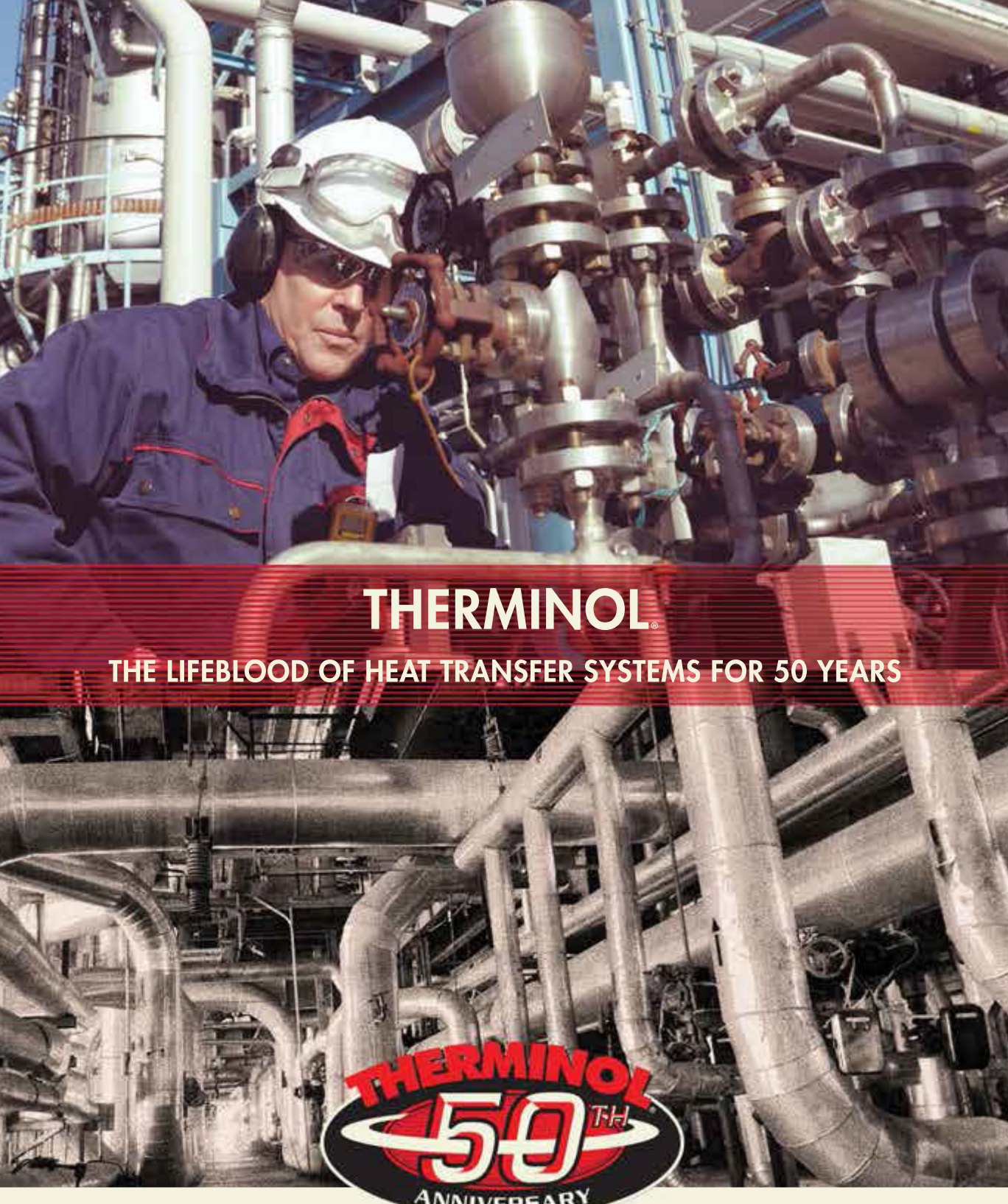
COMING IN MARCH

Look for: **Feature Reports** on Corrosion; and Scale-up of Fermentation Processes; an **Engineering Practice** article on Minimizing FDA Citations; A **Solids Processing** article on Pneumatic Conveying; An **Environmental Manager** article on Air Pollution Regulations; A **Focus** on Safety Equipment; A **Facts at Your Fingertips** on Level Measurement; **News** articles on Recycling; and Sensors; and more

Cover: David Whitcher

ONLY ON CHE.COM

Look for Web-exclusive articles; "Test your Knowledge" quizzes; New Products; Latest News; and more



THERMINOL®

THE LIFEBLOOD OF HEAT TRANSFER SYSTEMS FOR 50 YEARS

THERMINOL 50TH ANNIVERSARY

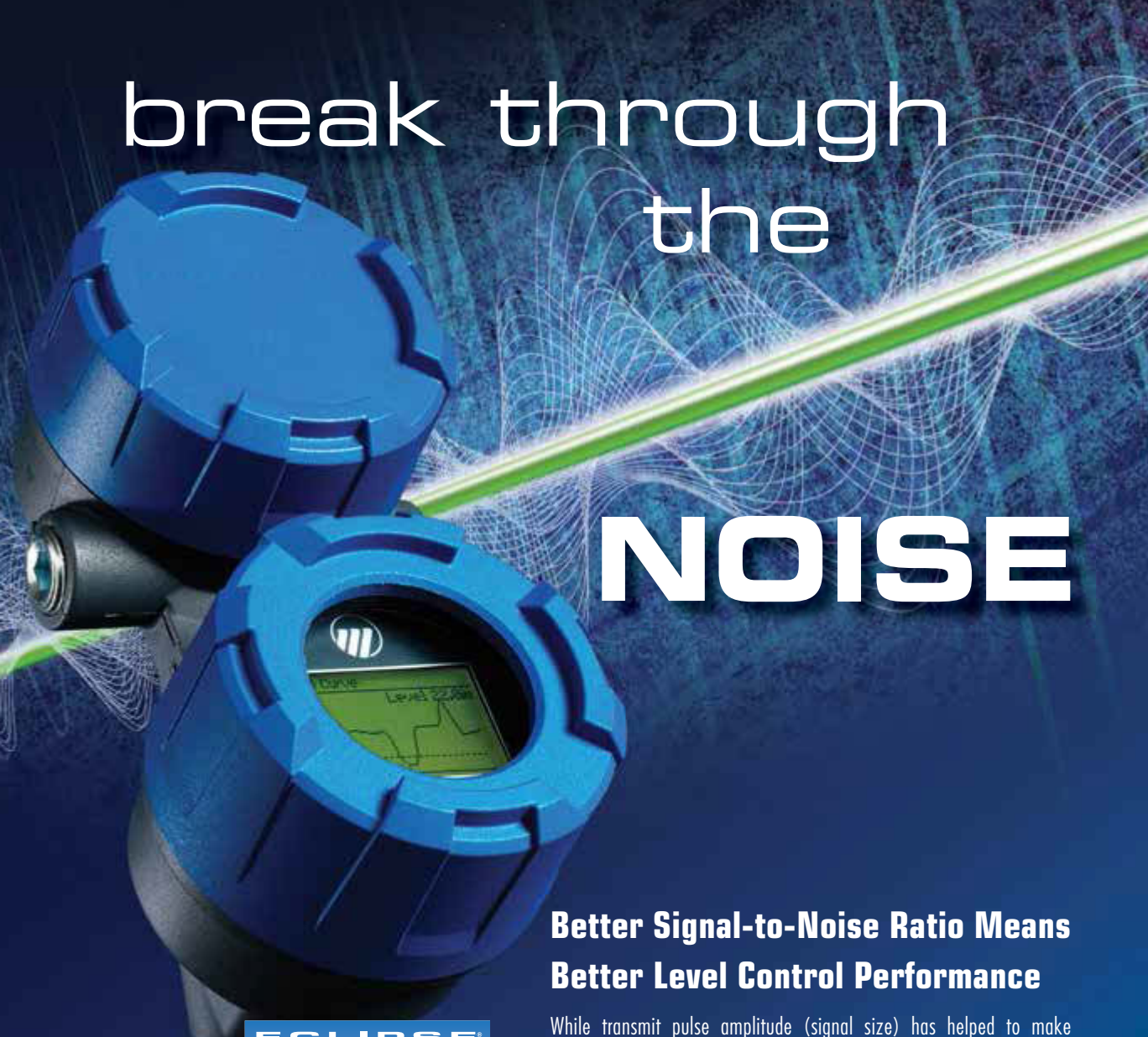
HEAT TRANSFER FLUIDS BY EASTMAN

50 years of performance, reliability and industry-leading service.

Find out how Therminol Heat Transfer Fluids can help keep your operation running smoothly now and in the future. Call 1-800-426-2463 in North America. In Europe, call 32.2.746.5134. www.Therminol.com

Circle 9 on p. 60 or go to adlinks.che.com/50973-09

break through the NOISE



ECLIPSE® 706GWR

3X Higher

4.40 Model 706 SNR

1.57 Competitor SNR

The ECLIPSE Model 706 transmitter has a signal-to-noise ratio nearly ***3 times higher*** than competitors.

Better Signal-to-Noise Ratio Means Better Level Control Performance

While transmit pulse amplitude (signal size) has helped to make guided wave radar technology the standard for accurate, reliable level measurement, the fact is signal-to-noise ratio (SNR) represents a far more critical indicator of level control performance. For superior SNR in all process conditions, no other GWR device beats the Eclipse® Model 706 transmitter from Magnetrol®.

To learn more about the breakthrough ECLIPSE Model 706 GWR transmitter visit eclipse.magnetrol.com or contact your MAGNETROL representative today.

Magnetrol®

magnetrol.com • 1-800-624-8765 • eclipse.magnetrol.com

Circle 20 on p. 60 or go to adlinks.che.com/50973-20

Winner of Eight Jesse H. Neal Awards for Editorial Excellence

CHEMICAL ENGINEERING

Published since 1902
An Access Intelligence Publication

HEADQUARTERS
88 Pine Street, 5th Floor, New York, NY 10005, U.S.
Tel: 212-621-4900 Fax: 212-621-4694

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

CIRCULATION REQUESTS:
Tel: 847-564-9290 Fax: 847-564-9453
Fullfillment Manager; P.O. Box 3588,
Northbrook, IL 60065-3588 email: chemeng@omeda.com

ADVERTISING REQUESTS: see p. 60
For reprints, licensing and permissions: Wright's Media, 1-877-652-5295,
sales@wrightsmedia.com

ACCESS INTELLIGENCE, LLC

Access Intelligence
4 Choke Cherry Road, Second Floor
Rockville, MD 20850 • www.accessintel.com

BPA

Editor's Page

Green chemistry reaps rewards

Each year, the U.S. Environmental Protection Agency (EPA; Washington, D.C.; www.epa.gov) honors innovative technologies that make an impact in reducing hazards to human health and the environment. As these are goals that the chemical process industries (CPI) continuously strive for, news of such achievements is of great interest.

Over the past 18 years of the Presidential Green Chemistry Challenge program, the EPA has received around 1,500 nominations and has presented awards for 93 technologies. The EPA reports that these technologies have collectively reduced the use, or generation of, more than 826 million pounds of hazardous chemicals, saved 21 billion gallons of water and eliminated 7.8 billion pounds of CO_2-equivalent releases to the air.

The winners of the 2013 Presidential Green Chemistry Challenge Awards were announced in December, and are briefly described here (Source: EPA):

Designing Greener Chemicals Award — Cargill Inc. (Minneapolis, Minn.; www.cargill.com) was the recipient of this award for developing a transformer fluid that is based on vegetable oil instead of petroleum. The advantages of Cargill's bio-based oil are said to be that it is significantly less flammable and less toxic than the mineral oils currently in use; it provides superior performance so that transformers can last longer in service and be made smaller; and it has a smaller carbon footprint.

Greener Reaction Conditions Award — The Dow Chemical Company (Midland, Mich., www.dow.com) received this award for helping to reduce the amount of titanium dioxide needed in paint formulations by developing a pre-composite polymer that coats the TiO_2 particles and improves their dispersion in the paint. TiO_2 is typically used as the white pigment in paint formulations, and often high levels of TiO_2, which is energy-intensive to produce, are needed. Dow Chemical's technology reduces energy usage, water consumption, NOx and SOx emissions and algae bloom.

Greener Synthetic Pathways Award — Life Technologies Corp. (Carlsbad, Calif.; www.lifetechnologies.com) was honored with this award for its development of a more efficient way to manufacture the key chemicals (deoxyribonucleotide triphosphates) used to perform genetic testing. The new process reduces the amount of hazardous waste by about 1.5 million pounds per year.

Academic Award — This award was presented to Richard Wool of the University of Delaware (Newark; www.udel.edu) for his work on using bio-based feedstocks to make products that can be used in applications such as adhesives, composites, foams and others. The advantages include saving water and energy, as well as producing less hazardous waste materials as compared to petroleum-based processes.

Small Business Award — Hexavalent chromium is used in certain chrome-plating applications. Cr(VI) is, however, a carcinogen. Faraday Technology, Inc. (Clayton, Ohio; www.faradaytechnology.com) won this award for developing a plating process that uses Cr(III), a much less toxic form of chromium, in place of Cr(VI).

More information about the awards, winners and overall program can be found at www2.epa.gov/green-chemistry. ■

Dorothy Lozowski, Editor in Chief

Letters

Submissions for National Safety Council award are being accepted

The National Safety Council (Itasca, Ill.; www.nsc.org) is inviting organizations from around the globe to apply for its highest honor in environmental, health and safety (EHS) — the Robert W. Campbell Award. Presented annually, the Campbell Award is given to an organization that integrates EHS management into the very core of its business operations. Companies that demonstrate EHS and business excellence are eligible to share their approach by applying for this international honor.

Applications are now being accepted for the 2014 award. Organizations can take a 10-question quiz at campbellaward.org/ready to determine whether they are ready to apply for the Campbell Award and where they are on their journey. More information along with application criteria can be found at campbellaward.org. Final submittals must be postmarked by May 16, 2014.

Applicants undergo a rigorous review process conducted by an international panel of experts in academia, government, labor and management, who provide each applicant with feedback. Simply applying for the award provides applicants with valuable insight to refine continuous improvement efforts.

The Campbell Award is underwritten by the ExxonMobil Corp. and named for Robert W. Campbell, a safety pioneer and the first president of the National Safety Council. Founded in 1913 and chartered by the U.S. Congress, the National Safety Council is a nonprofit organization whose mission is to save lives by preventing injuries and deaths at work, in homes and communities, and on the road through leadership, research, education and advocacy.

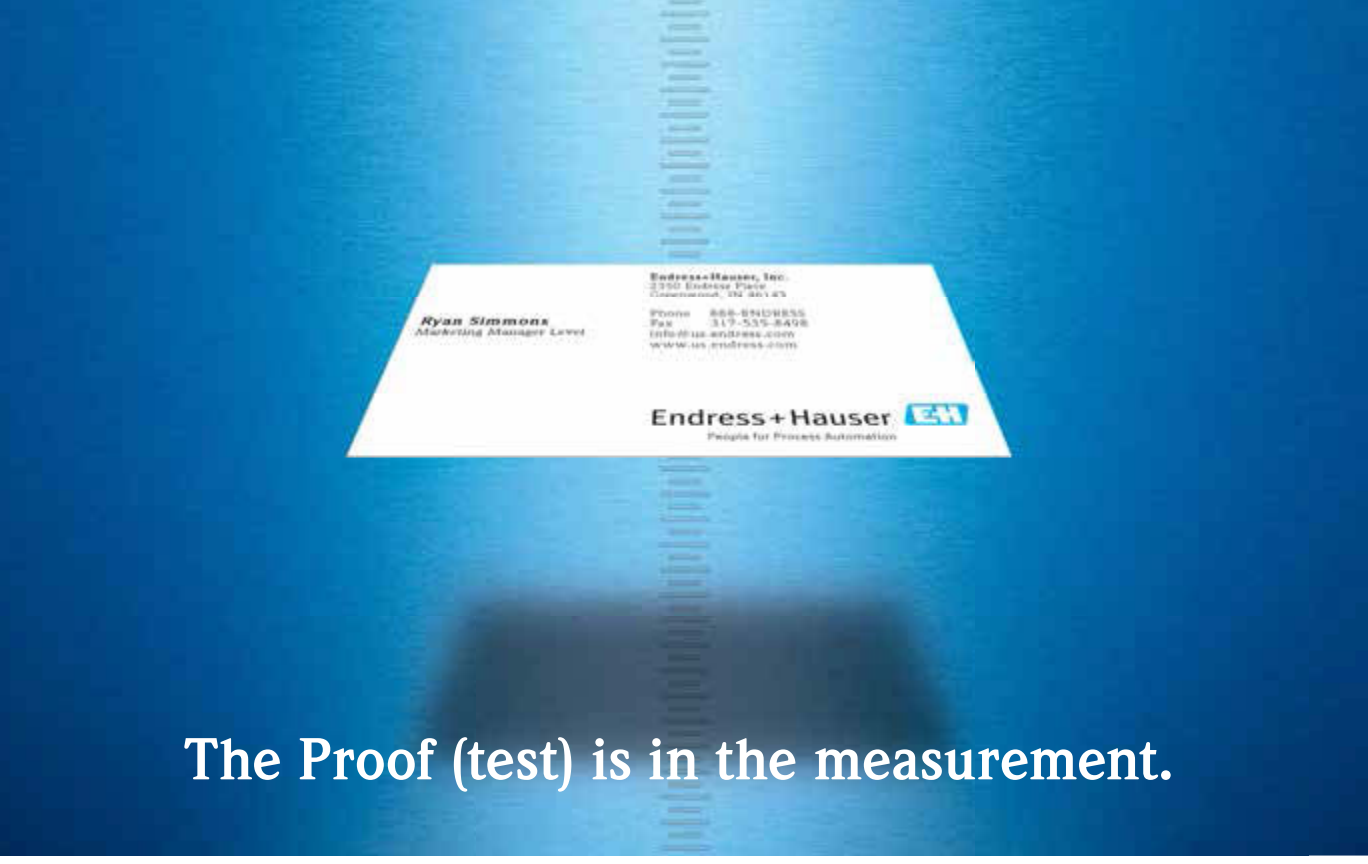
The National Safety Council
Itasca, Ill.; www.nsc.org

Do you have —

- Ideas to air?
- Feedback about our articles?
- Comments about today's engineering practice or education?
- Job-related issues to share?

If so — Send them, for our Letters column, to

Dorothy Lozowski
Chemical Engineering,
Access Intelligence,
88 Pine Street, 5th Floor
New York, NY 10005;
letters@che.com



The Proof (test) is in the measurement.

Levelflex FMP51
Guided wave radar

Micropilot FMR5x
Free space radar

Liquiphant FTL80
Point level switch

Is safety important to you?

Solution for in-situ proof testing

When you utilize a safety system such as SIL, SIS or API2350, you are familiar with mandatory level instrument proof tests. Most require you to take your vessel off line and manipulate the level in the vessel or remove the instrument completely for testing.
These methods typically:

- Require hours to complete the test
- Increase risk to personnel by placing maintenance staff on tall vessels
- Cost money due to extended down time and lost production

At Endress+Hauser, we can help you migrate to in-situ proof testing using free space radar, guided wave radar or vibrating tuning fork instruments installed in your safety system.
This solution provides the ability to:

- Verify the health of the instrument and the associated wiring
- Significantly reduce downtime and the risk to your staff
- Improve your maintenance cycle, productivity and bottom line
- Provide up to SIL3 rating in overfill prevention with one device

www.us.endress.com/process-safety

Endress+Hauser, Inc
2350 Endress Place
Greenwood, IN 46143
info@us.endress.com
www.us.endress.com

Sales: 888-ENDRESS
Service: 800-642-8737
Fax: 317-535-8498

Endress+Hauser
People for Process Automation

Circle 10 on p. 60 or go to adlinks.che.com/50973-10

Calendar

NORTH AMERICA

Corrosion 2014. National Assn. of Corrosion Engineers (NACE) International (Houston). Phone: 281-228-6200; Web: nace.org
San Antonio, Tex. **March 9–13**

247th Annual ACS National Meeting. American Chemical Soc. (ACS; Washington, D.C.). Phone: 202-872-4600; Web: acs.org
Dallas, Tex. **March 16–20**

Interphex 2014. Reed Exhibitions (Norwalk, Conn.). Phone: 203-840-5603; Web: interphex.com
New York, N.Y. **March 18–20**

2014 AFPM Annual Meeting. American Fuel & Petrochemical Manufacturers (AFPM; Washington, D.C.). Phone: 202-457-0480; Web: afpm.org
Orlando, Fla. **March 23–25**

2014 AIChE Spring Meeting and 10th Global Congress on Process Safety. AIChE (New York, N.Y.). Phone: 203-702-7660; Web: aiche.org
New Orleans, La. **March 30–April 3**

Electric Power. Tradefair Group, an Access Intelligence LLC Company. (Houston). Phone: 713-343-1893; Web: electricpowerexpo.com
New Orleans, La. **April 1–3**

Battcon 2014 Stationary Battery Conference and Trade Show. Albercorp/Battcon (Pompano Beach, Fla.). Phone: Phone: 800-851-4632; Web: battcon.com
Boca Raton, Fla. **May 5–7**

PTXi Powder and Bulk Solids 2014. UBM Canon (Los Angeles, Calif.). Phone: 310-445-4200 Web: powdershow.com
Rosemont, Ill. **May 6–8**

Identify, Characterize, Select and Isolate the Optimal Solid State Form for Pharmaceutical Development. Scientific Update (East Sussex, U.K.), in conjunction with Crystal Pharmatech (Princeton, N.J.) and Rutgers University (New Brunswick, N.J.). Phone: +44-1435-873062; Web: scientificupdate.co.uk
New Brunswick, N.J. **May 15–16**

EUROPE

Establishing and Maintaining a Safety Culture. Institution of Chemical Engineers (IChemE; Rugby, U.K.); Phone: +44-20-7927-8200; Web: icheme.org
London, U.K. **March 5–6**

10th Energy Efficiency & Renewable Energy Congress and Exhibition for Southeast Europe. Via Expo Ltd. (Plovdiv, Bulgaria). Phone:

+359-32-512-900; Web: via-expo.com/en/pages/ee-re-exhibition
Sofia, Bulgaria **March 5–7**

5th Conference and Exhibition on Waste Management, Recycling, Environment for South-East Europe. Via Expo (Plovdiv, Bulgaria). Phone: Phone: +359-32-512-900; Web: via-expo.com/en/pages/waste-management-recycling-exhibition
Sofia, Bulgaria **March 5–7**

New Horizons in Gasification. IChemE (Rugby, , U.K.). Phone: +44-20-7927-8200; Web: icheme.org/gasification2014
Rotterdam, The Netherlands **March 10–13**

Chemical Engineering for Scientists. IChemE; Rugby, U.K.). Phone:+44-1788-534431; Web: icheme.org
West Yorkshire, U.K. **March 24–28**

In-Cosmetics 2014. Reed Exhibitions Ltd. (Richmond, U.K.). Phone: +44-20-8271-2122; Web: in-cosmetics.com
Hamburg, Germany **April 1–3**

GPE 2014: 4th International Congress on Green Process Engineering. Instituto National Polytechnique de Toulouse (Toulouse, France). Phone: +34-5-34-32-36-84; Web: gpe2014.org
Sevilla, Spain **April 7–10**

Hannover Messe 2014. Hannover Messe AG (Hannover, Germany). Phone: +49-511-89-0; Web: hannovermesse.de
Hannover, Germany. **April 7–11**

Sustainable Nuclear Energy. IChemE (Rugby, U.K.). Phone: +44-1788-578214; Web: icheme.org/snec2014
Manchester, U.K. **April 9–11**

IFAT 2014: Trade Fair for Water, Sewage, Waste Management. Messe München GmbH (Munich, Germany). Phone: +49-89-949-21478; Web: ifat.de
Munich, Germany **May 5–9**

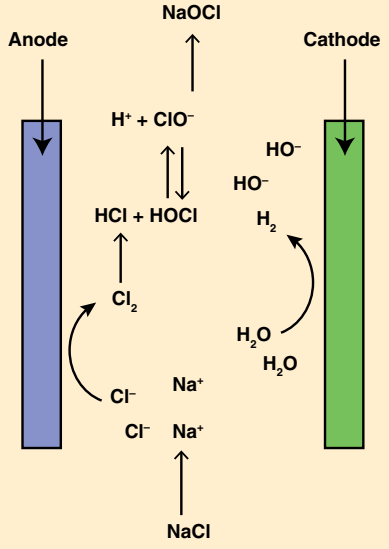
ASIA & ELSEWHERE

Africa Photovoltaic Solar Energy Conference and Exhibition. EU PVSEC (Munich, Germany) and SNEC (Shanghai, China); Phone: +39-055-500-2174, Ext. 204; Web: africapvsec.info
Durban, South Africa **March 27–29**

5th FIP Pharmaceutical Sciences World Congress. The International Pharmaceutical Federation (The Hague, Netherlands); Phone: +31-70-302-1984; Web: fip.org/pswc2014/
Melbourne, Australia **April 13–16** ■

Suzanne Shelley

A self-cleaning electrolytic cell that converts waste streams into disinfectants



Dealing with wastewater streams in petroleum refineries and petrochemical operations is often a trying task — environmentally, economically and logistically — especially as regulations on salinity in waste streams are tightened. However, many waste streams actually contain useful components, such as chloride compounds that can be converted electrolytically to oxidizers or disinfectants, such as sodium hypochlorite (diagram), which can then be used downstream in other aspects of the waste-treatment process.

MIOX Corp. (Albuquerque, N.M.; www.miox.com) is running pilot case studies where a chloride-concentrated waste stream is processed through a novel electrolytic cell to generate a chlorine-based oxidant. This generated stream is, in turn, recycled and used elsewhere in the process to remove other contaminants and provide disinfection. By using this process, disposal and raw-material costs could be significantly reduced.

However, an issue that arises with many electrolysis processes is the effect of fouling on electrode efficiency — the basic conditions at the cathode make it prone to scale buildup and many processes seek ever-purer (and more expensive) salt compounds to minimize fouling. MIOX claims to eliminate the need for high-purity salt through the electrolytic cell's proprietary "self-cleaning" mechanism, which effectively reverses polarity on the cell with each cycle. As impurities are built up on the cell during operation, the polarity-reversal process flushes particles from the cell, after which the cell is returned to normal mode and ready to begin a new cycle.

Potential applications for this process include wastewater-treatment plants, water-management at hydraulic fracturing sites and industrial desalination facilities. MIOX expects for this process to reach commercial status in the next year.

Rare-earth magnets enhance filtration of engine lubricants

FilterMag International (Scottsdale, Ariz.; www.filtermag.com) has developed neodymium magnetic devices that can boost the performance of lubricant filters for mining vehicles and industrial machinery. When the device is in place, filters retain 50–75% of contaminant particles that would otherwise be missed, a level that translates into a 30–60% increase in engine life, says the company. The results have been verified in third-party testing laboratories, reports CEO Herb Martin.

The magnetic device is applied directly to the outside of an oil filter, and works by attracting micron-scale metallic particles to the interior of the filter canister, retaining them there. Particles in the range of 3–14 microns are routinely generated by engine wear, and can significantly damage engine components. However, particles of that size range would pass through conventional lubricant filter designs, says Martin.

FilterMag's patented non-invasive device includes a shield to focus the neodymium's magnetic field inward, where it works to capture particles, rather than outward, where it could affect surrounding engine components. The device has been shown to capture particles that become charged in the fluid stream. This aspect of Filtermag's Nd-magnetic device allows the capture of soot, sand and other non-magnetic contaminants in addition to metallic particles.

The newly launched company has deployed the devices in mining applications, where they extend engine life on haul trucks; in oil-and-gas applications on land-based compressors; and in mud pumps on offshore oil rigs. The company is set to extend the use of the magnetic filtration devices into the lubricant and hydraulic systems of stationary industrial machines.

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

Cellulose nanocrystals

New research from Purdue University (West Lafayette, Ind.; www.purdue.edu) has shed some light on the physical properties of cellulose nanocrystals. The nanocrystals, which are about 3-nm wide and 500-nm long, have historically been difficult to analyze, but the Purdue researchers used quantum mechanical calculations to make some predictions about the crystals' properties and behavior.

Cellulose from trees is known to possess high strength and resilience, while remaining a lightweight material, but the new discoveries show that the nanocrystals exhibit stiffness properties similar to those of steel. These findings indicate that cellulose nanocrystals could be a feasible "green" alternative to carbon nanotubes. Applications could include biodegradable plastic films, batteries, drug-delivery systems and more.

Membrane technology

Fouling-resistant membrane technology from Lanxess (Cologne, Germany; www.lanxess.com) is being used at the Dam-

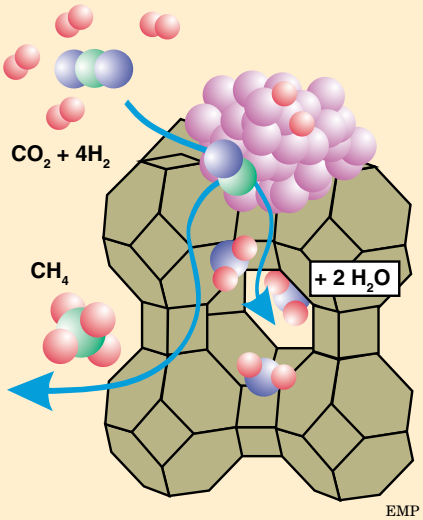
(*Continues on p. 12*)

A sorption-enhanced catalyst improves CO_2 methanation

Converting CO_2 into methane is a way to mimic the natural carbon cycle and close the energy cycle by producing synthetic hydrocarbons (see, for example, CO_2 Utilization, *Chem. Eng.,* July 2013, pp. 16–19). However, the Sabatier reaction ($CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$) is a complex surface reaction that is kinetically limited, says Andreas Borgschulte, a group leader at the Laboratory for Hydrogen and Energy of the Swiss Federal Laboratories for Materials Science and Technology (EMPA; Dübendorf, Switzerland; www.empa.ch). Commercial nickel-based catalysts for this reaction achieve a 90% conversion, but only at temperatures over 250°C; and at high temperatures, CO is also formed, he says.

To improve both the yield and selectivity, Borgschulte's group at EMPA has developed a new catalyst that simultaneously absorbs water (diagram), thereby shifting the reaction to the right according to Le Chatelier's principle. In laboratory trials, the so-called sorption catalyst has been shown to be more active than commercial catalysts with yields up to 100%.

The new catalyst consists of nanoparticles of Ni bound to a molecular sieve (type 5A zeolite with 5-Å sized pores). To make the catalyst, the zeolite is first mixed in a solution of $NiNO_3$, whereby alkali ions are exchanged by Ni^{+1} ions within the zeolite. The Ni^{+1}-loaded zeolite is then dried and calcined with H_2 at 650°C, which reduces the Ni^{+1} to form nanoparticles of Ni^0.



EMP

So far, the reaction has been carried out in a single, fixed-bed tubular reactor. The group plans to make the process semi-continuous by using several reactors alternating between reaction and regeneration (removing absorbed water). Because the regeneration time is roughly three times longer than the reaction time, Borgschulte says at least four reactors would be used. The group is also studying the effect of catalyst poisoning (by sulfur, for example, in biogas plants), and investigating the possibility of using other metals besides Ni. The researchers are in contact with potential industrial partners.

A new low-temperature shift catalyst passes longterm testing

A new water-gas shift catalyst has undergone 1,000 h of successful operation in a demonstration carried out by the New Energy and Industrial Technology Development Organization (NEDO, Kawasaki; www.nedo.go.jp) and Hitachi, Ltd. (Tokyo, both Japan; www.hitachi.com). The tests were performed at the Eagle pilot plant (*Chem. Eng.*, July 2013, p. 13) using coal-derived syngas, as part of an ongoing project to develop CCS-IGCC technology (carbon capture and storage – integrated coal gasification, combined cycle).

Developed by Hitachi, the new shift catalyst converts CO_2 and water vapor into CO and H_2 with a conversion rate of 40–70% — even at temperatures below 250°C, much lower than conventional high-temperature shift catalysts. The theoretical conversion rate of 70% was maintained after 1,000 h of operation, even under conditions of reduced water content (H_2O-to-CO_2 mole ratio of 1.2 — nearly two thirds that of normal conditions). The researchers believe that coal-fired power generation using the new shift catalyst at a CCS-IGCC facility system has the potential to reduce CO_2 emissions by 200,000 ton/yr compared to conventional coal-fired power generation (1,000 MW class).

(*Continued from p. 11*)

mweg thermal power station in Chemnitz, Germany. This is the first large-scale application of the technology in Europe. A set of 60 Lewabrane RO B400 FR filter elements apply a reverse-osmosis (RO) process to cleanse 50 to 60 m^3/h of pre-treated river water for steam-generation purposes. The RO facility in the Chemnitz power plant was developed and designed by Berkefeld, a subsidiary of Veolia Water Solutions & Technologies.

The Chemnitz plant uses cogeneration to generate power and district heating. The power plant draws water for the cooling processes and steam production from the rivers Chemnitz and Zschopau. The water's intended use — as cooling water, process water or almost pure, completely desalinated water (demineralized water) for steam generation — determines the need for complex mechanical and chemical treatment procedures. Even after it has been softened and desalinated using ion-exchange resins, the water still contains a considerable amount of organic substances that cause excessive conductivity in the water-steam cycle that is harmful to the turbine and other components. The membrane filter elements from Lanxess lower the degree of fluctuation in water quality and in particular, filter out organic substances.

Mineral analyzer

Researcher Graeme Hansford from the University of Leicester's Space Research Center (SRC) has recently started a collaborative project with Bruker Elemental GmbH (Kalkar, Germany; www.bruker.com/elemental) to develop a handheld mineral analyzer for mining applications — said to be the first of its kind.

The analyzer will allow rapid mineral identification and quantification in the field through a combination of X-ray diffraction (XRD) and X-ray fluorescence (XRF). The novel XRD method was invented at the University of Leicester and has been developed at the Space Research Center.

(*Continues on p. 14*)

Continuous crude-oil production from algae

Scientists at Pacific Northwest National Laboratory (PNNL; Richland, Wash.; www.pnnl.gov) have developed a continuous process for generating crude oil from algae that they believe can lower the cost of producing algae-based fuel.

The process works by combining hydrothermal liquefaction and catalytic hydrothermal gasification, heating and pressurizing a slurry of algae to 350°C and 3,000 psi. PNNL says its research reactor can convert 50–70% of the algae's carbon into crude oil. In addition to crude oil (which can yield aviation fuel, gasoline and diesel fuel), the process also generates fuel gas, as well as water and nitrogen, phosphorous and potassium nutrients that are used to help grow more algae.

While the high-pressure system is relatively expensive to build, it lowers costs by eliminating the need to extract oil with solvents and eliminating the energy-intensive step of drying the algae. Most current approaches to algae-based fuel include both of these elements. The PNNL reactor system processes 1.5 L of slurry per hour. The technology has been licensed by biofuels company Genifuel Corp. (Salt Lake City, Utah; www.genifuel.com) for further development.

Selectively recover CO with this soft nano-porous material

Professor Susumu Kitagawa's group at Kyoto University (Kyoto, www.sbchem.kyoto-u.ac.jp/kitagawa-lab/index-e.html) has developed a new soft nanoporous material that selectively adsorbs carbon monoxide from gas mixtures. The researchers believe their achievement will enable the separation and recycling of CO from the emissions of many large-scale industrial oxidation processes, as well as for the purification of CO.

The researchers synthesized a porous coordination polymer (PCP) — also known as a metal organic framework (MOF) crystal — that contains Cu^{+2} ions, which interact with CO and an organic ligand (5-azidoisophthalic acid) analogously to the interaction of O_2 and hemoglobin. The copper-based PCP has two types of flexible channels: open and restricted. As CO enters the open channels and interacts with the Cu^{+2}, the narrow channels widen to allow more CO to enter, thus accelerating the CO uptake.

In laboratory trials, the copper-based PCP was found to concentrate a 13 vol.% mixture of CO in N_2 to 95%-pure CO after three cycles. Such unprecedented selectivity for CO promises to enable highly efficient separation with reduced energy consumption, says Kitagawa. Potential applications include the purification of CO generated from steam reforming process and shale gas processes. Kitagawa plans to collaborate with industrial partners to further develop the technology.

Optimized carbon-adsorbent material for natural gas storage

Techniques for manufacturing carbon adsorbent materials with highly tuned pore properties have been developed by EnerG2 Technologies Inc. (Seattle, Wash.; www.energ2.com). The technology platform produces carbon adsorbents that enable the storage of natural gas at significantly lower pressures than those required for compressed natural gas (CNG) and liquefied natural gas (LNG). EnerG2's carbon materials are also used in advanced electrode materials for lithium-ion batteries (*Chem. Eng.*, October 2013, pp. 17–23).

Using proprietary methods, EnerG2 synthesizes polymers with carefully manipulated molecular structures, and then thermally carbonizes them. The result is a carbonaceous material with precisely controlled, nanoscale pore sizes that exactly match a particular gas. In the case of methane, the carbon material is engineered to have pore sizes close to 1.1 nm, which is ideal for a methane molecule.

"The Van der Waals forces of the carbon adsorbent surfaces overcome the natural repulsion of methane gas molecules," explains EnerG2 CEO Rick Luebbe, "so we can achieve liquid densities inside the micropores of the material."

Using activated carbon to capture gases is not new, but EnerG2 has introduced the ability to optimally tune carbon pore sizes to store large volumes of natural gas at relatively low pressures for powering vehicles and for facilitating transport of stranded natural gas. "Our materials can store natural gas at a capacity of more than 200 L of natural gas per liter of storage-tank volume at relatively low pressure," says Aaron Feaver, EnerG2 chief technology officer.

Natural gas can be a viable transportation fuel, but no infrastructure exists to allow its widespread use, explains Luebbe. Storing natural gas with adsorbent materials, such as those produced by EnerG2, requires compression technology that is much less costly than what is needed to achieve the high pressures (>3,000 psi) of CNG or the low temperatures of LNG. This means cheaper compression and less physical constraints on the shape of the fuel storage tank, he notes.

Making liquid fuels from waste plastics

Gasoline-like fuel suitable for internal combustion engines can be obtained from the pyrolysis of plastic waste, according to a study conducted by a team of people from Gadjah Mada University (Yogyakarta, Indonesia; www.ugm.ac.id), University Sains Malaysia (Penang, Malaysia; www.usm.my), and Tokyo Institute of Technology (Tokyo, Japan; www.titech.ac.jp).

To resemble real plastic wastes, the team studied the pyrolysis of five samples involving high-density polyethylene (HDPE), polypropylene (PP) and polystyrene (PS): 100% PP; 100% PS; 100% HDPE; 75% PP + 25% PS; and 25% PP + 75% PS. The feedstock was placed in a tightly sealed cylindrical container and pyrolyzed in a cylindrical reactor at 550–700°C and an initial pressure of 1 atm. Although the pyrolysis products were solids, liquid and flared gas, the team focused on liquid oil.

Oil from PS turned out to have the highest specific gravity (0.9208, compared with 0.8445 for diesel, and 0.75 for gasoline). HDPE as raw material yielded the highest kinematic viscosity, Reid vapor pressure and pour point, respectively 1.422 mm^2/s, 27.89 kPa, and 18°C. Its specific gravity, however, was the lowest. Oils obtained from PP, PS and their mixtures, had similar flash and pour points, below 10°C and below –33°C.

The team concluded that PS is the best feedstock in terms of liquid yield rate and percentage. HDPE is the worst one, and PP is in between. Specific gravities of oils from PP, PS and their mixtures are close or slightly above those of diesel fuel, while oil from HDPE has the lowest value, closer to gasoline. Kinematic viscosities of oils from PP, PS and their mixtures are similar to those of gasoline, while HDPE oil has the highest value, which is, however, too low compared with diesel fuel.

The team believes higher yield and better quality of liquid fuel can be obtained by improving and optimizing the process, through choice of the most appropriate temperature, addition of catalytic reforming, and lower cooling-water temperature.

(*Continued from p. 12*)

The addition of XRD capability represents an evolution of current handheld XRF instruments, which are sold by the thousands each year globally.

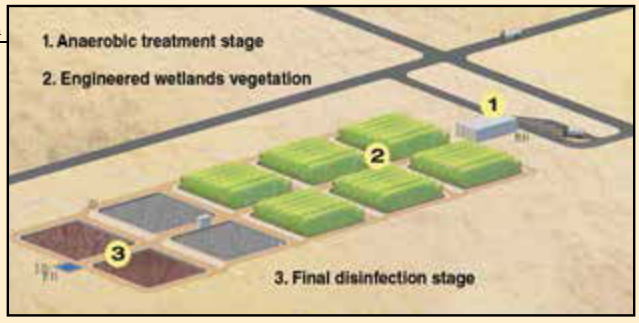
The handheld instrument is expected to weigh just 1.5 kg, will be capable of analyzing mining samples for mineral content within 1– 2 min, and requires no sample preparation. The analyzer is unique due to the insensitivity of the technique to the shape of the sample, which enables the direct analysis of samples without any form of preparation — something currently inconceivable using conventional XRD equipment.

Alexander Seyfarth, senior product manager at Bruker Elemental, says the project "will bring new measurement capabilities to our handheld equipment. In many cases this system will provide information on the crystallography of the sample in addition to the elemental analysis."

Pipeline scaling

Last month, Flowrox, Inc. (Orlando, Fla.; www.flowrox.com) introduced a new product designed to enable precise measurement of scale in pipelines and other fluid-control environments. The Flowrox Scaling Watch is a wafer piece of pipeline that has been engineered for insertion between two flanges that allows the detection of scale — the result of hardened mineral deposits that can reduce the flow of fluids through a pipeline. The device uses electrical capacitance tomography (ECT) technology, which enables operators to see inside piping systems without stopping the process or opening up the pipeline, and enables 3D-imaging and measurement of non-conductive media inside process pipelines and pipes (for more on ECT technology, see *Chem. Eng.* October 1995, pp. 30–33). The system uses a patented algorithm that creates a 3D image of the process fluid in the piping and generates trend data. It also shows free volume inside the pipe and the growth rate of scale over time. ❑

Alcoa



Engineered wetlands technology now available for wastewater treatment

Water treatment technology from Alcoa Inc. (Pittsburgh, Pa.; www.alcoa.com) that includes engineered areas of natural wetland vegetation is now available commercially for the first time. The engineered wetlands technology can lower capital and operating expenses, as well as energy consumption, compared to conventional tank-based water-treatment systems, according to scientists and engineers at Alcoa and partner Bauer Resources GmbH (Schrobenhausen, Germany; www.bauer.de).

Alcoa has been developing and deploying its natural wetlands technology since 2004, and has teamed with Bauer to offer the technology worldwide, explains John R. Smith, director of Sustaining Technologies, Products & Operations for Alcoa. "Now we are making the technology available outside Alcoa for replacing aging municipal or industrial water-treatment infrastructure. Bauer will act as the engineering, design and construction firm, Alcoa is bringing the innovative technology."

The three-step process (diagram) begins with a settling tank and anaerobic treatment apparatus that removes solids, metals and reduces organic compounds in the water. The water then flows into a passive, engineered plot of wetland vegetation, where subsurface water flow removes nitrogen- and phosphorous-containing nutrients, along with additional organic matter. The specific species of wetland plants chosen for the plots are dictated by the local climate and environment, says Smith. Also, "We are able to build systems that will give the required residence time (usually one to three days) for the profile of the treated water," Smith adds. Finally, the water enters a bauxite-based filter media that provides final polishing and disinfection treatment.

The resulting water, while non-potable, is equivalent to or better than what results from a conventional treatment system, and is suitable for irrigation or as process water. Further, the engineered wetlands technology requires a land footprint equal to that needed for a conventional water-treatment system, Smith says, at lowered cost and energy consumption. ■

What's launching March 18?

THE LATEST PHARMACEUTICAL & BIOPHARMACEUTICAL TECHNOLOGY

FRESH IDEAS & INSPIRING EDUCATION BY PDA (PARENTERAL DRUG ASSOCIATION)

IPS TECHNOLOGY FLOOR TOURS SHOWCASING THE LATEST EQUIPMENT & INNOVATIONS

YOUR INDUSTRY'S LARGEST GATHERING

ST. PATRICK'S DAY^{+2} CELEBRATION OF THE INDUSTRY'S ACCOMPLISHMENTS

X marks the spot.

INTERPHEX

ADVANCING THE PROCESSING OF LIFE-ENHANCING DRUGS

INTERPHEX is THE Single Source for Complete Biopharmaceutical and Pharmaceutical Manufacturing Solutions to Confidently Process All Dosage Forms for Life-enhancing Drugs.

March 18 – 20, 2014
Javits Center | New York City
#INTERPHEX

Register today for
free exhibit hall admission
www.INTERPHEX.com/CHE

PREMIER SPONSOR:
PDA Parenteral Drug Association

See all of these products at INTERPHEX (photos from left to right): EMD Millipore Corp., IMA Life North America Inc., GEA Process Engineering, Inc., Thomas Engineering Inc., Korber Medipak, Biologics Modular

Circle 16 on p. 60 or go to adlinks.che.com/50973-16

ASSET MANAGEMENT'S NEXT ACT

The newly released ISO 55000 standard represents a framework for maximizing company value from equipment and other assets

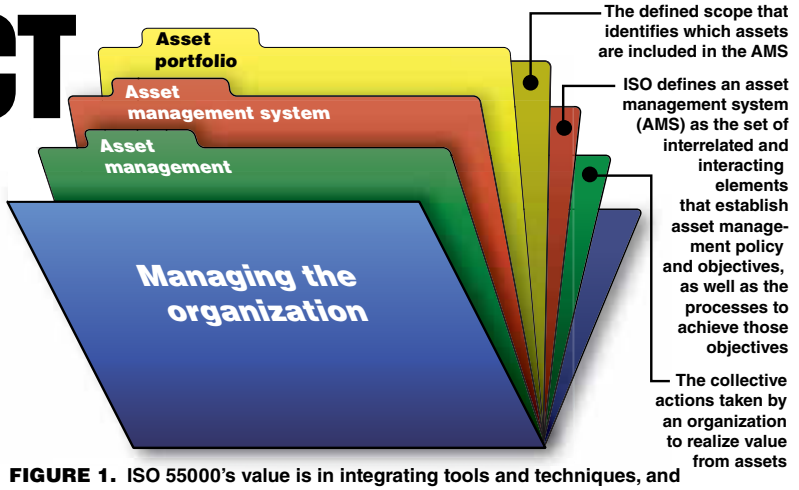


FIGURE 1. ISO 55000's value is in integrating tools and techniques, and packaging them within an organization-wide asset management system

In a culmination of more than three years of work by teams from across the globe, the International Organization for Standardization (ISO; Geneva, Switzerland; www.iso.org) on January 10 published the ISO 55000 series of standards surrounding asset management systems (AMS). The newly available standard can help companies in the chemical process industries (CPI) and other asset-intensive industries better leverage their physical assets in a way that optimizes the value those assets represent to an organization.

"Good asset management — whether by simply aligning practices and systems with ISO 55000 or by extending this to obtain formal certification against the standard — provides the opportunity for a more holistic optimization of asset management decisions across all phases of the asset lifecycle," says Scott Yates, principal consultant for Assetivity Pty Ltd. (South Perth, Australia; www.assetivity.com.au), a company that provides asset management training and ISO 55000 readiness assessments, among other consulting services.

The key values embodied in ISO 55000 are the use of assets for value creation and the identification of asset-related risks, says Mike Poland, director of asset management services at the consulting company Life Cycle Engineering (LCE; Charleston, S.C.; www.lce.com). The standard is really about "undertaking wholesale business transformation for maintaining assets, rather than just fixing what's broken," Poland says.

A holistic approach to asset-management decision-making promotes greater alignment across all business functions, explains Yates, so that decisions meet both the current and future needs of the organization as a whole, by trading off the competing factors of cost, performance and risk. Without such an approach, decisions are more likely to be sub-optimal because they focus on the best interest of one particular department or function.

Decisions that take into account both short term and longer term considerations — such as what might exist during short fluctuations in market activity — have the best chance of realizing organizational goals, Yates says, even though the outcomes will depend on current realities, such as market conditions, company cash flow, asset condition and performance, regulatory environment and workforce size and competence.

Asset management systems

ISO 55000 is actually a series of standards consisting of three parts: ISO 55000 provides an overview of the subject of asset management and the standard terms and definitions to be used; ISO 55001 is the requirements specification for an integrated management system for assets; and ISO 55002 provides guidance for the implementation of such a standard.

The ISO 55000 series will be available through the ISO member bodies in each country. For example, in the U.S., ISO 55000 can be purchased through the American National Standards Institute (ANSI; Washington, D.C.; www.ansi.org), a voluntary consensus standards developer, and the country's official ISO representative.

The ISO 55000 standard falls into the category of "management systems standards," which also includes several of ISO's most widely known and widely used standards, such as ISO 9000 for Quality Management Systems. These so-called management-system standards are intended to provide a model to follow when setting up and operating management systems (Figure 1).

The need for a global standard on asset management systems was clear, despite the wealth of techni-

cal information on managing physical assets. "There are already many good guidelines for the technical side of managing assets," explains Rhys Davies, president of the consultancy eAsset Management Ltd. (Great Bentley, U.K.; www.eassetm.com) and chair of the ISO project committee (PC251) that developed the ISO 55000 series of standards. "But what was lacking was a framework for what needs to be done to effectively implement asset management concepts." The standard is designed to tell organizations what needs to be done, but not necessarily how to go about doing it, Davies says, "so there's a lot of flexibility."

Value creation and risk

Among the recurring themes of the ISO 55000 standard are the concepts of value creation and risk-based decision-making. To underscore the major potential benefit of utilizing the standard — namely its ability to "help organizations realize value from their assets," PC251 chair Davies cites four key principles promoted by the standard. They can be summarized as follows: 1) Alignment of company objectives, from the senior leaders of the organization to the technicians responsible for the day-to-day operation of the assets; 2) Transparent and consistent decision-making that seeks to balance potentially conflicting initiatives and limited resources; 3) Involvement of risk in the decision-making process; and 4) Balancing longterm asset needs with short-term business planning cycles.

In the standard, the term "asset" is defined broadly, to encompass not only physical assets, such as equipment and hardware, but also intangible assets, such as intellectual property and reputation, as well as human assets. "The definition for asset we used in the committee is purposefully vague," says Davies. We wanted to make it clear to everyone that an asset can be anything — both tangible and intagible."

Surrounding the standard's emphasis on value creation, the tone and approach of ISO 55000 are decidedly geared toward longterm thinking and strategy. Davies points out that the life span of many assets can be much longer than the average corporate strategic plan. For example, tangible items, such as physical infrastructure as well as intangible concepts, such as a company's reputation are anticipated to far outlast a five-year plan. "So the longterm strategic asset management plan (SAMP) has to take this longer life span into account and plan for it," Davies explains.

"This longer term approach also forces us to get to know our assets better," continues Davies. "We may not always be aware of everything that has value or has the potential to create value for our organization."

Countries represented on ISO project committee 251 for ISO 55000 — Asset Management Systems

Argentina	Chile	Denmark	Ireland	Netherlands	Russia	United Kingdom
Australia	China	Finland	Italy	Mexico	South Africa	United States of America
Belgium	Colombia	France	Japan	Norway	Spain	
Brazil	Czech Republic	Germany	Republic of Korea	Peru	Switzerland	United Arab Emirates
Canada		India		Portugal	Sweden	

'Quick wins'

Despite the longterm outlook of the standard, the process of building an AMS can produce immediate benefits. "One of the great things about [the standard's] approach is that there are many 'quick wins' early on in the process," says Davies.

"Identifying assets, what we want to achieve with them and how to get there, requires in-depth knowledge of the asset in question," Davies explains, "which can help in operational decision making and an organization's performance overall."

In addition, he says, the approach to setting up an AMS, as embodied by ISO 55000, can help improve an organization's relationship with its stakeholders. The term value "doesn't necessarily mean monetary gain," and defining what the value is for an asset often involves conversations with people outside the organization," Davies says.

In a global economy, many organizations are likely to view compliance with ISO 55000 as a marketing advantage, or as a means to differentiate themselves from competitors. However, experts agree the marketing advantage is a side-benefit compared to the opportunities offered by making substantive improvements in managing assets.

For the CPI, expected organizational benefits would be improved return on investment and reduced risk, Yates says. The benefits would be realized in the form of "high-quality asset planning that ensures that early, correct decisions are made to invest in, or dispose of, assets, as well as clear performance measures that are used to focus attention on those assets that require decisions and other interventions," he says.

For most organizations, including those in the CPI, the most signficant opportunities lie in addressing "the gaps between business functions, the gaps between the shop floor and the boardroom, and the gaps between what should be done and what is actually being done," Yates says. "Integration helps to bridge those gaps, and realize those opportunities."

Origins of ISO 55000

In many ways, ISO 55000 evolved directly from PAS 55, a document originally developed by the BSI Group (London, U.K.; www.bsigroup.com) in 2004. PAS 55 was updated in 2008. Shortly after the revision, a proposal was made to establish an international standard on asset

management and ISO project committee PC251, with experts from 31 countries represented, was assembled to develop it.

Many of the principles and requirements contained in ISO 55000 came directly from PAS 55, but the two do have differences. Compared to PAS 55, ISO 55000 places a stronger emphasis on stakeholder involvement, and more emphasis on aligning the engineering side of things with the finance and accounting side of business.

Implementation and use

The ISO 55000 standards promise to be widely recognized and a relatively fast uptake is expected for the standard. However, there are challenges to its implementation. The nature of those challenges and how they are perceived by an organization depends a great deal on the level of maturity of its asset management systems and processes, says Scott Yates, from Assetivity. "Good asset management requires a high level of cross-functional alignment and coordination between the engineering, operations, maintenance and commercial side of the business," Yates explains, "and for organizations where those functions are largely siloed, simply getting these functions to talk can be extremely difficult — although also very beneficial."

For organizations new to AMSs, the most significant challenges tend to be cultural, Yates says. On the other hand, organizations whose asset management maturity is more advanced will find the challenge, at least early on, will be identifying assessors that have been certified as competent, he adds.

In addition, another potential challenge may result from variations in the way the standard's language, which tends to be general, is interpreted, Yates says. This could lessen over time, as a common understanding of the requirements emerges, he adds.

Another challenge involves leadership commitment. Implementing the standard in a real way will require buy-in from senior-level management from the beginning of the process, Davies says. "If done right, this can bring about a shift in culture" for asset management. "Culture change is difficult and can be painful, but that's where the real benefit lies," Davies remarks.

When it comes to how the standard may be used in the future, Yates believes that formal certification for, or at least alignment with, the ISO 55000 standard will increasingly become a requirement over time. Initially such requirements may occur in the power and water utilities sectors, as well as in the government sector, Yates remarks. Insurers may eventually look more favorably on ISO-55000-certified organizations, he adds, but probably only after their actuarial processes determine how the business risks change for those that are compliant versus those that are not.

Generally, however, the preferred approach would be for senior management to drive compliance from within the organization, rather than responding to an external mandate, Yates says. ■

Scott Jenkins

SUMMARY OF REQUIREMENTS IN ISO 55001

The 55001 portion of the standard outlines the requirements of the asset management system, emphasizing on what needs to be done, rather than how to do it. The following summarize several key elements within ISO 55001.

Determining scope. This section covers the creation of a strategic asset-management plan (SAMP), as well as requiring the organization to determine the criteria for asset-management decision making. The focus is on establishing the boundaries and applicability of the asset management system (AMS), and defining the specific asset portfolio that will be included in the AMS. The section also includes the requirement that the SAMP be aligned with and consistent with the organizational objectives.

Understanding stakeholder needs. The standard requires organizations to determine the stakeholders that are relevant to its AMS, and the expectations of each group.

Leadership commitment. The goal of this section is to require that the senior-level leaders of the organization demonstrate a firm commitment to the AMS by ensuring that it is integrated into the organization's business processes, as well as ensuring that the resources for the system are available, and that its importance is communicated clearly throughout the organization, among other activities. This section also issues requirements about establishing official organizational policy with regard to asset management and establishing which personnel are responsible for the various roles in maintaining and using the AMS.

Asset management planning. The planning portion of the standard focuses on addressing risks and opportunities for the AMS. The goal here is to ensure that the AMS is capable of achieving its intended outcomes and to prevent unintended and undesirable effects. This section stipulates that the asset management objectives noted in the plan are consistent with the asset management policy, are measureable to the extent possible and are monitored for possible update.

Resource support. The emphasis of this section is on determining and providing the resources necessary for the implementation, maintenance and improvement of the AMS within the organization. These resources include making sure employees performing work on asset performance and asset management have the required competencies. In addition, the resources required include other aspects, such as informational resources.

Documentation. This section of the ISO 55001 standard requires that the organization's AMS include documented information, and that the documentation is kept under appropriate control.

Operation and change management. The operation section of the standard ensures that processes are planned, implemented and controlled for implementing the actions cited in other sections of the standard. It also covers change management, including the need to address and manage risks associated with planned changes.

Performance evaluation. This section covers the need for monitoring, measurement, analysis and evaluation of asset performance, as well as the effectiveness of the overall AMS. The section requires the organization to conduct internal audits aimed at determining whether the AMS conforms to the ISO standard and is effectively implemented.

Continuous improvement. The improvement section outlines requirements for actions to be taken to correct nonconformities and incidents related to the organization's assets. In addition to corrective action, this section also covers the need for taking preventive action — proactively identifying potential failure mechanisms in asset performance — as well as requiring the organization to strive for continuous improvement in its asset management.

Related topics. ISO 55001 includes an appendix listing subject areas relevant to asset management that are addressed by other published standards. These include: data management; environmental management; systems and software engineering; non-destructive testing; project management; inspection, equipment management; energy management; and others. A bibliography cites the standards covering the above topics. ❑

MIXING IN THE SPOTLIGHT

In an attempt to increase efficiency, chemical processors consider new mixing technologies

Ajax Equipment

Chemineer

Amixon

FIGURE 1. (above left) The continuous mixer from Ajax Equipment features include an increased range of processing capability, rapid screw changeover and enhanced shaft seals

FIGURE 2. (above right) Chemineer's UltraTab static mixer is suitable for turbulent flow applications where a high degree of mixing is required in a compact space

FIGURE 3. (left) The vertical cone mixer from Amixon is suitable for mixing dry, moist and viscous materials at variable filling levels

Pressure to become more flexible and provide shorter cycle times have prompted chemical processors to examine their mixing operations to determine whether there is a way to increase process efficiency via mixing equipment. And, they just might be onto something, as modern mixing systems are designed for particular process requirements and mixing tasks, allowing them to operate efficiently. The greater efficiency allows increased productivity for existing production and enables processors to overcome existing limits with respect to product quality and quantity.

Here, experts weigh in on the various types of mixing equipment and how different technologies can provide efficiency improvements in the chemical manufacturing industry.

From batch to continuous

"In recent times, the inflexibility of batch mixers has come to the fore with their inherent interrupted process path, risk of spoiled or off-specification batches — not just waste but delaying subsequent process steps, equipment space and capacity issues," says Eddie McGee, technical director with Ajax Equipment (Bolton, U.K.; www.ajax.co.uk). "This has resulted in a movement towards continuous mixers, which offer a smaller footprint, a range of mix capacities and capabilities and the ability to monitor and adjust to ensure product mix quality in realtime."

In chemical processing, especially, continuous mixing offers significant advantages over batch mixing, he says. Continuous mixing handles a range of products, from dry powder and coating applications to wetting applications, and even the potential to mix pastes. The mixer body and the screw shafts can be heated (or cooled) as necessary, and additional materials can be added later in the mixing cycle to the already combined materials. Two other benefits of continuous mixers are the capability for continuous output and high processing flexibility. And, continuous mixing works at a smaller scale than batch mixing, giving a greater degree of control over the processing, and allowing continuous, consistent production.

For this reason, Ajax Equipment has recently introduced a new continuous mixer (Figure 1) for the chemical process industries (CPI). The mixer's features include increased range of processing capability, rapid screw changeover and enhanced shaft seals. The continuous mixer is available with both single- and twin-screw arrangements. Chemical powders are combined as they move along the screws with either dry mix or a combination of dry and wet. Ajax offers a choice of screw augers with ribbon flights or paddle flights for difficult-to-mix materials. Fabricated in stainless steel, the mixer can have a polished, crack- and crevice-free finish, if enhanced cleanability is required. These mixers can be easily cleaned between campaigns, offering flexibility on process run times and avoiding cross-contamination on sensitive applications. The screws can either be cleaned-in-place or quickly released without disrupting the drive-end motor.

Kevin Walsh, director of sales and marketing at Chemineer (Dayton, Ohio; www.chemineer.com), agrees that many chemical processors are moving away from batch mixing. "Batch mixing is often done with rotating agitators that are inventory intensive because it requires large vessels of product," he says. "Also, it's typically a higher energy-type mixing process, so many companies,

FIGURE 4. Because hydrogenation processes were traditionally limited by mass and heat transfer, and because the hydrogen is difficult to handle and such reactors must be operated absolutely gas-tight at high pressures, Ekato developed a self-aspirating gassing turbine, which is specifically applied in such reactions to overcome the mass-transfer limitation

for these reasons alone, are moving toward continuous processing or static mixing where you can mix inline, in a pipe and get your reactions and your process to perform more efficiently."

Chemineer's UltraTab static mixer (Figure 2) can provide these benefits, and more, in turbulent-flow applications where a high degree of mixing is required in a compact space. The integral wall injector upstream of the mixing element forces the additive through the high-energy dissipation region created by the mixing element, which provides mixing efficiency. Low-pressure drop through the UltraTab element enhances energy efficiency of the process and saves pump energy. And, the compact design and short mixing length reduce needed pipe lengths and optimize plant layout.

Vertical mixers

A major challenge for operators of mixing and processing plants, according to Matthias Boning, sales director and authorized officer at Amixon GmbH Mixing Technology (Paderborn, Germany; www.amixon.de) is the growing diversity of recipes at almost constant production quantities. In this respect, larger warehouses for raw materials must be kept. The supply of components "just in time" requires sophisticated production logistics. In addition, a greater variety of products also results in an increased necessity of set up and cleaning efforts, as a high degree of batch integrity and the absence of contamination are required.

For this reason, says Boning, it is important that the mixing apparatus meets all possible requirements in terms of process engineering. "It must achieve a technically perfect mixing quality in a short time. The preparation process must be adjustable to meet changing requirements and be very gentle when the components involved in the formulation are sensitive to abrasion and shear or provide effective deagglomeration treatment at high energy input, if aggregates or agglomerates should be dissolved, and all particles should be separated."

In addition, he says, the mixer must be able to disperse liquid substances into powder, no matter whether the goods are low or high viscosity, or if the distribution of the liquid material takes place in a gentle or intensive deagglomerating way. Finally, the mixer should be able to achieve an ideal mixing quality, regardless of its filling degree.

Amixon's vertical mixers (Figure 3) meet these requirements, according to Boning. The vertical cone mixer, especially, is suitable for mixing dry, moist and viscous materials at variable filling levels. The spiral mixing blade initiates a three-dimensional flow of the mixing goods, creating a helical upward movement on the periphery and downward flow in the center. The conical mixer guarantees very good mixing results and complete discharge. It can be used for dry powder, wet suspensions and liquids, pastes and doughs. If the mixing process requires deagglomeration, high-speed cutting rotors can be installed. The mixing device is driven from the top, using only a single top bearing. And jacketed and vacuum-rated versions serve as suitable mixer-dryers or reactors, providing further flexibility.

Tailor-made agitation systems

"The chemical industry is under constant pressure to manufacture an increasing number of chemical compounds in shorter and shorter

product life cycles," says Peter Rojan, deputy sales manager at Ekato (Schopfheim, Germany; www.ekato.de). "Modern manufacturing processes are as complex and just as varied as the products themselves. It is therefore difficult for chemical processors to develop the optimum agitation solution themselves with respect to process requirements, investment and operating costs and energy and resource efficiency."

While modern mixers are designed for particular process requirements and mixing tasks, allowing them to operate efficiently, an integrated approach to tailor such agitation systems to the actual process conditions makes them also extremely robust and reliable so that downtime and repair costs are also minimized, says Rojan.

"The integrated agitation solutions go beyond the actual agitator, and are based upon a case-by-case analysis of the actual industrial requirement," he says. "They apply state-of-the-art impellers that are adapted for the specific mixing task. The complete agitation systems are carefully tailored to the vessel geometry and are built out of materials and components that are individually designed to meet maximum reliability and minimum investment costs."

A typical example of such a tailor-made agitation system is Ekato's range of hydrogenation reactors (Figure 4). "Hydrogenation processes were traditionally limited by mass and heat transfer. At the same time, the hydrogen is difficult to handle and such reactors must be operated absolutely gas-tight at high pressures," he says. "At Ekato, we developed a self-aspirating gassing turbine, which is specifically applied in such reactions to overcome the mass-transfer limitation."

Charles Ross & Son

FIGURE 5. Charles Ross & Son's SLIM Solids Injection Technology consists of a rotor and stator mixing arrangement, specially designed to create negative pressure (vacuum) behind the rotor

High-shear mixing

"Sometimes processors are using equipment that isn't well suited to their process," says Ken Langhorn, technical director with Charles Ross & Son Co. (Hauppauge, N.Y.; mixers.com). "That's obviously an inefficiency in and of itself, but often we find they are using a low-speed agitator, which results in a reaction taking a long time to occur and using more energy than is necessary. Often, they can benefit by having a more intense mixing arrangement to process the product quicker. Instead of 12 hours of slow agitation, they can do the same batch in 20 mininutes using something more vigorous."

For this reason, Langhorn says many processes can benefit from high-shear mixing. "The interaction between the rotor and stator generates a lot of shear between liquids, which helps increase the efficiency," he says. "In some chemical processes, while generating an emulsion or dissolution, processors can benefit from having high shear mixing within the batch to more quickly generate the emulsion or more quickly dissolve the materials."

He adds that some of the high-shear mixers can directly incorporate powders into liquids. In many processes, that would normally require a two-step process, so this technology can provide a large efficiency gain.

Ross's SLIM Solids Injection

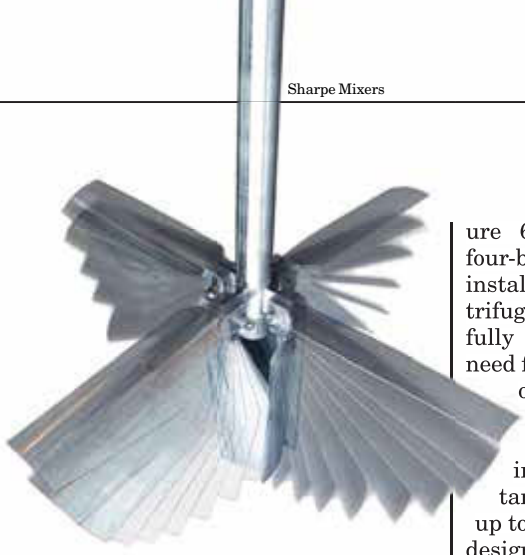


FIGURE 6. Sharpe Mixers offers a folding blade impeller, which features a hydrofoil-style, four-blade design that folds for easy installation and opens with centrifugal force, locking in place when fully opened

Technology (Figure 5) consists of a rotor and stator mixing arrangement, specially designed to create negative pressure (vacuum) behind the rotor, which can be used as the motive force to suck powdered (or liquid) ingredients directly into the stream of the incoming liquid. The resultant powder/liquid mixture is then expelled centrifugally through the openings in the fixed stator before exiting the tangential discharge connection.

The Inline SLIM differs from other powder induction systems in that it does not usually require the use of a centrifugal pump on the inlet or outlet side to create the suction for the induction of powders. Also, it does not use an eductor to create the suction, thereby making the Inline SLIM more tolerant of flow and viscosity changes.

Impeller improvements

"One of the many challenges faced by chemical processors includes lowering costs by reducing labor and increasing efficiency," says Jeremy Higginson, vice president of engineering with Sharpe Mixers (Seattle, Wash.; www.sharpemixers.com). "Some vessels require large expenditures of labor and permits to enter due to their hazardous nature, so we developed a folding impeller that can fit through the mixer nozzle and lock in place by itself after operation."

The folding blade impellers (Figure 6) feature a hydrofoil-style, four-blade design that folds for easy installation and opens with centrifugal force, locking in place when fully opened. This eliminates the need for personnel to enter the tank or vessel. They are designed for new and retrofit installations that do not allow for impeller assembly inside of a tank. They are available in sizes up to 210 inches in diameter. Their design permits greater flexibility in tank designs, and the blade locking mechanism can be accessed from outside the tank for removing the mixer if needed.

"Costs can also be reduced by using higher efficiency components," says Kyle Sides, applications engineer with Sharpe Mixers. "Premium efficient motors, higher efficiency gearboxes and hydrofoil-style impellers can all contribute to reduced costs. The more efficient impeller results in less power usage for the same mixing. This can add up to thousands of dollars over the course of a year for a given plant and improve the payback period of the new capital equipment."

Sharpe's Hyflo impellers are among the most energy efficient. The Hyflo 218 is a universal energy-efficient, low-blade angle impeller. The high-flow efficiency is a direct result of the blade characteristics. During development, particular attention was given to the camber of the blade and the blade angle. The camber approximates the shape of an airfoil to provide maximum flow efficiency. The camber is the amount of apparent arch to the blade when viewed from the end of the blade towards the hub. The proper amount of camber allows the blade to be operated at higher blade angles without incurring a stalled condition.

Obviously, it makes sense to get a feel for the mixing technologies that are available today. An update or different type of mixer may make your chemical process more time and energy-efficient, saving money, reducing downtime and increasing throughput. ■

Joy LePree

The Witte Co.

FOCUS ON

Drying and Evaporation

JM Science

Genevac

Dinnissen B.V.

An oil evaporator for difficult sample matrices

The AquaCounter EV-2000L oil evaporator (photo) utilizes azeotropic distillation and completely separates water from sample matrices, thus eliminating any side reactions with interfering substances. The oil evaporator is especially useful for determining moisture in difficult samples, such as heavy oils, grease, peanut butter and so on. The CE-approved EV-2000L can be used with the AquaCounter Karl Fischer titrators, or any other manufacturer's titrators. The heating range is from ambient temperature to 200°C. The carrier gas is N_2 gas or dry air and flow is 30–300 mL/min with an inlet pressure at 0.8 MPa or less. The dessicant used is a molecular sieve and the unit has an aluminum block heater. — *JM Science, Inc., Grand Island, N.Y.*
www.jmscience.com

A powerful evaporator for drug discovery

The HT-4X centrifugal evaporator (photo) provides optimized sample preparation capabilities for scientists working in the area of drug discovery. Corrosive vapors, such as trifluoroacetic acid, may be removed by the standard system and an inert purge option allows high-safety evaporation of flammable solvents. In addition, the HT-4X can also be used to achieve high-speed lyophilization of HPLC (high-performance liquid chromatography) fractions and solvents used for reformatting samples. The HT-4X features a built-in, dual-chamber refrigerated condenser that combines a powerful cryopump and solvent-recovery system, together with extra powerful infrared (IR) lamps. The combination accelerates the speed of evaporation, even for high-boiling-point solvents such as DMSO. In addition, efficient chamber cooling between runs is particularly useful to protect thermally sensitive samples when run immediately after higher boiling-point solvents. The company's patented SampleGuard and Dri-Pure technologies are included to protect samples from overheating and bumping. — *Genevac Ltd., Ipswich, U.K.*
www.genevac.com

A mixer that's also an energy-efficient dryer

The Pegasus Mixer features a double-shaft paddle mechanism that gently throws powders, granules and granulates into the air during mixing. The fluidized zone created allows the multifunctional processing unit to mix ingredients extremely gently, quickly and energy-efficiently, says the company. The new drying functionality built into the mixer also takes advantage of this fluidized zone, and prevents agglomeration during the drying process. — *Dinnissen B.V., Sevenum, the Netherlands*
www.dinnissen.nl

A stand-alone vacuum sampler for producing powders

This company has developed stand-alone vacuum sampler technology (photo) that can be retrofitted to large-volume powder-production lines widely used in the manufacture of infant formula and dairy powders. Vacuum sam-

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

The Grieve Corp.


GEA Avapac


Powder Systems Ltd.

pling technology enables a plant to monitor product quality more effectively than traditional "bobbin" or "screw" sampling methods, which can themselves introduce bacteria to the powder being processed. The vacuum sampler extracts small amounts of product throughout the manufacturing process. These samples are transferred via a one-way airflow to the sample unit. Vacuum pipes and valves are kept clean with regular purging (air cleaning) to remove any powder residue. The sample is then tested in a laboratory for possible inconsistencies, such as composition or the unwanted presence of bacteria. After successful analysis, the corresponding batch is released for packaging and distribution. — *GEA Avapac Ltd., Hamilton, New Zealand*
www.avapac.com

This walk-in oven dries resins at 750°F

The No. 941 (photo) is an electrically heated 750°F (~399°C) walk-in oven used for drying resin mixtures at an operator's facility. Power (60 kW) to heat the unit is installed in Incoloy-sheathed tubular elements, while a 4,200 ft^3/min, 3-hp recirculating blower provides horizontal airflow across the load. This walk-in oven features 6-in. insulated walls throughout, Type 304 2B stainless-steel interior with continuously welded seams, stainless-steel exterior with #4 brushed finish and heavy-duty double front doors. No. 941 also features a digital programming temperature controller and 10-in.-dia. circular chart recorder onboard. — *The Grieve Corp., Round Lake, Ill.*
www.grievecorp.com

Rail-mounted FB dryers provide easy access for cleaning

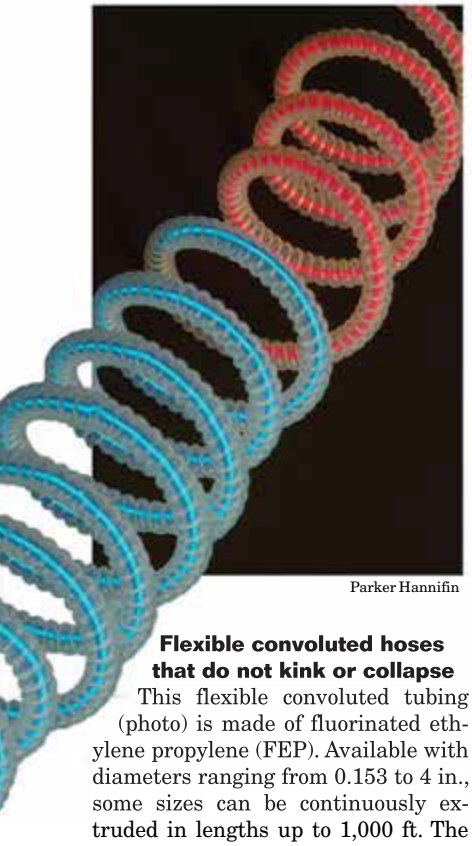
Vibrating fluidized-bed (FB) dryers and coolers from this process-equipment manufacturer are available mounted on rails (optional; photo) to allow easy, unobstructed access for cleaning, maintenance and visual inspection. During washdowns or for product changeovers, the entire drying and cooling sections spanning the complete length of the thermal processing system may be rolled out by one person and then rolled back into place without any tools. Specified for high-capacity fluidized-bed dryers and coolers where access for inspection and cleaning are paramount, the rail-mounted vibratory dryers and coolers are ideal for foods, pharmaceuticals, chemicals, aggregates and other products that require dry processing. The steel rails include cushioned bumpers and are mounted into the flooring during dryer installation. — *The Witte Co., Washington, N.J.*
www.witte.com

Microsphere formulation with this sterile filter dryer

Microspheres are small (5–250 μm) spherical particles manufactured from natural and synthetic materials, and are being used in applications from coatings to cosmetics and drug delivery. This company has developed processes for the production of such materials. The company's design uses side and bottom filtration, which achieves size classification — the most difficult task associated with microsphere production. Some processes require a scalping pre-filtration step to reduce the large volumes of liquid involved and to eliminate the oversized microspheres. This is achieved in the company's Scalping Filter prior to transfer into the Microsphere Filter Dryer. The equipment is designed with steam-in-place and drainability capabilities. The Microsphere Sterile Filter Dryer (photo) is tiltable to accommodate a sterile discharge. — *Powder Systems Ltd. (PSL), Liverpool, U.K.*
www.powdersystems.com ■

Gerald Ondrey

FEBRUARY
New Products



Parker Hannifin

Asahi/America

Radleys

Seepex

Flexible convoluted hoses that do not kink or collapse

This flexible convoluted tubing (photo) is made of fluorinated ethylene propylene (FEP). Available with diameters ranging from 0.153 to 4 in., some sizes can be continuously extruded in lengths up to 1,000 ft. The tube's convolutions give flexibility, allowing tubes to turn sharp corners and be routed through tight areas without kinking or collapsing, while still retaining the ability to self-drain. Spring wire can be added if additional crush resistance is needed. FEP convoluted tubes can operate at temperatures up to 400°F (205°C) and can be customized to fit specific application requirements, including pitch configurations and product tolerances. — *Parker Hannifin Corp., Cleveland, Ohio*
www.parker.com

This tool removes oxidation from plastic pipes prior to welding

The new PREP (peel, remove, edge and plane) tool (photo) prepares thermoplastic pipes for socket welding by removing oxidation. Being able to remove naturally occurring oxidation from pipe made from thermoplastic materials, such as polypropylene and polyethylene, decreases installation and maintenance time. Using this tool, the outside layer of the pipe is removed, the edge of the pipe is beveled to ensure easy insertion into the socket fitting, and the face of the pipe is planed to straighten uneven cuts. Available in six sizes ranging from ½- to 2-in., the PREP tools are available individually or in kit format, with manual handles and spare blades also available. — *Asahi/America, Inc., Malden, Mass.*
www.asahi-america.com

Metering pumps that are safe for water-treatment processes

These metering pumps (photo) have been certified to meet the NSF 61 standard for use in treating water and wastewater, as well as drinking water processes. The pumps are certified as safe for use in applications involving sodium hypochlorite, ferric chloride, sodium bisulfate, potassium permanganate, sodium silicofluoride, calcium fluoride, and most other chemicals commonly used in water and wastewater flocculation, clarification, sterilization and buffering. This certification requires leaching and toxicity texts for pump components, as well as traceability for all pump components back to the mill, foundry or chemical plant that produced the materials of construction. — *Seepex Inc., Enon, Ohio*
www.seepex.com

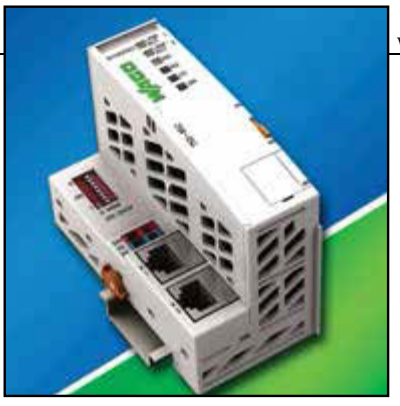
This pilot-scale reaction system saves space and setup time

The new Reactor-Ready pilot (photo) is a universal, pilot-scale jacketed reaction system designed for use with a range of vessels (from 5–20 L) in process development, scaleup and pilot-plant laboratory applications. This reactor workstation can replace multiple frameworks, saving fume-hood space and eliminating the need for multiple setups. The pilot assembly features quick-release couplings for clamps and hoses, which allow rapid vessel changeover, without the need for extra tools.

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

Larson Electronics

WAGO



Wide-bore hose and vessel connections offer maximum flowrates, effective heating and cooling performance and easy thermofluid draining during vessel exchange. Powerful overhead stirring is possible through the unique self-aligning stirrer coupling. — *Radleys Discovery Technologies, Essex, U.K.*
www.radleys.com

Illuminate vessel interiors with this portable tank lamp

The new EPLC2-16C-150LED explosion-proof LED tank light (photo) is mounted on a wheelbarrow with 250 ft of cord included for portability and easy access to equipment. The LED lamp provides light coverage to work areas as large as 10,000 ft^2, and its floodlight pattern is intended especially for illuminating enclosed areas. Its 16-in. removable light head allows the unit to fit through standard-sized vessel manholes or entry passages. The lamp also offers 360 deg of rotation and 90 deg of tilt. Included with the lamp are 25 mylar overspray lamp-protectors that protect against dirt and debris. The unit is multi-voltage capable and can be configured to operate on 120–277 V. — *Larson Electronics, LLC, Kemp, Tex.*
www.larsonelectronics.com

Manage this controller via a convenient Web-based portal

The 780-852 Eco Ethernet Controller (photo) simplifies network wiring with its built-in two-port Ethernet switch. This versatile, programmable controller allows users to quickly complete configuration and diagnostics through an integrated Web-based management system, accessible through a Web browser. Power is supplied via a connector that is integrated into the compact controller's outer housing, saving space and increasing I/O placement flexibility. The 780-852 also features an enhanced high-speed processor. — *WAGO Corp., Germantown, Wisc.*
www.wago.us ■

Mary Page Bailey

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Chemical Protective Clothing

Workers in the chemical process industries (CPI) can wear chemical protective clothing to protect themselves from exposure to potentially hazardous chemicals in the form of vapor, liquid and solid particles. While chemical protective clothing has not been regulated to the extent that safety glasses, hard hats and some other forms of personal protective equipment (PPE) have been, an international standard is available for classifying the performance of chemical protective equipment.

When testing chemical protective clothing (CPC), a two-pronged approach is taken, where the whole garment is tested as well as the individual components. Testing both separately is an integral part of evaluating the overall integrity and expected performance of the CPC.

ISO 16602

ISO 16602 ("Protective clothing for protection against chemicals—classification, labeling and performance requirements") provides an objective system to appropriately test, classify and label chemical-protective apparel. The requirements outlined in ISO 16602 provide a common language for the performance of chemical protective clothing.

ISO 16602 designates minimum performance levels of protective clothing for six types of chemical hazards. The performance requirements are based on results from existing test-method standards, and the garment type designation is based upon the physical state of the hazard (vapors, liquids, aerosols or particles; Figure 1). The garment types are as follows:

- Type 6: Limited protection against liquid mist
- Type 5: Protection against airborne solid particulate chemicals
- Type 4: Protection against liquid aerosols
- Type 3: Protection against pressurized liquid chemicals
- Type 2: Non-gas-tight protection
- Type 1: Gas-tight (vapor-protective) protection against chemicals and vapors and toxic particles

Although ISO 16602 permits a range of performance levels for a series of key properties, it also establishes a minimum level of performance for each major type of hazard.

Each workplace environment is unique, and the ISO 16602 Standard does not consider all specific hazards that may be present. Safety and occupational health professionals should consider hazards that are specific to their work conditions and then consult the ISO 16602 standard to determine the minimum requirements of chemical protective garments used in the particular situation.

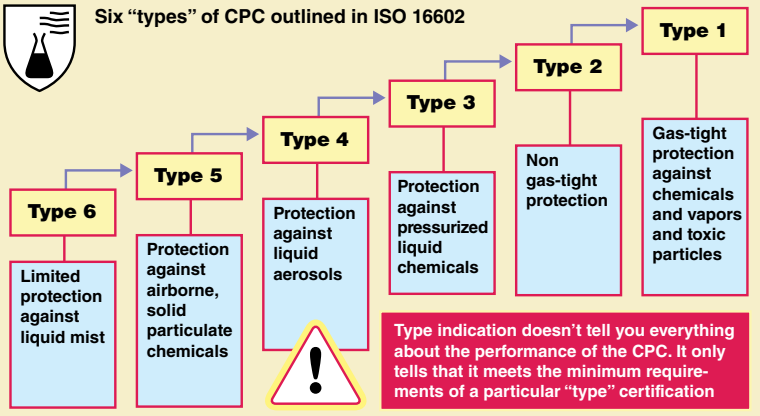


FIGURE 1. ISO 16602 provides an objective system to appropriately test, classify and label chemical-protective apparel. The standard designates minimum performance levels of protective clothing for six types of chemical hazards. The garment type designation is based upon the physical state of the hazard (vapors, liquids, aerosols or particles)

ISO 16602 focuses exclusively on typical chemical hazards and protective clothing requirements for those hazards, so each work situation will likely require additional forms of PPE, possibly including footwear, gloves, face protection, fall protection and respirators.

Hazard assessment

A hazard assessment provides a basis for understanding what chemical protective clothing and other PPE are necessary to protect the workers operating in specific situations. The environment, chemical hazard and work activity must be considered in selecting the protective clothing — including the fabric, seam type and garment design — that is most suitable. The goal is to select clothing with adequate protection, but without overprotecting a worker with unnecessary clothing, which can result in heat stress, reduced field of vision, restricted mobility and increased physical exertion for the wearer, as well as higher costs for the employer.

Performance testing

When setting the requirements for each clothing type in ISO 16602, the entire garment is tested in addition to the individual components.

Whole-garment tests. During whole-garment tests, a human subject wears the test garment and accompanying PPE, such as gloves, boots and respirator. The subject is exposed to non-hazardous test chemicals inside an enclosed chamber while performing a series of movements meant to simulate actual work activities. This whole-garment testing is used to validate the barrier performance of the entire ensemble against a specific type of chemical threat (gas, liquid or particle). Test chemicals are used to determine how much of a similar-phase chemical will leak into the suit.

Class tests. Whole-garment tests do not evaluate the chemical permeation properties of the garments. This is assessed in the class testing portion of ISO 16602. Beyond the whole-garment tests, additional tests are conducted on the garment's fabric(s) and components to qualify the class performance level.

Within each of the six garment types, there are also requirements directed at the mechanical, barrier and basic flammability properties of the fabrics, and components used to make chemical protective clothing. Laboratory tests are used to determine the mechanical durability, the barrier against specific chemical hazards, and ease of ignition of the garment materials. The results of these tests will fall into a unique performance class. Each type within ISO 16602 specifies a combination of barrier and durability tests levels, establishing a minimum performance class for each of the tests to meet the specific type requirements. A higher class rating denotes a higher level of performance for that property.

The flammability requirements outlined in ISO 16602 establish a minimum performance level of flame spread once the material is ignited; it does not qualify an ensemble as suitable for protection against heat and flame hazards. Heat and flame protection is not in the purview of ISO 16602, but is covered within fire safety standards from the National Fire Protection Association (NFPA; Quincy, Mass.; www.nfpa.org).

Editor's note: This "Facts at your Fingertips" column was adapted from the following article: Lovasic, S., Chemical Protective Clothing, Chem. Eng., March 2011, pp. 51–53.

Technology Profile

Polypropylene Production via Gas-Phase Process: Stirred-bed reactor

By Intratec Solutions

Since 1956, polypropylene has been commercially produced using catalysts and technology that were developed from independent research by Karl Ziegler and Giulio Natta. Their namesake catalysts have enabled the widespread use of this polymer in the decades since. Polypropylene has become a major part of the modern plastics-resin market because of its unique physical properties, and is now employed in a wide range of applications from food packaging to automotive plastics.

Historically, polypropylene has been produced at industrial scale by three main polymerization approaches: hydrocarbon slurry or suspension processes, bulk-phase processes and gas-phase processes. Two leading technologies for gas-phase polypropylene production are Unipol, a fluidized-bed reactor process offered by the Dow Chemical Co. (Midland, Mich.; www.dow.com), and Novolen, a stirred-bed reactor process developed by Lummus Novolen, now a part of Chicago Bridge and Iron Co. N.V. (The Hague, The Netherlands; www.cbi.com). A process similar to Unipol was discussed in this column last year (*Chem. Eng.*, May 2013, p. 33). Here, Figure 1 depicts a gas-phase process similar to Lummus Novolen's stirred-bed reactor technology.

The process

Propylene conversion to polypropylene is achieved through the use of a Ziegler-Natta catalyst. This process occurs in a continuous vertical stirred reactor at mild temperatures (about 80°C). The overall yields are typically >99 wt.%. The process can be divided in three main areas: purification and reaction; resin degassing and pelletizing; and vent recovery.

Purification and reaction. The polymerization catalysts are sensitive to several impurities, such as oxygen and water. To meet these exposure restrictions, purification equipment is used before the reaction.

In the polymerization area, fresh purified propylene is mixed with a recycled monomer stream and is fed to the reactor along with the catalyst, co-catalyst and hydrogen. The heat of polymerization is removed from the reactor by condensing propylene gas from the top of the reactor and recycling the liquid back into the agitated reactor.

Resin degassing and pelletizing. The outlet reactor stream goes to a discharge vessel to be separated. The polymer powder is sent to a purge vessel, while the carrier gas goes through a cyclone and a filter and is finally sent for recovery. Nitrogen is used to remove residual monomer from the polymer powder and then the N_2 gas is also sent for recovery.

The polymer powder then goes to a screw extruder, where the powder and additives are melted, compounded and homogenized. After being extruded, the pellets are carried to a centrifugal dryer.

Vent recovery. The carrier gas is compressed and one portion of it is sent back to the reactor. The other portion is sent to a recovery unit. The nitrogen and propylene streams from the purge vessel are recovered and separated in a membrane unit. The nitrogen is recovered to the process, while the monomer goes to a propylene-propane splitter (inside the purification area of the propylene supplier, if the plant is part of a petrochemical complex).

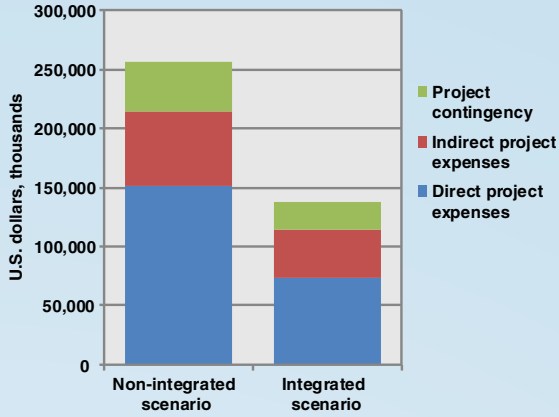


FIGURE 2. Total fixed investment according to integration scenario

Economic performance

An economic evaluation of the process was conducted based on data from the first quarter of 2013 for a plant with a nominal capacity of 300,000 ton/yr, erected in the U.S. Gulf Coast region (the required process equipment is represented in the simplified flowsheet). Two scenarios were analyzed:

1) Integrated scenario. This case is based on the construction of a plant linked to a propylene supplier. In this scenario, the nearby unit continuously provides propylene, and receives impure propylene for purification. Thus, no storage for propylene is required. However, storage of products is equal to 20 days of operation.

2) Non-integrated scenario. This case corresponds to a grassroots unit. Thus, 20 days of operation was considered for both products and raw materials. In addition, this scenario includes a propane-propylene splitter.

The level of integration is a key factor in this process, since it can determine whether the process is profitable or not. The level of integration causes the total fixed investment (Figure 2) and manufacturing expenses to vary greatly. In terms of manufacturing expenses, in non-integrated plants, propylene is purchased at higher prices, while in integrated complexes, it can be obtained directly from the supplier at a lower cost. ■

Edited by Scott Jenkins

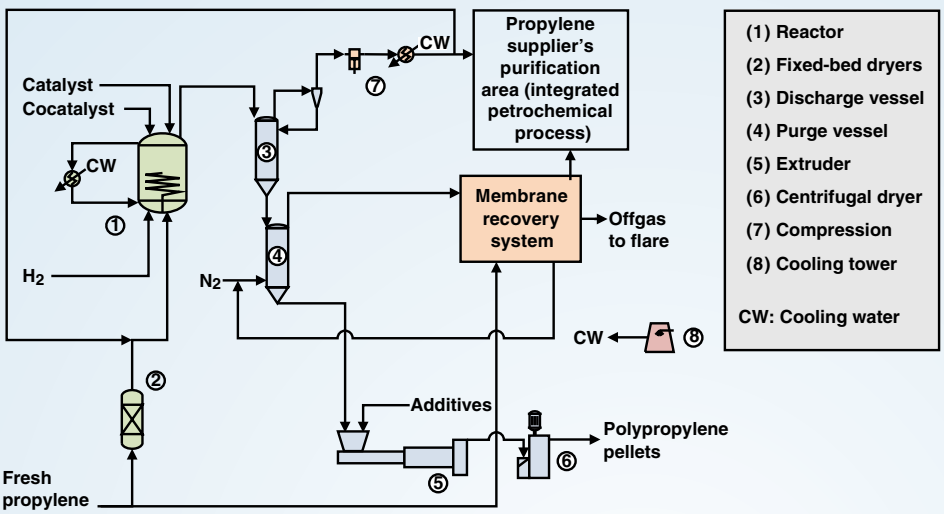


FIGURE 1. Polypropylene production via a gas-phase process similar to that of Lummus Novolen

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 herein are prepared on the basis of publicly available and non-confidential information. The information and analysis are the opinions of Intratec and do not represent the point of view of any third parties. More information about the methodology for preparing this type of analysis can be found, along with terms of use, at www.intratec.us/che.

Compressible Fluid Flow Calculation Methods

A generalized comparison of three pressure-drop calculation methods is developed, guiding engineers in making the proper assumptions when evaluating compressible fluid flow

Fucheng Teng, Pedro Medina and **Mark Heigold**
Jacobs Canada, Inc.

Compressible gas flow with significant variation in density along pipes is commonplace in the chemical processing industries (CPI). In designing these pipes for compressible flow, it is important to calculate the pressure loss or maximum gas-handling capacity for safety and economic reasons.

Due to the complexity of the equations for compressible flow, which often require time-consuming iterations, current engineering practice considers three special flow conditions to simplify calculations: incompressible (fluid density is constant), isothermal (fluid temperature is constant) and adiabatic (there is no heat transfer between the fluid and its surroundings). However, when flow conditions are unknown, and assumptions must be made, engineers can become concerned with the accuracy of calculations. Through thorough derivations and analysis of literature, this article will delve deeper into pressure-drop calculation methods to form a valid comparison of each method.

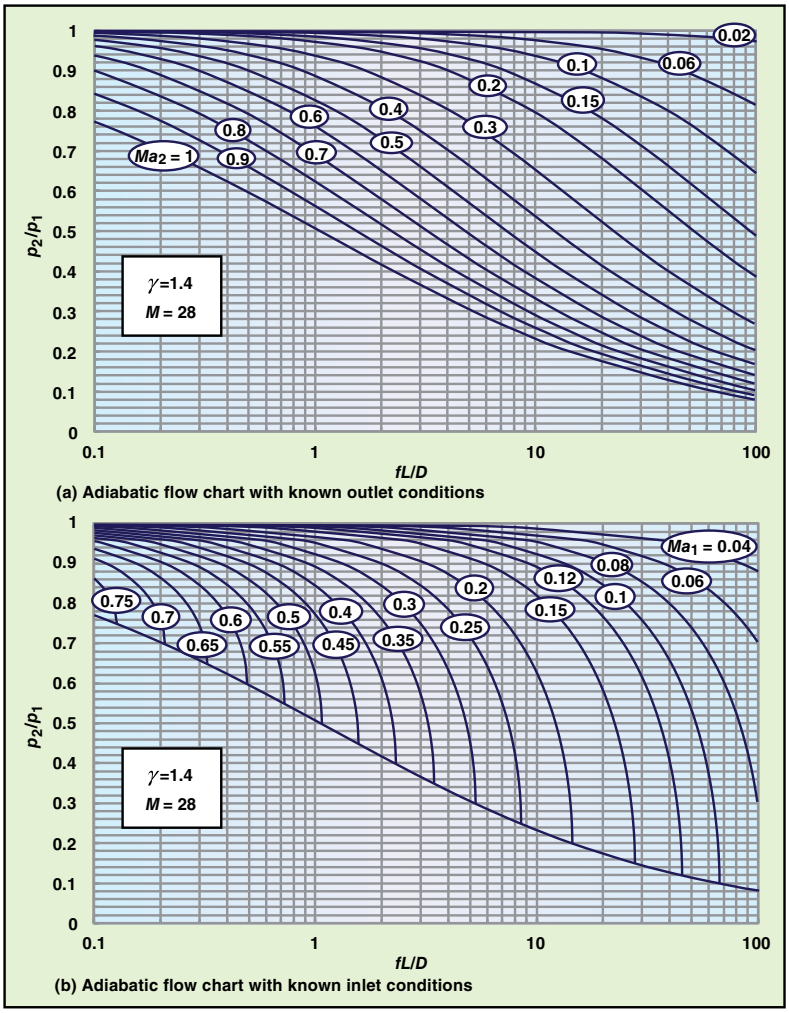


FIGURE 1. These typical adiabatic flow charts can be used to determine pressure drop for known inlet or outlet piping conditions

Amidst the confusion of choosing the proper pressure-drop calculation method, two questions arise that must be addressed. Firstly, engineers may wonder which equation is more conservative, in terms of pressure-drop calculations: isothermal or adiabatic? API Standard 521 [*1*] recommends the isothermal method to size all pipes in relief systems, with the exception of cryogenic conditions, where the adiabatic equation is preferable. Yu [*2*] finds that the isothermal equation method is not always as conservative when compared with the adiabatic method, which is sometimes more conservative depending on inlet pressure and other fluid properties.

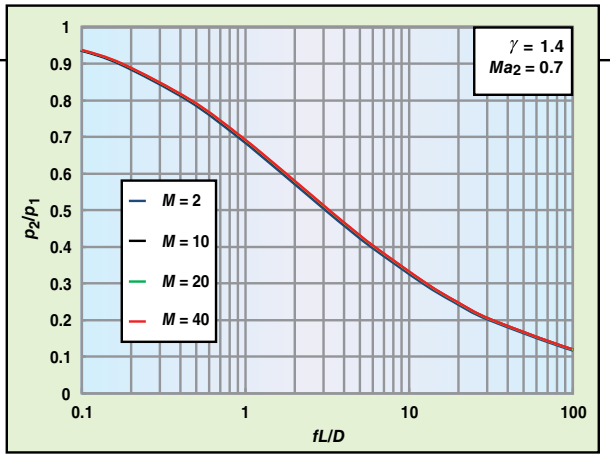


FIGURE 2. The effect of molecular weight on adiabatic pressure drop with known outlet conditions is minimal

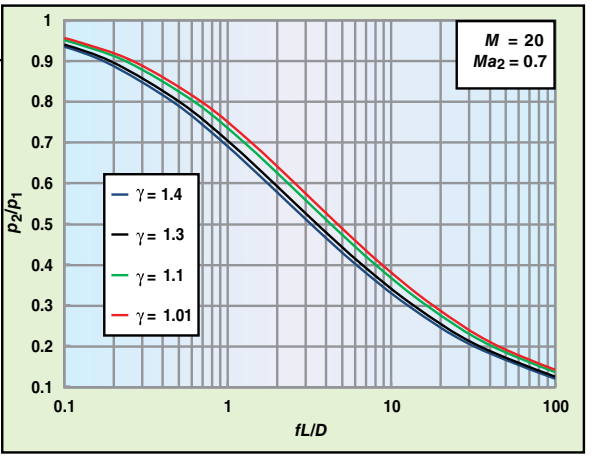


FIGURE 3. Specific heat ratio's effect on pressure drop is shown for fluid in adiabatic flow with known outlet conditions

NOMENCLATURE

c_p	Heat capacity (constant pressure)
D	Pipe diameter
f	Darcy friction factor
f_a	Acceleration factor
G	Mass flux
h	Enthalpy, static
L	Total pipe length
M	Molecular weight
n	Molar flux
p	Pressure
R	Ideal gas constant
T	Temperature
X	Pipe length
α	Ratio of downstream to upstream pressure
β	Ratio of squared upstream Mach number to squared downstream Mach number
υ	Velocity
ρ	Density
γ	Specific heat ratio
φ	Dimensionless group defined by Equation (23)
η	Difference between calculated pressure using isothermal equation and incompressible equation

SUBSCRIPTS

1	Pipe inlet	i	Isothermal	c	Critical
2	Pipe outlet	a	Adiabatic	m	Average

The second major concern engineers may have is determining when it is appropriate to assume incompressible flow. Accepted literature [3] concludes that the incompressible equation can be applied if the density does not vary by more than around 30%. It is reported [4] that the incompressible equation can be employed using an average density when the pressure drop is less than 40% of the inlet pressure. This article will clarify these concerns and will demonstrate which pressure-drop calculation methods are most appropriate in various scenarios.

Compressible fluid flow

First, the basics of fluid flow in pipes must be discussed. The flow of an ideal gas through a horizontal pipe with constant cross-sectional area is governed by Newton's second law, the first law of thermodynamics, the ideal gas law and the law of conservation of mass. Equation (1) defines Newton's second law. For definitions of the symbols and abbreviations used throughout this article, please refer to the "Nomenclature" section.

$$dp + \frac{f}{D}\frac{\rho v^2}{2}dx + \rho v dv = 0 \quad (1)$$

The first law of thermodynamics (steady-state) is shown in Equation (2), where h is specific enthalpy.

$$dh + d\frac{v^2}{2} = 0 \quad (2)$$

The ideal gas law, shown in Equation (3), is crucial for fluid-flow calculations.

$$pv = nRT \quad (3)$$

Equation (4) illustrates the law of conservation of mass.

$$dpv = 0 \quad (4)$$

The conditions corresponding to incompressible, isothermal and adiabatic flow must also be defined. These are shown in Equations (5), (6) and (7) below.

Incompressible flow:

$$d\rho = 0 \quad (5)$$

Isothermal flow:

$$dT = 0 \quad (6)$$

Adiabatic flow:

$$dh = -c_p dT \quad (7)$$

By inserting any of Equations (5), (6) and (7) into Equations (1) through (4), the incompressible, isothermal and adiabatic flow equations can be derived accordingly.

Another important term that must be defined is the Mach Number (Ma), which is the ratio of gas velocity to the local sonic velocity, as shown in Equation (8).

$$Ma = \frac{v}{\sqrt{\frac{\gamma RT}{M}}} \quad (8)$$

When Ma ≥ 1 (gas velocity exceeds sonic velocity), sonic choking occurs. The expression for Mach number is independent of flow conditions.

Isothermal flow

In isothermal flow, the fluid temperature remains constant. By using Equations (1) through (4) and Equation (6), Equations (9) and (10) for isothermal flow of ideal gases at known upstream or downstream conditions can be derived [5].

Equation (9) is used when upstream conditions are known. Here, Mi is used to denote Mach Number, as the specific heat ratio γ is not present.

$$f\frac{L}{D} = \frac{1}{Mi_1^2}\left[1 - \left(\frac{p_2}{p_1}\right)^2\right] - \ln\left(\frac{p_1}{p_2}\right)^2 \quad (9)$$

Equation (10) is used when downstream conditions are known.

$$f\frac{L}{D} = \frac{1}{Mi_2^2}\left[\left(\frac{p_1}{p_2}\right)^2\right]\left[1 - \left(\frac{p_2}{p_1}\right)^2\right] - \ln\left(\frac{p_1}{p_2}\right)^2 \quad (10)$$

In Equations (9) and (10), Mi_1 and Mi_2 are inlet Mach number and outlet Mach number, respectively, and they are given by Equations (11) and (12).

$$Mi_1 = \frac{\upsilon_1}{\sqrt{\frac{RT}{M}}} \quad (11)$$

$$Mi_2 = \frac{\upsilon_2}{\sqrt{\frac{RT}{M}}} \quad (12)$$

Unlike Equation (8), Equations (11) and (12) do not have a physical meaning, they are just the result of grouping υ, T and M together when deriving the isothermal equation [5]. In order to distinguish from the Mach number expressed in Equation (8), Mi is used instead of Ma when there is no specific heat ratio (γ) in the expressions throughout this article. It can be simply demonstrated that the maximum Mi_1 is equal to one based on two boundary conditions: $fL/D \geq 0$ and $0 < p_2/p_1 \leq 1$. Since the ratio of Mi to Ma is equal to the square root of γ the isothermal flow will be choked when Ma equals one over the square root of γ.

An isothermal flow chart developed by Mak [6] is one of two graphical methods that have been adopted by API Standard 521 [1] to size discharge pipes for relief devices. In the chart, p_2/p_1 is plotted against fL/D using either Equation (9) with known inlet conditions or Equation (10) with known outlet conditions. The interested reader is referred to Branan's book [7] for the detailed procedure on how to use Mak's chart. In this article, Mak's chart is extensively used to compare the aforementioned three pressure-drop calculation methods.

Adiabatic flow

Adiabatic flow has no heat transfer into or out of the fluid. Adiabatic conditions prevail if the pipe is well insulated or if the heat transfer rate is very small compared to the fluid flow. The adiabatic flow expression illustrated in Equation (13) can be derived by using Equations (1) through (4) and Equation (7).

$$f\frac{L}{D} = \frac{1}{\gamma}\left(\frac{1}{Ma_1^2} - \frac{1}{Ma_2^2}\right) + \frac{\gamma+1}{2\gamma}\ln\frac{Ma_1^2}{Ma_2^2}\left(\frac{1+\frac{\gamma-1}{2}Ma_2^2}{1+\frac{\gamma-1}{2}Ma_1^2}\right) \quad (13)$$

There are both inlet and outlet Mach numbers in Equation (13), in contrast to only one Mach number in the isothermal equation expressions derived in Equations (9) and (10). In order to plot the adiabatic flow equation in Mak's chart, we have to find the relationship between Ma_1 and Ma_2 and eliminate one of them from Equation (13). The ratio of downstream to upstream pressure is given by Equation (14).

$$\beta = \frac{p_2}{p_1} \quad (14)$$

The ratio of squared upstream to downstream Mach number is denoted below in Equation (15).

$$\alpha = \frac{Ma_1^2}{Ma_2^2} = \frac{M\upsilon_1^2}{\gamma RT_1}\frac{\gamma RT_2}{M\upsilon_2^2} = \frac{\upsilon_1^2}{\upsilon_2^2}\frac{T_2}{T_1} \quad (15)$$

Using the ideal gas law, we arrive at Equation (16).

$$\frac{p_2}{p_1}\frac{\upsilon_2}{\upsilon_1} = \frac{T_2}{T_1} \quad (16)$$

Rearranging Equations (14), (15) and (16) gives expressions for υ_1

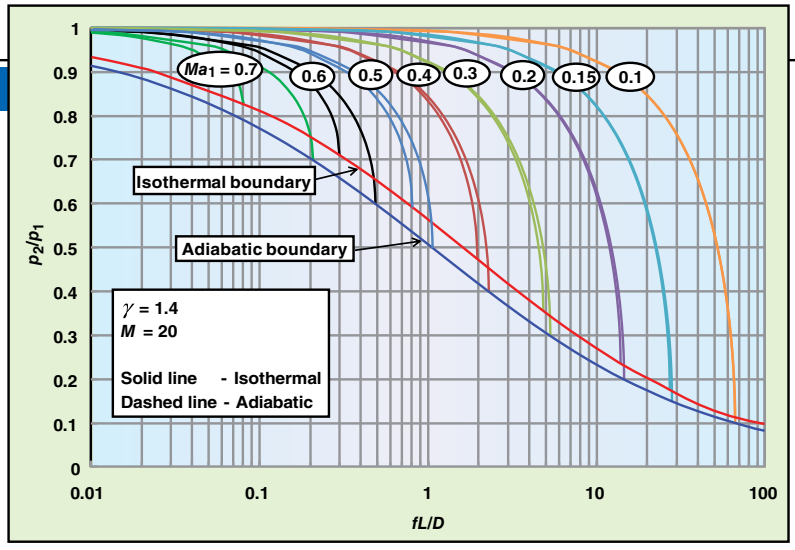


FIGURE 4. With known inlet conditions, adiabatic and isothermal fluid flow equations are compared

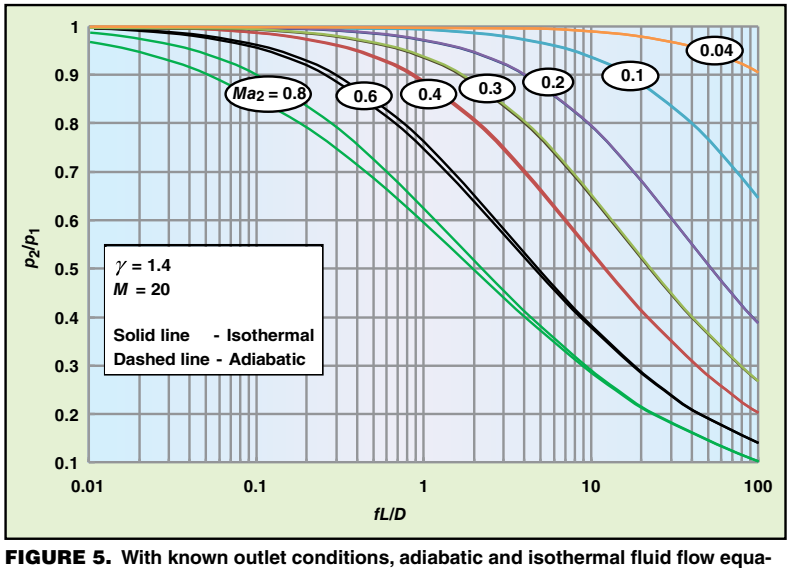


FIGURE 5. With known outlet conditions, adiabatic and isothermal fluid flow equations are compared

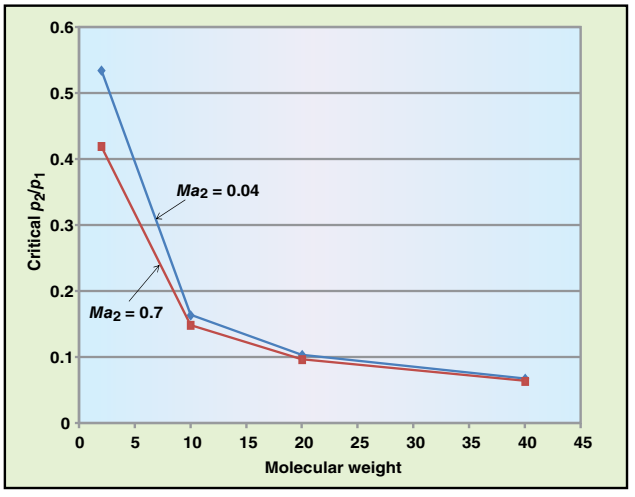


FIGURE 6. As molecular weight decreases, so does critical p_2/p_1

and T_1, shown respectively in Equations (17) and (18).

$$\upsilon_1 = \frac{\alpha}{\beta}\upsilon_2 \quad (17)$$

$$T_1 = \frac{\alpha}{\beta^2}T_2 \quad (18)$$

For an ideal gas, we know that $dh = c_p dT$ and $c_p = \gamma R/(\gamma - 1)$. Integrating Equation (2) from inlet to outlet yields Equation (19).

$$\frac{2\gamma R}{\gamma - 1}(T_1 - T_2) = \upsilon_2^2 - \upsilon_1^2 \quad (19)$$

Assuming that $T_2 > T_1$ in Equation (19), T_1 and υ_1 can be eliminated by inserting Equations (17) and (18) into Equation (19), resulting in Equation (20).

$$\frac{2\gamma R}{\gamma - 1}T_2\left(\frac{\alpha}{\beta^2} - 1\right) = \upsilon_2^2\left(1 - \frac{\alpha^2}{\beta^2}\right) \quad (20)$$

Rearranging Equation (20) gives Equation (21).

$$\frac{2\gamma R}{\gamma - 1}\frac{T_2}{\upsilon_2^2} = \frac{\beta^2 - \alpha^2}{\alpha - \beta^2} \quad (21)$$

By grouping T_2 and υ_2, Equation (21) becomes Equation (22).

$$\frac{2M}{\gamma - 1}\frac{1}{Ma_2^2} = \frac{\beta^2 - \alpha^2}{\alpha - \beta^2} \quad (22)$$

Equation (23) simplifies matters by denoting the lefthand side of Equation (22) as φ.

$$\varphi = \frac{2M}{\gamma - 1}\frac{1}{Ma_2^2} \quad (23)$$

Solving for the roots of Equation (22), and knowing that both α and φ are greater than zero, the expression's valid root is given in Equation (24).

$$\alpha = \frac{-\varphi + \sqrt{\varphi^2 + 4(1+\varphi)\beta^2}}{2} \quad (24)$$

By inserting Equation (15) into Equation (13), we get Equation (25).

$$f\frac{L}{D} = \frac{1}{\gamma}\frac{1}{Ma_2^2}\left(\frac{1}{\alpha} - 1\right) + \frac{\gamma+1}{2\gamma}\ln\alpha\left(\frac{1 + \frac{\gamma-1}{2}Ma_2^2}{1 + \frac{\gamma-1}{2}\alpha Ma_2^2}\right) \quad (25)$$

The term α is expressed as in Equation (24), or, alternatively, as shown as in Equations (26) and (27).

$$f\frac{L}{D} = \frac{1}{\gamma}\frac{1}{Ma_1^2}\left(1 - \frac{1}{\alpha}\right) + \frac{\gamma+1}{2\gamma}\ln\alpha\left(\frac{1 + \frac{\gamma-1}{2}\frac{Ma_1^2}{\alpha}}{1 + \frac{\gamma-1}{2}Ma_1^2}\right) \quad (26)$$

$$\alpha = \frac{\varphi\beta^2 + \sqrt{\varphi^2\beta^4 + 4(1+\varphi)\beta^2}}{2(1+\varphi)} \quad (27)$$

With only one Mach number in Equations (25) and (26), we can now plot the adiabatic flow equation using Mak's chart. A typical graphical representation of Equations (25) and Equation (26) is shown in Figure 1, for known outlet and inlet conditions. In Figure 1b, the dashed line represents the boundary between the subsonic and supersonic regions. Ma_2 is equal to one along the dashed line.

From Equations (25) and (26), we can also see that p_2/p_1 is affected by pipe data (fL/D), Mach number (Ma_1 or Ma_2), specific heat ratio (γ) and molecular weight (M). Figure 1 clearly shows how p_2/p_1 varies with different fL/D and Mach number. In the following section, the effect of molecular weight and specific heat ratio will be investigated.

Four virtual fluids with the same specific heat ratio (γ = 1.4) and different molecular weight (2, 10, 20 and 40) are selected for comparison. They pass through the same pipe (diameter and length) at the same mass flowrate. The outlet pressure (p_2) and Mach number (Ma_2) for all four fluids are identical. The calculated p_2/p_1 change with fL/D is shown in Figure 2. The clustering of the four curves in Figure 2 indicates that the effect of molecular weight on pressure drop is negligible.

Similarly, the p_2/p_1 values of four fluids with the same molecular weight and different γ is plotted against fL/D. In contrast to Figure 2, Figure 3 shows four curves with wide separation, indicating that, unlike molecular weight, specific heat ratio significantly affects pressure drop. At the same pipe length, p_2/p_1 decreases with increasing specific heat ratio. Since all four fluids have the same outlet pressure (p_2), a smaller p_2/p_1 in Figure 3 corresponds to larger p_1 and larger pressure drop. At fL/D values of around one, the calculated p_1 for a fluid with γ of 1.4 is about 6% higher than that for fluid with γ of 1.1.

Isothermal versus adiabatic

With the adiabatic flow equation plotted in Mak's chart, we now can compare isothermal and adiabatic flow in graphical form. A virtual fluid with γ = 1.4 and M = 20 is chosen for the comparison. The fluid passes through a pipe with a length of L and an internal diameter of D. The real flow condition is unknown, instead, we assume iso-

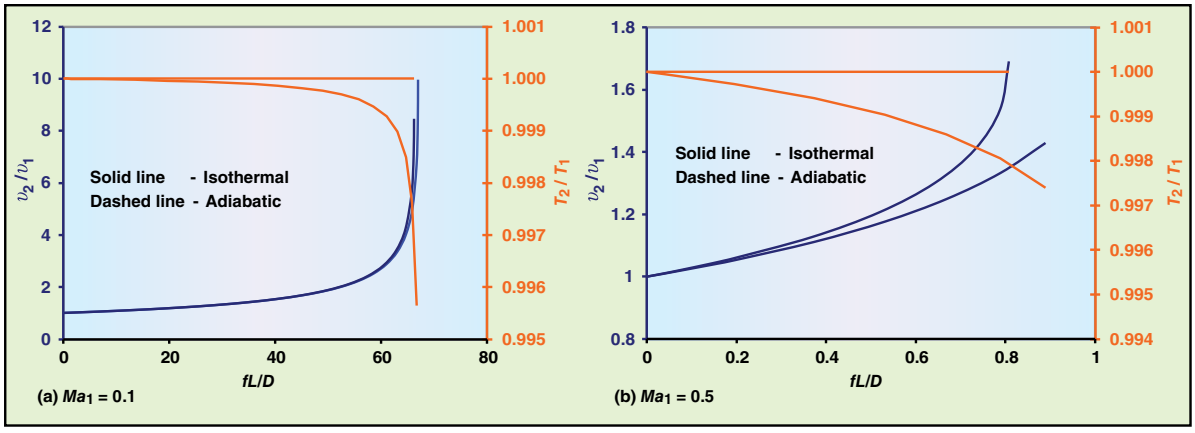


FIGURE 7. Velocity and temperature profiles of isothermal and adiabatic flow with known inlet conditions for two different Ma_1 values show that isothermal flow assumptions are generally more conservative in terms of pressure-drop calculations

thermal and adiabatic conditions for the pressure-drop calculation. The results are then compared. Two scenarios are considered in the calculation, one with known inlet conditions, and one with known outlet conditions. For both isothermal and adiabatic flow, the Mach number (Ma) based on sonic velocity, as defined in Equation (8), is used in the comparison.

Scenario 1: known inlet conditions. With inlet conditions p_1, υ_1, T_1 and Ma_1 known, outlet conditions p_2, υ_2, T_2 (which is the same as T_1 for isothermal flow) and Ma_2 must be calculated. Using Equations (9) and (26), adiabatic and isothermal curves are plotted for p_2/p_1 versus fL/D in Figure 4, where the red and blue lines represent the boundary between subsonic and supersonic region. In Figure 4, it is notable that, at large Ma_1 values, the solid line is below the dashed line, which means that calculated p_2 values for isothermal flow are smaller than that for adiabatic flow at the same fL/D.

In other words, isothermal flow provides more conservative results regarding pressure-drop calculations. Also, it should be noted that the solid and dashed lines nearly overlap with each other at small values of Ma_1, implying that the difference between isothermal and adiabatic flow assumptions is insignificant. The discrepancy only becomes obvious when the Mach number is very large (>0.3). Additionally, the red line is above the blue line, which shows that the critical pressure at the pipe's outlet (p_2), for a given flowrate and pipe length, is lower for adiabatic flow than for isothermal flow.

Scenario 2: known outlet conditions. In the next scenario, p_1, υ_1, T_1 and Ma_1 under isothermal and adiabatic flow are to be calculated and compared using known outlet parameters (p_2, υ_2, T_2 and Ma_2). The result is shown in Figure 5. Similar to the previous scenario with known inlet conditions, the solid line and dashed line almost overlap with each other at small Mach numbers ($Ma_2 < 0.3$), implying that the difference between the two methods is negligible. When Ma_2 becomes larger ($Ma_2 \geq 0.4$), the two lines separate and the solid line is below the dashed line, suggesting that isothermal flow gives a larger p_1 value than predicted by adiabatic flow. It is also worth mentioning that the difference between isothermal and adiabatic flow is small at large fL/D values (greater than 10) regardless of the Mach number. Thus, we can apply either isothermal or adiabatic flow equations in this scenario.

Overall, the isothermal flow equation is more conservative than the adiabatic equation in terms of pressure-drop calculations, because the solid line is below the dashed line in Figures 4 and 5 at most conditions. However, the question arises as to whether isothermal flow is always conservative, even when the solid and dashed lines are visually inseparable. A careful look at Figures 4 and 5 finds that the answer is "yes" for known inlet conditions but "no" for known outlet conditions, in which the dashed line turns out to be above the solid line when p_2/p_1 decreases to a critical value. This critical p_2/p_1 value is found to be greatly dependent on the fluid's molecular weight, but not on specific heat ratio. As shown in Figure 6, critical p_2/p_1 continues to decrease with molecular weight. For hydrogen with a molecular weight of 2 and a specific heat ratio of 1.3, the adiabatic equation becomes more conservative (larger p_1) as p_2/p_1 drops below 0.53 when the outlet Mach number Ma_2 is 0.04.

Temperature and velocity

The pressure drop and variation in temperature and velocity along a pipe are always interrelated. With known inlet conditions, the dimensionless temperature (T_2/T_1) and velocity profiles (υ_2/υ_1) for both isothermal and adiabatic flow are depicted in Figure 7. At both small and large Mach number values, it can be clearly seen that υ_2/υ_1 under isothermal flow is larger than that under adiabatic flow at the same pipe length (fL/D). Since higher velocity will result in larger pressure drop, Figure 7 indirectly explains

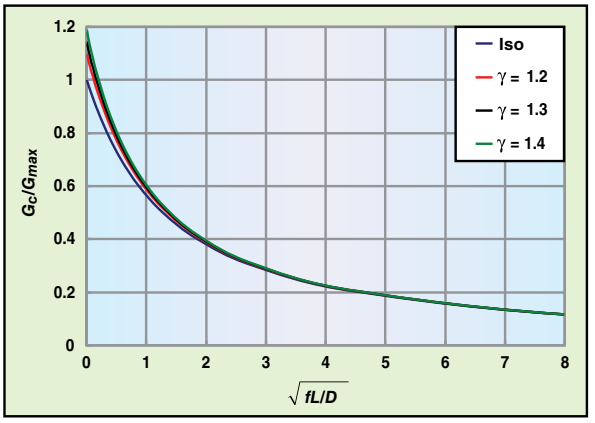


FIGURE 8. The ratio of critical mass flux to maximum mass flux as a function of pipe length varies with specific heat ratio

why isothermal flow is more conservative in term of pressure-drop calculations. Figure 7a also shows that the temperature drop for adiabatic flow is very small (<0.1% when $fL/D < 50$).

So we may conclude that the temperature remains constant at a small inlet Mach number (Ma_1), even if the flow is adiabatic. Comparing Figure 7a and Figure 4, we can understand why the solid and dashed lines overlap each other when Ma_1 is less than 0.3.

Critical mass flux

Critical mass flux under isothermal flow is defined as the maximum mass flowrate per unit duct area at $Mi_1 = 1$. It is reported by Lapple [*8*] and referenced in API Standard 521 [*1*] that the critical mass flux of adiabatic flow (where $\gamma = 1.4$) is 12.9% higher than that of isothermal flow under the same inlet conditions. However, Lappel's model represents gas expansion from an infinite reservoir through a frictionless convergent nozzle, which has an inlet velocity equal to zero. This assumption is not valid for gas flowing in pipelines. With the equations derived in this article, we can calculate and compare the critical mass flux for isothermal and adiabatic flow and find that the reported value of 12.9% is not accurate. The detailed calculations are presented below. First, we define critical mass flux under isothermal flow at $Mi_1 = 1$ as the maximum mass flux (G_{max}) in Equation (28).

$$G_{\max} = p_1\sqrt{\frac{M}{RT_1}} \tag{28}$$

At any pipe length, G_{max} under isothermal flow can be expressed as Equation (29).

$$G_{ci} = \rho_{2i}\upsilon_{2i} = p_{2i}\sqrt{\frac{M}{RT_1}} \tag{29}$$

Where p_{2i} and υ_{2i} are outlet pressure and velocity when the conditions in Equation (30) are true.

$$Mi_2 = \frac{\upsilon_{2i}}{\sqrt{\frac{RT_1}{M}}} = 1 \tag{30}$$

Therefore, the ratio of critical mass flux at any pipe length to maximum mass flux under isothermal flow is given in Equation (31).

$$\frac{G_{ci}}{G_{\max}} = \frac{p_{2i}}{p_1} \tag{31}$$

By solving Equation (10) and setting Mi_2 equal to one, p_{2i}/p_1 can be determined. At any pipe length, the critical mass flux under adiabatic flow can be expressed as Equation (32).

$$G_{ca} = \rho_{2a}\upsilon_{2a} = p_{2a}\sqrt{\frac{\gamma M}{RT_{2a}}} \tag{32}$$

The ratio of critical mass flux under adiabatic flow to maximum mass flux under isothermal flow is shown by Equation (33).

$$\frac{G_{ca}}{G_{\max}} = \frac{p_{2a}}{p_1}\sqrt{\gamma\frac{T_1}{T_{2a}}} \tag{33}$$

Based on Equations (14) through (17), we arrive at Equation (34).

$$\frac{G_{ca}}{G_{\max}} = \beta\sqrt{\frac{\gamma\alpha}{\beta^2}} = \sqrt{\gamma\alpha} = \frac{Ma_{1a}}{Ma_{2a}}\sqrt{\gamma} \tag{34}$$

At critical flow, Ma_{2a} is equal to 1, so Equation (34) is simplified to Equation (35).

$$\frac{G_{ca}}{G_{\max}} = \frac{Ma_{1a}}{Ma_{2a}}\sqrt{\gamma} = Ma_{1a}\sqrt{\gamma} \tag{35}$$

In Equation (35), Ma_{1a} can be calculated by solving Equation (13) at any fL/D and setting Ma_{2a} equal to one. Equations (31) and (35) are plotted in Figure 8 for three fluids with different specific heat ratios. At any pipe length, the ratio of critical mass flux of adiabatic flow to isothermal is given by Equation (36).

$$\frac{G_{ca}}{G_{ci}} = \frac{G_{ca}}{G_{\max}}\frac{G_{\max}}{G_{ci}} = Ma_{1a}\sqrt{\gamma}\frac{p_1}{p_{2a}} \tag{36}$$

Equation (36) can be simplified to Equation (37) since p_1/p_{2a} and Ma_{1a} equal one when the square root of fL/D equals zero.

$$\frac{G_{ca}}{G_{ci}} = \sqrt{\gamma} \tag{37}$$

At $\gamma = 1.4$, G_{ca}/G_{ci} is equal to 1.183, so the critical mass flux under adiabatic flow is 18.3% higher than that under isothermal flow, which is different from the reported value of 12.9% from API Standard 521.

Isothermal versus incompressible

In deciding whether to apply the incompressible flow equation for compressible fluid flow conditions, engineers often rely on certain rules of thumb. However, some of these rules of thumb can be quite misleading [*9*]. In the following section, we examine the difference between isothermal and incompressible equations for pressure-drop calculations.

For an ideal gas flowing through a horizontal pipe, Equation (38) shows that the total pressure drop is the summation of pressure drop caused by friction and acceleration.

$$\Delta p_{Total} = \Delta p_{Friction} + \Delta p_{Acceleration} \quad (38)$$

For incompressible flow, the acceleration term is negligible. So Equation (38) becomes Equation (39).

$$\Delta p = \Delta p_{Friction} = f\frac{L}{D}\frac{\rho_m \upsilon_m^2}{2} \quad (39)$$

In Equation (39), ρ_m and υ_m are the averaged density and velocity, which are defined in Equations (40) and (41), respectively.

$$\rho_m = \frac{p_1 + p_2}{2}\frac{M}{RT} \quad (40)$$

$$\frac{1}{\upsilon_m} = \frac{\rho_m}{G} = \frac{1}{2}\left(\frac{1}{\upsilon_1} + \frac{1}{\upsilon_2}\right) \quad (41)$$

Moving fL/D to the lefthand side in Equation (39) gives Equation (42).

$$f\frac{L}{D} = \frac{2\Delta p}{\rho_m \upsilon_m^2} = \frac{2(p_1 - p_2)}{\rho_m \upsilon_m^2} \quad (42)$$

Substituting ρ_m and υ_m with Equation (40) and (41) in Equation (42) results in the expression shown in Equation (43).

$$f\frac{L}{D} = \frac{2(p_1 - p_2)}{\frac{p_1 + p_2}{2}\frac{M}{RT}\left(\frac{2\upsilon_1}{1 + \frac{p_2}{p_1}}\right)^2} = \frac{1}{M_{i1}^2}\left[1 - \left(\frac{p_2}{p_1}\right)^2\right] \quad (43)$$

Equation (43) can be transformed to Equation (44) with a known outlet Mach number Mi_2.

$$f\frac{L}{D} = \frac{1}{M_{i2}^2}\left[\left(\frac{p_2}{p_1}\right)^{-2} - 1\right] \quad (44)$$

Equations (43) and (44) are the incompressible flow equations. Comparing with the isothermal equation defined in Equation (9), it is seen that the natural log term is cancelled out. Since pressure drop due to acceleration is negligible for incompressible flow, it can be deduced that the natural log term in Equation (9) accounts for acceleration and the first term accounts for friction, as illustrated in Equation (45).

$$f\frac{L}{D} = \underbrace{\frac{1}{Mi_1^2}\left[1 - \left(\frac{p_2}{p_1}\right)^2\right]}_{\text{Friction}} \underbrace{-1n\left(\frac{p_1}{p_2}\right)^2}_{\text{Acceleration}} \quad (45)$$

The difference between the calculated pressure using the isothermal equations defined by Equations (9) and (10) and the incompressible equations defined by Equations (43) and (44) is shown in Tables 1A and 1B for both known inlet and outlet conditions. The difference is expressed for known outlet and inlet conditions by Equations (46) and (47), respectively.

For known outlet conditions:

$$\eta = \frac{p_{1(isothermal)} - p_{1(incompressible)}}{p_{1(isothermal)}} \times 100\% \quad (46)$$

For known inlet conditions:

$$\eta = \frac{p_{2(incompressible)} - p_{2(isothermal)}}{p_{2(isothermal)}} \times 100\% \quad (47)$$

It can be seen from Table 1 that η depends on both pressure drop (p_2/p_1) and Mach number (Mi). At certain Mi values, η is at its maximum at p_2/p_1 values of around 0.7–0.8 and gradually decreases with p_2/p_1. However, η might not be practically correct when p_2/p_1 is very small since it requires immense energy to maintain constant temperature. The values with a difference larger than 1% are highlighted in green in Table 1. Since Equations (43) and (44) do not contain natural log terms, we can very quickly size compressible fluid pipe with known error as shown in Table 1. Detailed below are the steps for calculating

TABLE 1A. MACH NUMBER AT PIPE OUTLET (Mi_2)

p_2/p_1 (incompressible)

	0.01	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.01	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.02%	0.03%	0.04%	0.05%
0.05	0.00%	0.00%	0.01%	0.03%	0.07%	0.12%	0.19%	0.27%	0.37%	0.48%	0.60%	0.74%
0.1	0.00%	0.01%	0.02%	0.09%	0.21%	0.37%	0.57%	0.82%	1.11%	1.45%	1.83%	2.25%
0.2	0.00%	0.02%	0.06%	0.26%	0.58%	1.02%	1.59%	2.27%	3.07%	3.97%	4.98%	6.08%
0.3	0.00%	0.03%	0.11%	0.43%	0.97%	1.71%	2.66%	3.80%	5.12%	6.61%	8.26%	10.04%
0.4	0.00%	0.04%	0.15%	0.59%	1.31%	2.32%	3.61%	5.15%	6.95%	8.97%	11.21%	13.61%
0.5	0.00%	0.04%	0.17%	0.69%	1.56%	2.77%	4.31%	6.19%	8.38%	10.86%	13.61%	16.59%
0.6	0.00%	0.05%	0.18%	0.74%	1.67%	2.98%	4.68%	6.77%	9.26%	12.12%	15.33%	18.84%
0.7	0.00%	0.04%	0.18%	0.71%	1.60%	2.90%	4.61%	6.77%	9.42%	12.56%	16.18%	20.21%
0.8	0.00%	0.04%	0.14%	0.58%	1.34%	2.45%	3.97%	5.98%	8.56%	11.81%	15.76%	20.38%
0.9	0.00%	0.02%	0.09%	0.35%	0.82%	1.53%	2.56%	4.01%	6.07%	8.96%	12.99%	18.30%
0.91	0.00%	0.02%	0.08%	0.32%	0.75%	1.41%	2.36%	3.72%	5.68%	8.48%	12.47%	17.85%
0.92	0.00%	0.02%	0.07%	0.29%	0.68%	1.28%	2.15%	3.42%	5.25%	7.94%	11.88%	17.34%
0.93	0.00%	0.02%	0.06%	0.26%	0.61%	1.14%	1.93%	3.09%	4.79%	7.34%	11.20%	16.73%
0.94	0.00%	0.01%	0.06%	0.23%	0.53%	1.00%	1.70%	2.73%	4.28%	6.67%	10.41%	16.02%
0.95	0.00%	0.01%	0.05%	0.19%	0.45%	0.85%	1.46%	2.35%	3.73%	5.91%	9.50%	15.16%
0.96	0.00%	0.01%	0.04%	0.16%	0.37%	0.70%	1.20%	1.95%	3.12%	5.06%	8.41%	14.12%
0.97	0.00%	0.01%	0.03%	0.12%	0.28%	0.53%	0.92%	1.51%	2.46%	4.08%	7.10%	12.79%
0.98	0.00%	0.00%	0.02%	0.08%	0.19%	0.36%	0.63%	1.05%	1.72%	2.94%	5.45%	11.03%
0.99	0.00%	0.00%	0.01%	0.04%	0.10%	0.19%	0.32%	0.54%	0.91%	1.61%	3.27%	8.37%
0.992	0.00%	0.00%	0.01%	0.03%	0.08%	0.15%	0.26%	0.44%	0.73%	1.31%	2.73%	7.63%
0.995	0.00%	0.00%	0.01%	0.02%	0.05%	0.09%	0.16%	0.28%	0.47%	0.84%	1.84%	6.23%
0.999	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.03%	0.06%	0.10%	0.18%	0.41%	2.99%

$$\frac{p_{1(isothermal)} - p_{1(incompressible)}}{p_{1(isothermal)}} \times 100\% \geq 1\%$$

(a) Calculated inlet pressure difference (at known outlet conditions) between using the incompressible and isothermal equations (η >1% is highlighted green)

p_2/p_1 (incompressible)	TABLE 1B. MACH NUMBER AT PIPE INLET (Mi_1)										
	0.01	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.01	—	—	—	—	—	—	—	—	—	—	—
0.05	15.56%	—	—	—	—	—	—	—	—	—	—
0.1	2.41%	—	—	—	—	—	—	—	—	—	—
0.2	0.41%	12.97%	—	—	—	—	—	—	—	—	—
0.3	0.13%	3.63%	20.26%	—	—	—	—	—	—	—	—
0.4	0.06%	1.49%	6.77%	—	—	—	—	—	—	—	—
0.5	0.03%	0.71%	3.02%	17.26%	—	—	—	—	—	—	—
0.6	0.01%	0.36%	1.49%	7.14%	26.14%	—	—	—	—	—	—
0.7	0.01%	0.18%	0.75%	3.34%	9.36%	29.04%	—	—	—	—	—
0.8	0.00%	0.09%	0.36%	1.52%	3.89%	8.66%	22.34%	—	—	—	—
0.9	0.00%	0.03%	0.13%	0.55%	1.35%	2.72%	5.19%	10.71%	—	—	—
0.91	0.00%	0.03%	0.12%	0.48%	1.17%	2.35%	4.44%	8.81%	—	—	—
0.92	0.00%	0.02%	0.10%	0.42%	1.01%	2.01%	3.75%	7.23%	21.16%	—	—
0.93	0.00%	0.02%	0.08%	0.35%	0.85%	1.70%	3.13%	5.88%	14.05%	—	—
0.94	0.00%	0.02%	0.07%	0.29%	0.71%	1.40%	2.56%	4.71%	10.16%	—	—
0.95	0.00%	0.01%	0.06%	0.24%	0.57%	1.13%	2.04%	3.68%	7.43%	—	—
0.96	0.00%	0.01%	0.04%	0.19%	0.44%	0.87%	1.56%	2.78%	5.33%	—	—
0.97	0.00%	0.01%	0.03%	0.14%	0.32%	0.63%	1.13%	1.97%	3.63%	9.12%	—
0.98	0.00%	0.01%	0.02%	0.09%	0.21%	0.41%	0.72%	1.24%	2.23%	4.78%	—
0.99	0.00%	0.00%	0.01%	0.04%	0.10%	0.20%	0.35%	0.59%	1.03%	2.03%	—
0.992	0.00%	0.00%	0.01%	0.03%	0.08%	0.16%	0.27%	0.47%	0.81%	1.58%	5.37%
0.995	0.00%	0.00%	0.01%	0.02%	0.05%	0.10%	0.17%	0.29%	0.50%	0.95%	2.66%
0.999	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.03%	0.06%	0.10%	0.18%	0.44%

$$\frac{p_{2(isothermal)} - p_{2(incompressible)}}{p_{2(isothermal)}} \times 100\% \geq 1\%$$

(b) Calculated outlet pressure difference (at known inlet conditions) between using the incompressible and isothermal equations (η >1% is highlighted green)

p_2 using Equations (43) and (44). By rearranging Equation (44), we arrive at Equation (48), an expression for p_2/p_1.

$$\left(\frac{p_2}{p_1}\right)_{incomp} = \sqrt{\frac{1}{f\frac{L}{D}Mi_2^2 + 1}} \quad (48)$$

For given pipe characteristics (length, diameter and roughness), fluid flowrate, Mi_2 and p_2, fL/D is first calculated — f can be read from a Moody diagram or calculated with various equations. Next, we must calculate p_2/p_1 using Equation (48). Afterwards, we determine η from Table 1A based on Mi_2 and $p_2/p_{1(incomp.)}$. If η is acceptable, then p_1 is reported as the final result. If η is not acceptable, the isothermal expression in Equation (10) must be used to re-calculate $p_2/p_{1(isothermal)}$ and report a new p_1 value.

Modified incompressible flow

From Table 1 and Equations (43) and (44), it can be seen that the isothermal flow equation is more conservative than the incompressible equation because the latter does not include the acceleration term. Here, we present a modified incompressible equation to account for the missing acceleration term in Equations (43) and (44). Equation (49) defines f_a, the acceleration factor, where υ_m and p_m are averaged velocity and pressure.

$$f_a = \frac{G\upsilon_m}{p_m} \quad (49)$$

The total pressure drop and pressure drop due to friction can be linked as in Equation (50) below [2].

$$\Delta p_{total} = \frac{\Delta p_{friction}}{1 - f_a} \quad (50)$$

Further expanding Equation (49) gives Equations (51) and (52).

$$f_a = \frac{2G}{p_1 + p_2}\frac{2G}{p_1 + p_2}\frac{RT}{M} = \frac{4G^2}{(p_1 + p_2)^2}\frac{RT}{M} \quad (51)$$

$$f_a = \frac{4G^2}{(p_1 + p_2)^2}\frac{RT}{M} = \frac{4\frac{G^2}{p_1^2}}{\frac{(p_1 + p_2)^2}{p_1^2}}\frac{RT}{M}$$

$$= \frac{4\frac{M}{RT}\upsilon_1^2}{\left(1 + \frac{p_2}{p_1}\right)^2} = \frac{4Mi_1^2}{\left(1 + \frac{p_2}{p_1}\right)^2} \quad (52)$$

The pressure drop due to friction is expressed in Equation (39). By substituting υ_m and p_m, Equation (39) becomes Equation (53).

$$\Delta p_{friction} = f\frac{L}{D}\frac{G^2}{\frac{M}{RT}(p_1 + p_2)} = f\frac{L}{D}\frac{Mi_1^2 p_1^2}{p_1 + p_2} \quad (53)$$

Inserting Equations (51) and (53) into Equation (50) yields Equation (54).

$$p_1 - p_2 = f\frac{L}{D}\frac{Mi_1^2 p_1^2}{p_1 + p_2}\frac{1}{1 - \frac{4Mi_1^2}{\left(1 + \frac{p_2}{p_1}\right)^2}} \quad (54)$$

Moving fL/D to the lefthand side brings us to the expressions in Equations (55) and (56).

$$f\frac{L}{D} = \frac{(p_1 - p_2)(p_1 + p_2)}{p_1^2}\frac{1}{Mi_1^2}\left(1 - \frac{4Mi_1^2}{\left(1 + \frac{p_2}{p_1}\right)^2}\right)$$

$$= \frac{1}{Mi_1^2}\left[1 - \left(\frac{p_2}{p_1}\right)^2\right] - 4\frac{1 - \frac{p_2}{p_1}}{1 + \frac{p_2}{p_1}} \quad (55)$$

With known outlet conditions, Equations (55) becomes Equation (56).

$$f\frac{L}{D} = \frac{1}{Mi_1^2}\left[1 - \left(\frac{p_2}{p_1}\right)^2\right] - 4\frac{1 - \frac{p_2}{p_1}}{1 + \frac{p_2}{p_1}} \quad (56)$$

Equation (56) is the modified incompressible flow equation. Comparing Equation (56) with Equation (43), it can be seen that the second term on the righthand side accounts for acceleration. Equation (56) and Equation (10) are plotted in Figure 9, which shows the solid and dashed lines overlapping each other at all chosen values for the Mach number. Therefore, the modified incompressible flow equation can be used to size pipes where fluid flow is compressible.

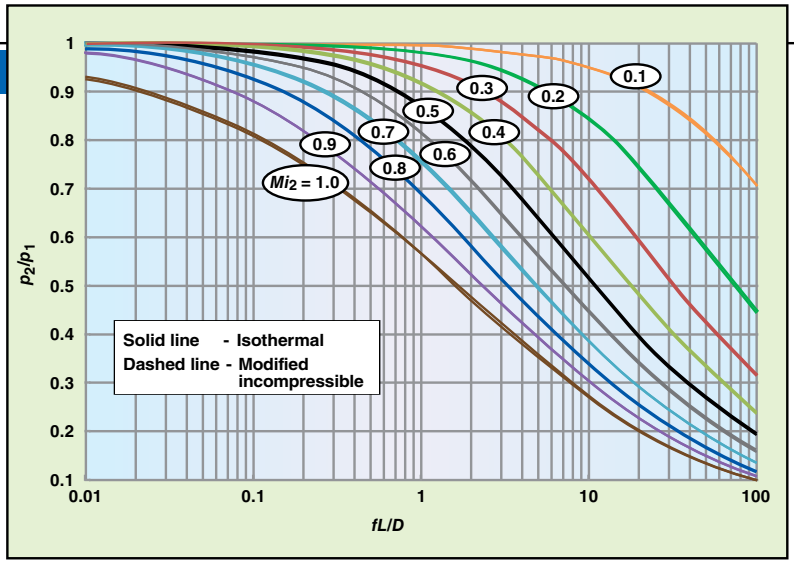


FIGURE 9. Comparison of isothermal and incompressible flow under the same inlet conditions shows that is it acceptable to use the modified incompressible flow equation to size compressible fluid flow systems

Conclusions

Based on the derivations in this article, some important conclusions can be made:

1. For pipe sizing with compressible fluids, the isothermal flow equation is preferable since it gives a more conservative pressure drop estimate in the scope of practical engineering design.
2. When considering whether it is acceptable to use the incompressible equation to size gas pipes, both pressure drop and Mach number should be considered.
3. For a given pipe length and diameter, the critical mass flux under adiabatic conditions is larger than that under isothermal conditions. The maximum ratio between critical mass flux under adiabatic and isothermal

condition is equal to the square root of γ.

4. Under adiabatic flow, specific heat ratio has significant effect on pressure drop, but the effect of molecular weight is negligible.

With these conclusions in mind and the equations derived in this article, engineers can begin to make educated assumptions when they are asked to size and determine pressure drop for pipes with compressible fluid flow. ■

Edited by Mary Page Bailey

Authors

Fucheng Teng is a process technologist/specialist at Jacobs Canada Inc. (205 Quarry Park Blvd. S.E., Calgary, Alberta, Canada T2C3E7; Phone: +1 403-640-8149, Email: fucheng.teng@jacobs.com). He holds a B.S. degree in polymer material and engineering from Dalian University of Technology and an M.S.Ch.E. from the University of Alberta. He has accumulated seven years of engineering experience, including commissioning and startup, wastewater treatment, mineral processing and SAGD (steam-assisted gravity drainage) facility design. Teng is a Certified Six Sigma Green Belt (CSSGB) from the American Society of Quality.

Pedro Medina (Phone: +1 403–692–2302; Fax: +1–403 255–1421; Email: pedro.medina@jacobs.com) has over seventeen years of experience as a process engineer with expertise in process design of both new and retrofit projects in the petrochemicals and oil-and-gas industries. For the last seven years, he has been with Jacobs Canada Inc. as a principal process engineer. For the last five years, he has been assigned to SAGD projects for major bitumen production companies in Northern Alberta. He is a professional engineer accredited by the Association of Professional Engineers and Geoscientists of Alberta. Medina graduated from Simón Bolívar University in Caracas, Venezuela where he received an M.S.Ch.E.

Mark Heigold (Phone: +1 403-258-6440, Email: mark.heigold@jacobs.com) is a technical design supervisor at Jacobs Canada Inc. He holds a B.S.Ch.E. from the University of Calgary. He has more than 19 years experience in process design in the fields of power generation, SAGD, heavy oil, upstream gas processing and water treatment. Heigold is a member of the Association of Professional Engineers and Geoscientists of Alberta.

References

1. American Petroleum Institute, Standard 521, Pressure-relieving and Depressuring Systems, 5th Ed., Washington D.C., 2007.
2. Yu, F.C., Compressible Fluid Pressure Drop Calculation-Isothermal Versus Adiabatic, *Hydrocarbon Processing*, pp. 89–95, May 1999.
3. Darby, Ron, "Chemical Engineering Fluid Mechanics", 2nd Ed., CRC, 2001.
4. Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No.410, Crane Co., Joliet, Ill., 1988.
5. Saad, M.A., "Compressible Fluid Flow", 2nd Ed., Prentice-Hall, Englewood Cliffs, NJ, 1998.
6. Mak, H.Y., New Method Speeds Pressure-Relief Manifold Design, *Oil and Gas Journal*, Nov. 1978.
7. Branan, Carl R., "Rules of Thumb for Chemical Engineers", 4th Ed., Gulf Professional Publishing, Burlington, Mass., 2005.
8. Lapple, C.F., "Fluid and Particle Mechanics", University of Delaware, Newark, Del., 1951.
9. Walters, T., Gas-Flow Calculations: Don't Choke, *Chem. Eng.*, Jan. 2000.

Quick Pipe and Duct Flow Calculations

Bruce R. Smith
Sidock Group

Simple calculation methods for estimating flow characteristics in pipes and ducts save engineers' time

Would you like to make a quick mental calculation to determine approximate flowrate, velocity, or pipe and duct sizes for many common situations? This article presents two methods for estimating flow characteristics without the aid of charts, tables, calculators or software programs. One method applies to liquid flow in pipes, and the other to air flow in ducts. The techniques are intended to be simple enough to yield useful answers within a few seconds.

Liquid flow in pipes

Sizing pipes for liquid transport nearly always requires an engineer to seek a preferred velocity to establish favorable flow characteristics. This calculation technique allows an engineer to estimate velocity, flowrate and pipe diameter relationships when reference data is unavailable. The technique first establishes a flowrate (Q, in gpm) corresponding to a velocity of 10 ft/s in a Schedule 40 pipe with diameter D (inches). That information can then be extrapolated for flow properties at other conditions. Equation (1) applies to the flow of liquids through pipes.

$$Q_{10} = D^2 \times 25 \quad (1)$$

Consider the following examples, which employ Equation (1) to quickly approximate pipe velocity.

Example 1. What flowrate will yield a velocity of 8 ft/s in a 2-in. pipe? First, mentally calculate the following using Equation (1): $Q_{10} = 2^2 \times 25 = 100$ gpm. This means that 100 gpm will flow in the 2-in. pipe at 10 ft/s. We want to determine the flowrate in the same pipe at 8 ft/s. We know that 8 ft/s is 80% of 10 ft/s, so similarly, 80% of 100 gpm is 80 gpm. Literature shows the velocity of 80 gpm in a 2-in. Schedule 40 pipe is 7.65 ft/s. Our estimate is within 5% of the literature value.

Example 2. What is the velocity of 2,500 gpm flowing in a 12-in. pipe? Again, we use Equation (1) to mentally calculate the flow at the reference velocity of 10 ft/s: $Q_{10} = 12^2 \times 25 = 3{,}600$ gpm flowrate at 10 ft/s. To determine the velocity at 2,500 gpm, we start with the fact that 2,500 is roughly 70% of 3,600. 70% of 10 ft/s is 7 ft/s. Literature shows the velocity of 2,500 gpm in a 12-in. Schedule 40 pipe is 7.17 ft/s. Our estimate is within 3% of the literature value.

Each problem is solved in two basic steps. The first is to multiply the square of the pipe diameter by 25. The second step is to determine the ratio of the target flow to the flow yielding 10 ft/s to arrive at the desired conditions. In a manner similar to the examples above, pipe diameters can be derived from flow and velocity data. That calculation is performed by assuming a pipe diameter, calculating its flow at 10 ft/s, comparing its flow properties at desired flow or velocity, and iterating to another diameter if necessary.

This technique is not exact, but it gives the engineer relatively accurate results very quickly. While Equation (1) is intended for Schedule 40 pipes, and accuracies for pipes with varying wall thicknesses will be slightly different, this calculation method will quickly yield a close estimation. Figure 1 displays how calculated values compare to literature values. The error between estimated values and actual values should be accurate enough for initial sizing estimates. However, accuracy is diminished significantly for pipes with a diameter of less than one inch.

Air flow in ducts

The technique used for liquids in pipes can be applied to air in ducts at standard (atmospheric) pressure and temperature. Equation (2) applies to air flowing at these conditions, using a reference air velocity of 2,000 ft/min.

$$Q_{2000} = D^2 \times 11 \quad (2)$$

Consider the following examples, which employ Equation (2) to evaluate flowrate (Q, in ft^3/min) in sheet-metal air ducts.

Example 3. What flowrate will yield a velocity of 3,000 ft/min in a 10-in. duct? We must first use Equation (2) to mentally calculate the following: $Q_{2000} = 10^2 \times 11 = 1{,}100$ ft^3/min, which is the flowrate yielding an air velocity of 2,000 ft/min. We want to determine the flowrate that results in a velocity of 3,000 ft/min. 3,000 ft/min is 150% of 2,000 ft/min. Therefore, 150% of 1,100 ft^3/min = 1,650 ft^3/min. A check against the literature values shows that the velocity of 1,650 ft^3/min in a 10-in. galvanized sheet-metal duct is 3,100 ft/min. Our mental

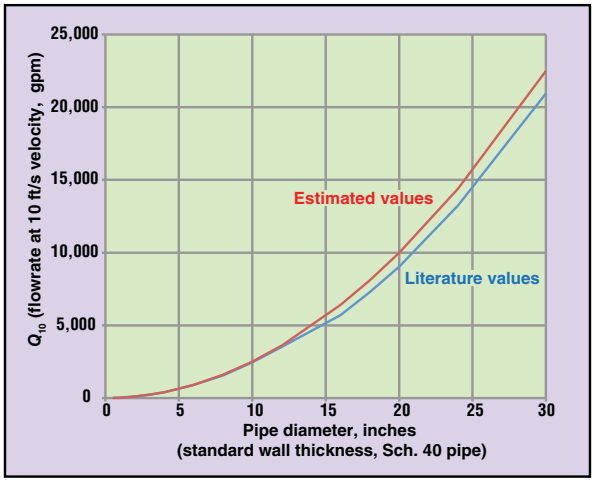


FIGURE 1. A comparison of literature values with calculated values shows that these quick, simplified pipe-flow calculations are accurate enough for initial sizing estimates

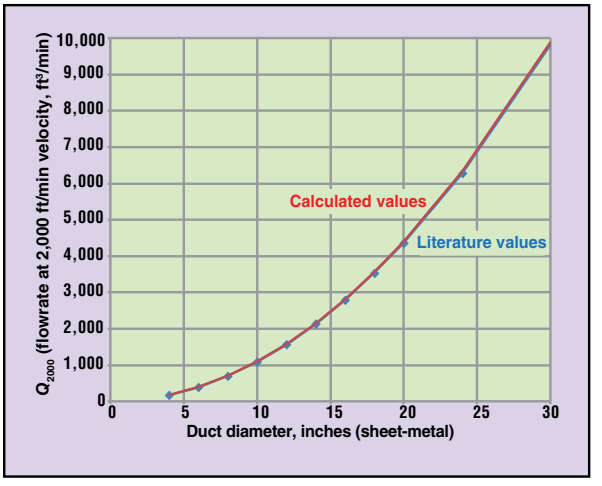


FIGURE 2. The rough estimates resulting from the duct-flow calculation method are extremely close to literature values for airflow in sheet-metal ducts

calculation is within 3.2% of the literature value.

Example 4. What is the velocity that corresponds to a flowrate of 6,000 ft³/min in a 20-in. duct? First, of course, we must mentally calculate the flowrate corresponding to the reference velocity of 2,000 ft/min: $Q_{2000} = 20^2 \times 11 = 4{,}400$ ft³/min. Now, we can solve for the velocity which corresponds to 6,000 ft³/min flow in the pipe — 6,000 is slightly less than 150% of 4,400, and 150% of 2,000 ft/min is 3,000 ft/min. Literature shows the velocity of 6,000 ft³/min in a 20-in. sheet-metal duct is 2,800 ft/min. Our estimate is 7% greater than the literature value, but a value somewhat greater than the actual was expected when we rounded to 150%.

This technique is accurate to within 1% if exact numbers are calculated for the flowrate percentages. As seen in Examples 3 and 4, accuracy diminishes if estimates are not exact. While this technique is intended for use with sheet-metal ducts, accuracies for ducts with varying wall thicknesses will not be significantly different. Figure 2 compares these calculations to literature values. The two lines are practically identical when calculations are precise, rather than rough estimates.

In conclusion, when rough initial estimates are needed, engineers can confidently apply these simple, time-saving methods to characterize flow in pipes and ducts. ■

Edited by Mary Page Bailey

Author

Bruce Smith is a project manager at Sidock Group, Inc. (379 W. Western Ave., Muskegon, Mich. 49441; Phone: 231-722-4900; Email: bsmith@sidockgroup.com). Previously, he was employed as a senior research engineer at The Dow Chemical Co. after working as an engineer in the automotive and mining industries. He has experience with a wide variety of technologies and is a registered professional engineer in multiple states. Smith is credited with several patents and technical articles. He holds a B.S.Ch.E. from Michigan Technological University.

Advanced Thermal Dispersion Mass Flowmeters

A look at the principles of operation, installation and calibration

John G. Olin
Sierra Instruments, Inc.

Thermal dispersion (TD) mass flowmeters measure the mass flowrate of fluids (primarily gases) flowing through a closed conduit, such as a pipe. This article describes the operation and installation of TD mass flowmeters, and gives the reader information about what applications these meters are most suited for.

Background

The first general description of TD mass flowmeters is attributed to L.V. King who, in 1914 [*1*], published his famous King's Law revealing how a heated wire immersed in a fluid flow measures the mass velocity at a point in the flow. He called his instrument a "hot-wire anemometer." The first application of this technology was hot-wire and hot-film anemometers and other light-duty TD flow sensors used in fluid mechanics research and as light-duty mass flowmeters and point velocity instruments. This class of TD mass flowmeters is described in Ref. 2.

It was not until the 1960s and 1970s when industrial-grade TD mass flowmeters emerged that could solve the wide range of general industry's more rugged needs for directly measuring the mass flowrate of air, natural gas and other gases in pipes and ducts. That is the class of instruments described here.

TD mass flowmeters measure the heat convected into the boundary layer of the gas flowing over the surface of a heated velocity sensor immersed in the flow. Since it is the molecules of the gas, which bear its mass, that carry away the heat, TD mass flowmeters directly measure mass flowrate. Capillary-tube thermal mass flowmeters constitute a second type of thermal mass flow technology, but their principle of operation and their applications are sufficiently different from TD mass flowmeters that the American Society of Mechanical Engineers (ASME) has published separate national standards for each type [*3, 4*].

Typical gases monitored by industrial TD mass flowmeters include: air, methane, natural gas, carbon dioxide, nitrogen, oxygen, argon, helium, hydrogen, propane and stack gases, as well as mixtures of these gases and mixtures of hydrocarbon gases. Common applications are: combustion air; preheated air; compressed air; fluid power; boilers;

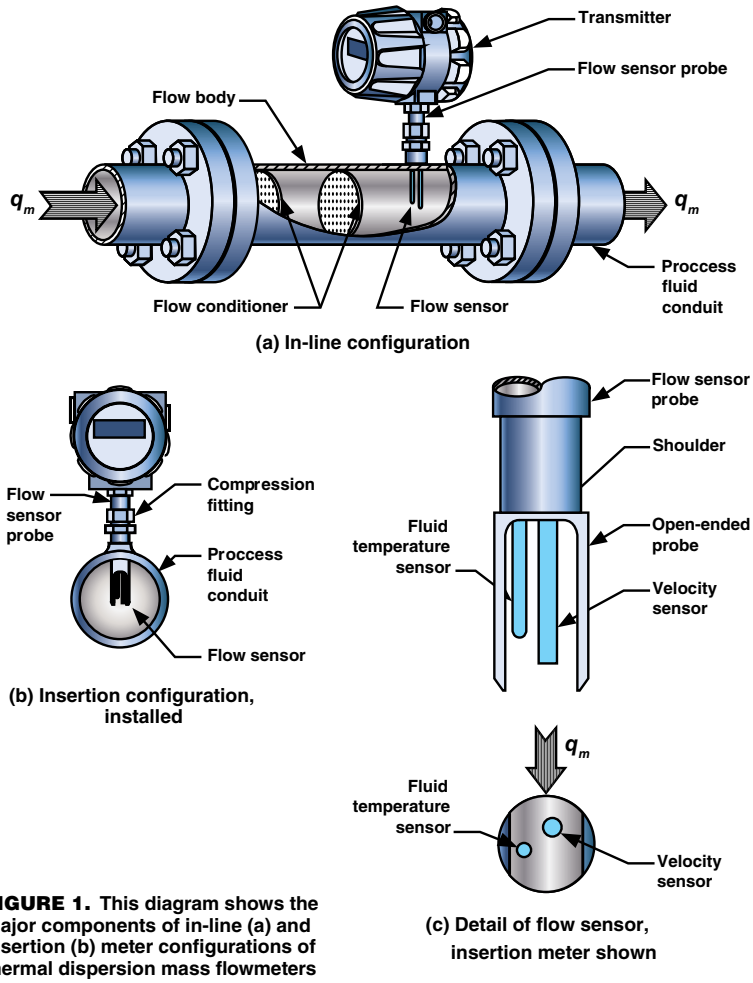


FIGURE 1. This diagram shows the major components of in-line (a) and insertion (b) meter configurations of thermal dispersion mass flowmeters

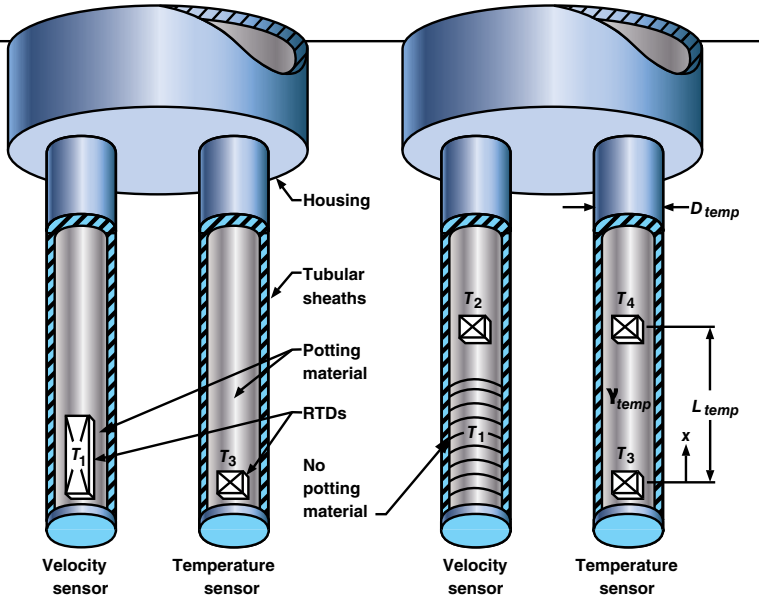


FIGURE 2. Two kinds of thermal-dispersion mass flow sensors are shown here

electric power plants; cooling, heating, and mixing; drying of materials; food and beverage industries; natural gas distribution; aeration and digester gas monitoring in wastewater-treatment plants; cogeneration with biogas; fuel gas; flare gas; semiconductor manufacturing; heating, ventilation and air conditioning; single and multipoint stack-gas monitoring; and chemical reactors.

General description

TD mass flowmeters directly measure the mass flowrate of single-phase pure gases and gas mixtures of known composition flowing through pipes or other flow conduits. As discussed in a later subsection, they also have limited application to single-phase liquids of known composition. In most of the following, we shall assume that the fluid is a gas, without the loss of applicability to liquids. Multivariable versions additionaly provide an output for gas temperature and also, but less commonly, of gas pressure.

TD mass flowmeters have two primary configurations: in-line and insertion. Figures 1a and 1b, respectively, show these two configurations and their major components. Figure 1c shows the flow sensor that is common to both configurations, although in smaller in-line meters the flow sensor may not have a shield.

In-line. In-line flowmeters are applied to pipes and ducts with pipe-size diameters typically ranging from about 10 to 100 mm (0.25 to 4.0 in.), but some manufacturers offer pipe sizes up to 300 mm (12.0 in.) dia. Process connections include flanges, pipe threads and compression fittings. The built-in flow conditioner, described later, reduces the length of upstream straight pipe required to achieve independence of upstream flow disturbances.

Insertion. Insertion flowmeters [*5*] usually are applied to larger pipes, ducts and other flow conduits having equivalent diameters typically ranging from approximately 75 mm to 5 m. Because insertion meters are more economical than in-line meters, they also have found wide use as flow switches. Compression fittings and flanges are commonly used process connections. Insertion meters measure the mass velocity at a point in the conduit's cross-sectional area, but for applications with smaller conduits, they may be flow calibrated to measure the total mass flowrate through the conduit.

Multipoint insertion meters measure the mass velocities at the centroids of equal areas in the cross-section of large pipes, ducts and stacks. The total mass flowrate through the entire conduit is the average mass velocity of the several points multiplied by the total cross-sectional area and the standard mass density of the gas [*6*].

Types of flow sensors

The flow sensor for the insertion flowmeter shown in Figure 1c has a unique design incorporating an open-ended probe with a shoulder. Traditional insertion meters have a shield with a closed end that can cause the flow over the velocity sensor to be non-uniform and turbulent. The open-ended probe shown in Figure 1c protects the sensors but does not have this problem. Additionally, the probe in traditional insertion meters has a constant diameter and no shoulder.

Whereas the largest portion of the flow around such traditional insertion probes flows circumferentially around the probe, a smaller fraction flows axially down the probe, enters the window in the shield, and passes over the velocity sensor, causing it to measure a velocity higher than the actual velocity in the flow conduit. Since the amount of this secondary flow varies with the depth of insertion into the flow stream, its magnitude during flow calibration may be different than that of the actual field application. This can impair the accuracy of velocity measurement. The probe in Figure 1c has a length of reduced diameter and a shoulder just above the flow sensor that redirects this axial downwash so that it flows circumferentially around the probe before it can pass over the velocity sensor, thereby minimizing this source of inaccuracy.

Traditional sensors. Figure 2a shows a traditional TD flow sensor used in in-line and insertion mass flowmeters intended for industrial-grade applications. This flow sensor has a velocity sensor and a separate temperature sensor immersed in the flow stream. For that reason, TD mass flowmeters are also named "immersible" thermal mass flowmeters. The velocity sensor has a single electrically self-heated temperature sensor element located in its tip

that both heats the velocity sensor and measures its own average temperature T_1. The gas temperature sensor has a single non-self-heated temperature sensor element T_3 located in its tip that measures the gas temperature T. Because it has a total of two temperature sensing elements, the flow sensor in Figure 2a is called a "two-temperature" flow sensor. The velocity sensor and the temperature sensor are mounted side-by-side. Each is enclosed in a rugged, sealed, single-ended, corrosion-resistant metallic tube, usually composed of 316 stainless steel or a nickel alloy. The introduction of this kind of rugged construction in the 1960s and 1970s is responsible for transforming thermal anemometers into industrial-grade instruments. In traditional velocity sensors of the kind shown in Figure 2a, the T_1 sensor is potted into the tip of the tubular sheath. Typically, the potting, or filler material is ceramic cement or epoxy. Heat sink grease also has been used for this purpose.

For higher accuracy and higher stability applications, the temperature sensing elements in the velocity sensor and the temperature sensor in Figures 2a and 2b are either wire-wound or thin-film platinum resistance temperature detectors (RTDs) protected by a thin insulation layer of glass or ceramic. The electrical resistance of RTDs increases as temperature increases, providing the means for transducing their electrical output into temperature. The platinum RTD sensor element in the velocity sensor is called the T_1 element and has a relatively low electrical resistance in the range of about 10 to 30 Ohms. The platinum RTD element in the temperature sensor is called the T_3 element and has a relatively high electrical resistance in the range of 300 to 1,000 Ohms. Other types of temperature sensing elements, such as thermistors, thermocouples and micro-electronic machined devices, have been used for applications with lower accuracy requirements. In the following, we shall assume that the T_1 and $T3$ elements are platinum RTDs.

The outside temperature external to the flow sensor may be different than the gas temperature in the flow conduit. For that reason, heat can be conducted into or out of the stems of the velocity sensor and the temperature sensor. In the field, the heat conducted in this manner through each stem may be different from its value at the time of flow calibration if the outside temperatures are different. Additionally, heat can be conducted from the hot velocity sensor to the cooler temperature sensor via their stems. Both effects are further complicated because they depend on the mass flowrate. These phenomena are collectively called "stem conduction." Stem conduction is a large fraction of the total heat supplied to the velocity sensor and is an unwanted quantity. Left uncorrected, stem conduction constitutes a major source of error in measuring mass flowrate. Flow sensors with long stems have less stem conduction than those with short, stubby stems.

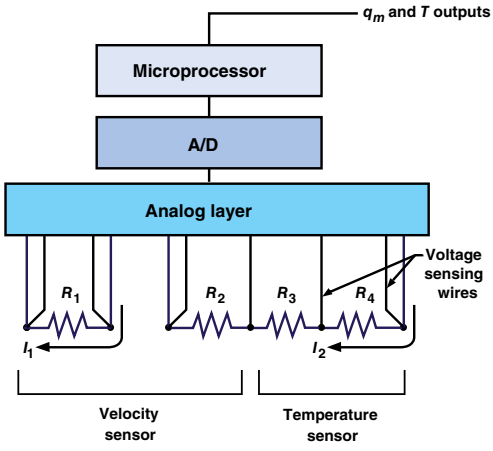


FIGURE 3. In the four-temperature microprocessor-based system, the flowmeter drives the velocity sensor so that the temperature difference $\Delta T = T_1 - T$ is maintained constant. The system automatically corrects for changes in gas selection, gas temperature and gas pressure

Four-temperature sensor. Figure 2b shows a TD flow sensor that solves the stem conduction problem by employing a total of four platinum RTD temperature-sensing elements. The velocity sensor in this "four-temperature" flow sensor has a T_1 element as before, but now has a second T_2 element in its stem that is separated from the T_1 element. The temperature sensor has a T_3 element as before, but now has a second T_4 element in its stem that is separated a distance from the T_3 element.

The T_1 element is a wire-wound platinum RTD with a resistance ranging from 10 to 30 Ohms. The T_2, T_3 and T_4 sensors are thin-film RTDs with a resistance ranging from 500 to 1,000 Ohms. In operation, the T_1 and T_2 elements together act as a heat-flux gage that measures the fraction of heat conducted down the stem of the velocity sensor. The T_3 and T_4 elements perform the same function for the temperature sensor. The addition of the T_2 and T_4 temperature sensing elements in the four-temperature flow sensor facilitates correction for stem conduction, whatever the cause.

The use of the potting material between the T_1 element in Figure 2a and the internal surface of the sheath has potential long-term stability problems because the potting material can crack or otherwise degrade due to differences in the thermal expansion coefficients of the potting material and the sheath material when exposed to gas temperatures that cycle, change frequently, or are elevated. Any change in the potting material causes a change in the "skin resistance" of the velocity sensor and thereby its stability. As discussed in the following, skin resistance, along with stem conduction, are the two major factors that can degrade measurement accuracy if not managed properly.

The construction and assembly of the T_1 element of the four-temperature flow sensor in Figure 2b eliminates the skin resistance problem by: (1) avoiding altogether the use of any potting materials between the T_1 element and the internal surface of the sheath and (2) using mating materials that have the same coefficient of thermal expansion. Filler materials are avoided

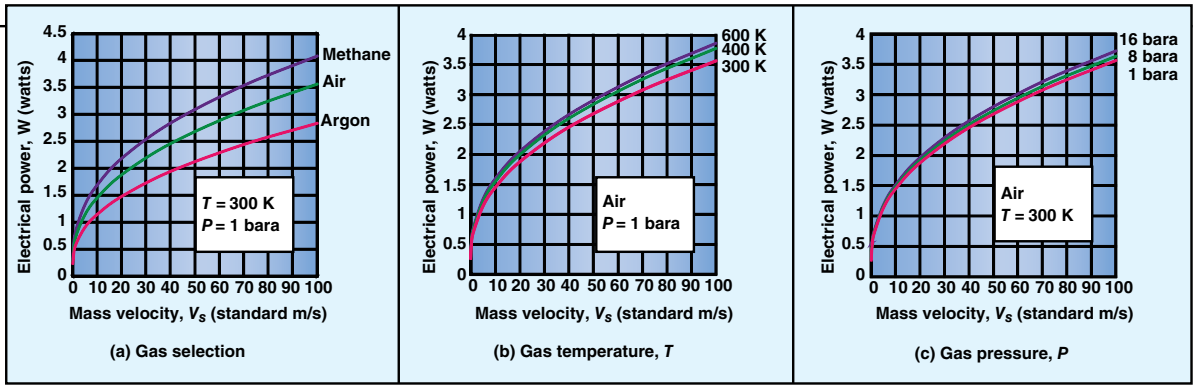


FIGURE 4. These plots show the management of changes in gas selection, gas temperature, and gas pressure with the four-temperature microprocessor-based system. ΔT = 50K. In all figures the "standard" conditions for V_S (standard m/s) are 70°F and 1 atm

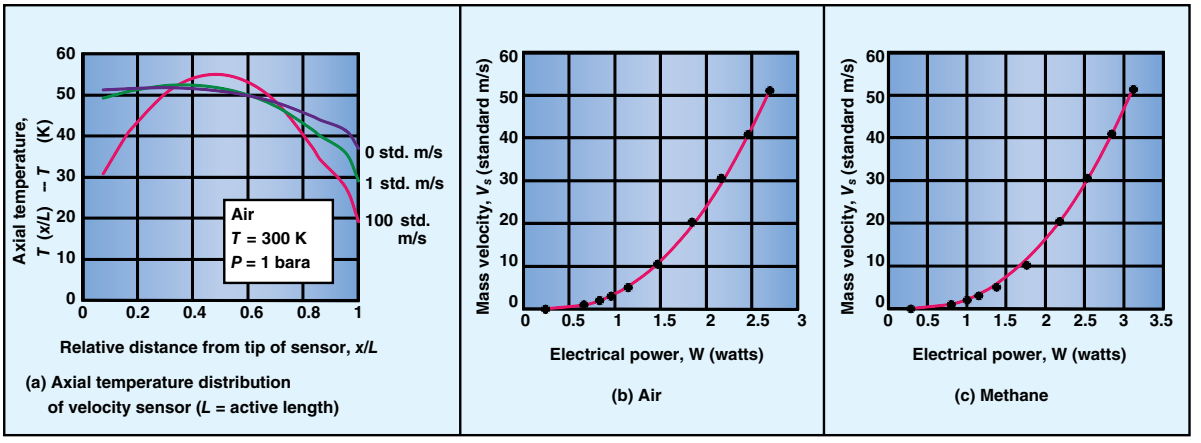


FIGURE 5. These plots compare flow calibration data and the output of the four-temperature microprocessor-based system. ΔT = 50K, and T and P are at room (ambient) conditions. "Standard" conditions for V_S (standard m/s) are 70°F and 1 atm

by means of tightly fitting, as in swaging or press fitting, the wire-wound T_1 element into the sheath. Such velocity sensors are known as "dry" sensors, as opposed to velocity sensors fabricated with potting cements or epoxies that are wet when mixed. In contrast with the velocity sensor, any degradation of potting materials in the temperature sensor changes only its time response, a relatively minor effect.

In operation, the gas temperature sensor in the TD mass flowmeter measures the gas temperature T. The sensor drive in the transmitter electronics delivers an electrical current I_1 to the velocity sensor, such that it is self-heated to an average temperature T_1 that is elevated above the gas temperature. Since it is the molecules of the gas, which bear its mass, that flow over the heated velocity sensor and carry away its heat, TD flowmeters directly measure the mass flowrate q_m of the gas or gas mixture. Heat convected from the velocity sensor in this manner depends on the properties of the gas, and therefore the composition of the gas must be known.

In yet another thermal flow sensor construction for in-line meters, the flow sensor is embedded in wall of the flow body and is not immersed in the flow. This flow sensor consists of a heater element with adjacent upstream and downstream temperature sensing elements. The difference in the two temperatures increases as flow increases, providing the output. This construction is used primarily for low-flow liquid applications.

Transmitter

The transmitter shown in Figure 1 is the electronic system that provides the flow sensor drive and many other functions for the flowmeter. It accepts the inputs from the two or four temperature sensing elements as well as the heating current I_1 input and transforms these independent variables into linear outputs of the primary dependent variable, mass flowrate q_m, and, in the case of multivariable versions, the gas temperature T. Transmitters can be housed in an enclosure that conforms with relevant U.S. and international codes, such as hazardous area codes or area classifications. Digital transmitters with digital displays in engineering units facilitate additional functions, including flowmeter diagnostics, validation, calibration adjustment and reconfiguration. Later, this article describes an advanced system consisting of a microprocessor-based digital transmitter and a four-temperature flow sensor that provides gas selection and automatic correction for changes in gas temperature, gas pressure and outside temperature.

Many transport properties of the gas that are involved in convective heat transfer, such as thermal conductivity, viscosity and Prandtl number, depend on temperature. Likewise, the thermal conductivity

of some of the materials in the flow sensor depends on temperature. For this reason, TD mass flowmeters must correct for changes in gas temperature. In traditional flowmeters, this is done by means of an analog Wheatstone bridge at the front end of the flow sensor drive. The velocity sensor and the temperature sensor are located at opposite legs of the bridge. This provides compensation for changes in fluid temperature by adjusting the overheat of the velocity sensor. The bridge voltage is a high-level output signal on the order of several volts that provides a high signal-to-noise ratio. The Wheatstone bridge and its temperature-compensation capabilities are thoroughly described in the literature [*2, 6–9*]. Modern flowmeters with a microprocessor-based flow sensor drive digitally correct for changes in temperature without requiring a Wheatstone bridge.

The flow sensor drive in TD mass flowmeters has two modes of operation: the constant-temperature-differential mode and the constant-current mode. In the constant-temperature-differential mode of operation, the flow sensor drive maintains at a constant value the difference $\Delta T = T_1 - T$ between the heated velocity sensor T_1 and the gas temperature T. The output signal is the electrical power W supplied to the heated velocity sensor that is required to keep ΔT constant.

In the constant-current mode of operation, the flow sensor drive maintains at a constant value the current I_1 supplied to the heated velocity sensor. In this case, the output signal is ΔT. Measuring mass flowrate with constant current operation is slower than constant temperature differential operation because the temperature of the entire mass of the velocity sensor must change when velocity changes and also because the masses of the velocity and temperature sensors may be imbalanced. In the following, we assume constant temperature differential operation and that therefore ΔT is a constant, usually in the range of 20 to 100K.

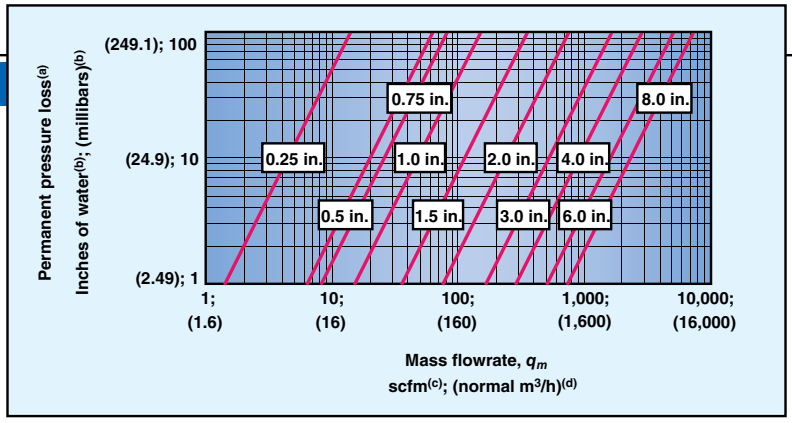


FIGURE 6. This graph shows the permanent pressure loss for in-line flowmeters with a built-in flow conditioner consisting of two upsteam separated perforated plates. Notes: (a) for air and nitrogen at 21.1°C and 1 atm; (b) 1 in. of water = 0.0361 psi; (c) at standard conditions of 21.1°C and 1 atm; and (d) at standard (normal) conditions of 0°C and 1 atm

Liquid flow applications

The vast majority of applications are gas flow applications because they benefit from the exceptional low-flow sensitivity and wide rangeabililty of measurement. Thermal dispersion technology is not well suited for liquid flow applications because at the zero-flow condition, a majority of the heat budget is carried away by the liquid via conduction, instead of the desired convection. This is caused by the high thermal conductivity of liquids relative to gases. The result is reduced measurement sensitivity for liquid flows.

Additionally, for liquid flows, the temperature differential $\Delta T = T_1 - T$ must not exceed an upper critical limit, or else at higher flowrates the liquid may flash to the vapor phase and subsequent cavitation may occur, creating unwanted erratic readings. For water flows, this upper critical limit in ΔT is approximately 10 to 20°C. The constant-differential-temperature mode of operation is preferred for liquid flows because ΔT is controlled, whereas in the constant-current mode ΔT varies and may exceed the upper critical limit. Application of thermal dispersion technology to liquid flows has been limited to cases, such as ultra-low flow applications, where it offers advantages over other technologies.

Advanced system

Figure 3 shows a simplified block diagram of the microprocessor-based thermal dispersion mass flowmeter with the four-temperature flow sensor shown in Figure 2b. It has a dry velocity sensor and is operated in the constant temperature differential mode. As before, we call this configuration the four-temperature microprocessor-based system. The voltage sensing wires in Figure 3 make the measurement of the RTD resistances independent of the length of the flow sensor cable, facilitating remote location of the transmitter. The heating current I_1 depends on the electrical resistance R_1 and the electrical power input W required to maintain constant ΔT. W ranges from about 0.2 to 5 W depending on the overheat ΔT, the mass flowrate, and the size of the velocity sensor. The temperature sensing current I_2 is held constant and is less than 1 mA to avoid self-heating the T_2 sensor. The analog layer shown in Figure 4 includes precision resistors for measuring the currents I_1 and I_2 but has no bridge circuit.

The four-temperature microprocessor-based system shown in Figure 3 digitally linearizes the q_m output and, optionally, the T and P outputs and provides analog outputs for these variables. The system has algorithms based on the principle of operation that manage changes in gas selection, gas temperature and gas pressure.

Figures 4 a–c show how the four-temperature microprocessor-based system manages changes in gas selection, gas temperature, and gas pressure for air, methane, and argon. These figures are plotted in the conventional manner with the mass velocity, V_s, shown as the

TABLE 1. TYPICAL SPECIFICATIONS FOR THERMAL DISPERSION MASS FLOWMETERS

Specification	Two-temperature system	Four-temperature system
Gases	Most clean gases, including air, methane, Ar, CO_2, He, N_2, O_2, C_3H_8, and mixtures of these components	Most clean gases, including air, methane, Ar, CO_2, He, N_2, O_2, C_3H_8, and mixtures of these components
In-line flow body sizes[a]	0.25, 0.5, 1.0, 1.5, 2.0, 4.0 in.; DN6 to DN100	0.25, 0.5, 1.0, 1.5, 2.0, 4.0 in.; DN6 to DN100
In-line meter mass flowrate range for air	0.0001 to 1.5 kg/s; 0.1 to 2,600 scfm[b]	0 to 1.5 kg/s; 0 to 2,600 scfm[b]
Insertion meter mass-velocity range for air	1.4 to 140 normal m/s; 300 to 30,000 standard ft/min[c]	0 to 140 normal m/s; 0 to 30,000 standard ft/min[c]
Temperature range[d]	–40 to 200°C; –40 to 392°F	–40 to 200°C; –40 to 392°F
Pressure range	0.01 to 16 bara	0.01 to 16 bara
Accuracy[e]	1% of reading plus 0.5% of full scale (FS)	1% of reading from 10 to 100% of FS; 1% of reading plus 0.5% FS from 0 to 10% FS
Rangeability	100 : 1	100 : 1
Repeatability	0.2 % of full scale	0.15 % of full scale
Time response[f]	3 s (constant power operation); 1.2 s (constant ΔT operation)	2 s
Stability	1 year; typical drift 1 to 2% per year	10 years; typical drift 0.1% per year

Notes to Table 1: (a) Some manufacturers offer sizes up to 12.0 in. (DN300); (b) Based on the point mass-velocity range for insertion flowmeters cited below; (c) "Normal" conditions are 0°C and 1 atm, and "standard" conditions are 70°F and 1 atm; (d) High-temperature models are available up to approximately 450°C = 842°F; (e) FS = full scale; and (f) Time response is the time required to reach 63% of the final value (that is, the 1 sigma value).

independent variable and the electrical power, W, shown as the dependent variable, whereas in the system they have reversed roles. The three figures reflect the strong direct dependence the electrical power has on the thermal conductivity of the gases. Thus, Figure 4a results from the fact that $k_{methane} > k_{air} > k_{argon}$, and Figures 4b and 4c result from the fact that thermal conductivity increases as gas temperature and pressure increase, respectively. The fact that thermal conductivity, and therefore W, increases with gas pressure as shown in Figure 4c is a phenomenon that has heretofore been ignored, but for higher accuracy applications should be included.

Figures 4 a–c also reveal the non-linear, logarithmic nature of the output. A log versus log plot of these figures will reveal a nearly straight line over approximately 1 to 150 standard m/s. This logarithmic property is responsible for the exceptional rangeability and low-velocity sensitivity of TD mass flowmeters. A rangeability as high as 100:1 is common. Even higher rangeabilities are achieved with multi-range flow calibration. Detectable minimum-point mass velocities as low as approximately 0.1 standard m/s (20 standard ft/min) are reported by some manufacturers. In the early days of analog electronics, it was difficult to linearize the output of TD mass flowmeters. But now, with microprocessor-based electronics, it is not a problem, and the non-linear, logarithmic nature of the output bears only advantages.

Figures 5 a–c show further results of the four-temperature microprocessor-based system. Figure 5a reveals how the temperature distribution $T_1(x)$ of the heated section of the velocity sensor undergoes major changes as V_s increases from 0 to 100 standard m/s. Figures 5a and 5b show, for air and methane, the excellent comparison between results calculated via the four-temperature microprocessor-based system and actual flow calibration data. Comparisons for other gases are likewise as good. Algorithims exist that make the output of the system match flow calibration data even better.

Specifications

Table 1 shows specifications for currently available TD mass flowmeters. Specifications for the column labeled "Two-temperature system" refer to the flow sensor shown in Figure 2a and may vary from manufacturer to manufacturer. Specifications for the column labeled "Four-temperature system" refer to the microprocessor-based system with the four-temperature flow sensor having the dry velocity sensor shown in Figure 2b. Accuracy specifications in Table 1 may apply to gas temperatures and gas pressures that lie within bands around their respective values at flow calibration. Table 1 is also useful in selecting and sizing the proper TD mass flowmeter for the application.

Installation

In all cases, specifications and instructions provided by the manufacturer should be followed in sizing and installing in-line and insertion TD mass flowmeters. Ref. 3 is an excellent source for details regarding sizing, installation, safety and flow calibration.

Figure 6 is helpful in the flowmeter selection process for in-line TD mass flowmeters. The permanent pressure loss shown in Figure 6 applies to an in-line meter with a built-in flow conditioner consisting of two upstream separated perforated plates. In sizing TD mass flowmeters, as with all flowmeters used for gas flow applications, the Mach number of the gas flow should be kept under approximately 0.3 to avoid compressibility effects. At an absolute gas pressure of 1 bara (approximately 1 atmosphere), the permanent pressure loss is about 0.1 bar (approximately 2 psi) at all full-scale mass flowrates. This is one or two orders of magnitude less than that required by Coriolis mass flowmeters for gas flow applications. Almost all of the permanent pressure loss shown in Figure 6 is due to the built-in flow conditioner.

Insertion flowmeters have very low permanent pressure loss, especially for larger line sizes. In-line flowmeters without a built-in flow

conditioner and no shield on the flow sensor likewise have low pressure drops. These two configurations are why TD mass flowmeters are considered to be in the class of flowmeters with low pressure drops.

As with most kinds of flowmeters, the performance of TD mass flowmeters can be degraded if the flowmeter is installed where flow conditions are different than those for which it was flow-calibrated. Improper installation is the single biggest cause of measurement inaccuracy for any kind of flowmeter. Components in the piping system upstream and, to a far lesser extent, downstream of the flowmeter can create non-uniformities in the flow profile, swirls and turbulence. All of these phenomena degrade performance. Such flow-disturbing components include single and multiple elbows, expansions, contractions, tees, valves and pumps. Fortunately, viscous forces in a sufficiently long length of straight pipe upstream and downstream of the flowmeter reduce swirl and drive the flow toward a fully developed velocity profile.

Table 2 shows the straight pipe length requirements for both in-line and insertion TD mass flowmeters and, for purposes of comparison, an orifice-plate flowmeter with a 0.7 beta ratio (ratio of the orifice diameter to the pipe internal diameter). The in-line flowmeter in Table 2 has a built-in flow conditioner consisting of two upstream separated perforated plates. Figure 7 shows the upstream straight-pipe requirements downstream of a single elbow for three kinds of flowmeters. This shows the marked contrast between the one pipe diameter length required for the TD mass flowmeter with the built-in flow conditioner versus the ten and twenty-eight diameter lengths required for typical vortex and orifice-plate flowmeters, respectively. Since piping systems in the industrial process-control field seldom have suitably long straight piping runs preceding the desired location for flowmeter installation, Table 2 and Figure 7 reveal the

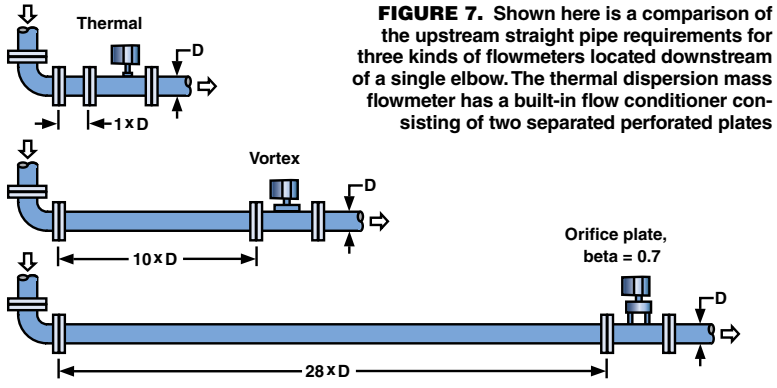


FIGURE 7. Shown here is a comparison of the upstream straight pipe requirements for three kinds of flowmeters located downstream of a single elbow. The thermal dispersion mass flowmeter has a built-in flow conditioner consisting of two separated perforated plates

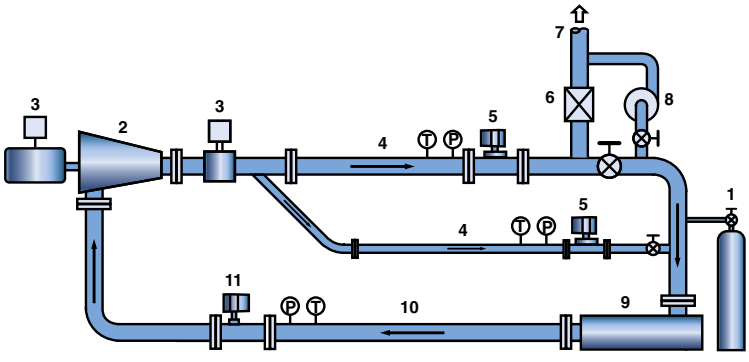


FIGURE 8. A setup for a pressurized closed-loop gas-flow calibration system is presented here. The numbered components are as follows: 1 is the gas charging source; 2 is the flow source; 3 is the flow control element; 4 is a flow-conditioning section for a flow calibration standard (two shown); 5 is an in-line flow calibration standard (two shown); 6 is the pressure relief element; 7 is the vent to the outside environment or to a scrubber or other gas purifying device; 8 is the vacuum pump for evacuating the gas charge; 9 is the heating section; 10 is the flow-conditioning section for the flowmeter under test; and 11 is the flowmeter under test

installation advantage in-line TD mass flowmeters with the built-in flow conditioner have over alternative flowmeters. In essence, in-line flowmeters with the built-in flow conditioner trade the advantage of greater accuracy for a small amount of pressure drop.

Normally, the transmitter is mounted directly on the flow body or probe. In cases where the ambient temperature at the pipe line exceeds the specified limit for the transmitter (usually, approximately 60°C), then the transmitter must be located remotely. Additionally, in some cases the application requires that the transmitter be located remotely for easier access. Since the wires leading to the sensors are part of each sensor's electrical circuit, remote location can cause measurement errors if the cable length is altered in the field from that for which it was flow calibrated. The four-temperature microprocessor-based system avoids this problem by incorporating high-impedance voltage sensing wires in the flowmeter's cable (see Figure 3) that essentially make remote transmitter location independent of cable length.

Some applications require that the flow in the process line not be interrupted. This case is solved by employing an insertion flowmeter installed in the pipe with hot-tap hardware. The hot-tap method and assembly provides an isolation

TABLE 2. STRAIGHT PIPE LENGTH REQUIREMENTS FOR THERMAL-DISPERSION MASS FLOWMETERS IN MULTIPLES OF PIPE DIAMETER[a]

Flow disturbance	Thermal dispersion mass flowmeters				Orifice plate, $\beta = 0.7$[c]	
	In-line[b]		Insertion			
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Single elbow	1	0	15	5	28	7
4:1 Reduction	3	0	15	5	14	7
4:1 Expansion	3	0	30	10	30	7
Control valve[d] or *P* regulator	3	0	40	5	32	7
Two elbows in the same plane	3	0	20	5	36	7
Two elbows in different planes[e]	5	0	40	10	62	7

Notes to Table 1: (a) Requirements for the length of intervening straight pipe in multiples of pipe diameter at 1 bara pressure; consult manufacturer for pressure effects; specifications may vary from manufacturer to manufacturer; (b) For an in-line meter with a built-in flow conditioner consisting of two upstream separated perforated plates; (c) For comparison purposes only; based on ISO standard 5167 [*10*]; (d) If the control valve is always wide open, base the length requirement on the valve's inlet or outlet fitting size; (e) For three elbows, the required length is doubled.

valve facilitating installation, insertion, retraction and removal of the insertion flowmeter from an active process pipe line without interruption of the flow or the leakage of process gas. The retraction mechanism provides operator safety for pressurized process lines.

Flow calibration

Because the critical dimensions of the flow sensor of TD mass flowmeters are so small, manufacturing technology is generally incapable of maintaining sufficiently small tolerances to ensure a high degree of reproducibility from flow sensor to flow sensor. Additionally, the internal diameters of the pipes used in in-line flow bodies have substantial variations. For these reasons, every general-purpose TD mass flowmeter is flow calibrated by the manufacturer, just like most other kinds of flowmeters. Exceptions may include flow switches and low-accuracy flowmeters.

The gas-flow calibration facilities of manufacturers, flow calibration laboratories and users should be capable of: (1) generating a stable, steady-state, reproducible gas mass flowrate; (2) accommodating the entire mass flowrate range specified; (3) having a flow calibration standard that has an accuracy at least three times better than the flowmeter under test; and (4) reproducing the gas composition, temperature and pressure to be encountered in the actual application. Gas-flow calibration facilities are of two types: open loop and closed loop.

Closed-loop facilities are recommended because they allow flow calibration at elevated pressures and temperatures, and with gases other than air. The preferred pressurized closed-loop system for high-accuracy applications has the following major components (Figure 8), listed in flow sequence: (1) a gas charging source, such as a compressed gas tank; (2) a flow source, such as a high-pressure axial or centrifugal in-line pump; (3) a flow controller, such as a precision flow control valve or variable speed motor drive; (4) flow-conditioning section(s) upstream of the flow calibration standard(s); (5) the in-line flow calibration standard (more than one may be needed to cover the mass flowrate range); (6) a heating section, such as an in-line electric heater; (7) a flow-conditioning section upstream of the flowmeter under test; and (8) the flowmeter under test. Additionally, the facility should have: accurate gas temperature and pressure instrumentation at both the flow calibration standard and the flowmeter under test; pressure relief and venting components; a vacuum pump for evacuating the system prior to charging; and, optionally, a cooling section downstream of the flowmeter under test. High-accuracy in-line flow calibration standards include custody-transfer grade multi-path ultrasonic flowmeters; turbine flowmeters; flow nozzles; and positive-displacement flowmeters. ■

Edited by Gerald Ondrey

References

1. King, L. V., On the convection of heat from small cylinders in a stream of fluid: Determination of the convection constants of small platinum wires with application to hot-wire anemometry, *Phil. Trans. Roy. Soc.,* A214, pp. 373–432, 1914.
2. Olin, J. G., Thermal anemometry, in "The Measurements, Instrumentation, and Sensors Handbook," ed. Webster, J. G., pp. 29-18 to 29-37, CRC Press, Boca Raton, 1999.
3. ASME MFC-21.2-2010. Measurement of fluid flow by means of thermal dispersion mass flowmeters.
4. ASME MFC-21.1M. Measurement of fluid flow by means of capillary tube thermal mass flowmeters and controllers.
5. ASME MFC-15M. Insertion metering.
6. Olin, J. G., A thermal mass flow monitor for continuous emissions monitoring systems (CEMS), Proc. ISA/93 International Conference, Exhibition and Training Program, 93-404, pp.1,635–1,653, 1993.
7. Bruun, H. H., "Hot-Wire Anemometry: Principles and Signal Analysis," Oxford Univ. Press, Oxford, U.K., 1995.
8. Olin, J. G., Industrial thermal mass flowmeters — Part 1: Principles of operation, *Measurements and Control,* 193, pp. 83–90, Feb. 1999.
9. Olin, J. G., Industrial thermal mass flowmeters — Part 2: Applications, *Measurements and Control*, 194, pp. 1–6, April, 1999.
10. Miller, R.W., "Flow Measurement Engineering Handbook," 3rd ed., McGraw Hill, N.Y., 1996.

Author

John G. Olin is the founder and CEO of Sierra Instruments, Inc. (5 Harris Court, Building L, Monterey, California 93940; Phone: 831-373-0200; Fax: 831-373-4402; Email: j_olin@sierrainstruments.com). Olin received his B.S degree from Illinois Institute of Technology and his M.S. and Ph.D. from Stanford University, all in mechanical engineering. At Stanford, Olin specialized in fluid mechanics and heat transfer and used hot-wire anemometers in research pursuant to his doctoral dissertation. He founded Sierra Instruments in 1973 with the purpose of offering industrial-grade thermal dispersion mass flowmeters to solve industry's need for rugged, reliable flowmeters based on the thermal principle. Olin has a dozen patents and over 60 publications in the field.

Small-matrix, Model-less Multivariable Control

Allan Kern
Consultant

Historical reliance on big-matrix, model-based multivariable control is giving way to a shift toward small-matrix, model-less multivariable control, with compelling improvements

Beginning with the early days of automated multivariable control in the 1980s, the trend has always been toward the use of larger matrices and more models. Today's multivariable controllers commonly comprise dozens of variables and hundreds of models. But the next big advancement in multivariable control may be a shift toward the use of small-matrix, model-less multivariable control practice.

Small-matrix practice means that the multivariable controller design is based on practical operating and optimization criteria. This usually involves only a relatively small handful of key variables, typically the ones that operators and process engineers normally use to effect process optimization and constraint management prior to the application of multivariable control. Model-less multivariable control means that the control action is more conservative, and is based on pre-determined safe rates of change and maintaining process stability. This reflects how most industrial processes are actually operated and does not require the use of detailed models (Note: The key terms and concepts used in this article are defined in the sidebar on p. 53).

Taken together (although they can be taken separately), small-matrix, model-less practice offers a path forward for multivariable control technology that bypasses most of the costs and complexities that have come to be associated with the big-matrix model-based practice. This has the potential to make automated multivariable control much more accessible — that is, less expensive and more easily managed — to industry. This is important, because multivariable control always has been, and always will be, a core competency of the chemical process industries (CPI).

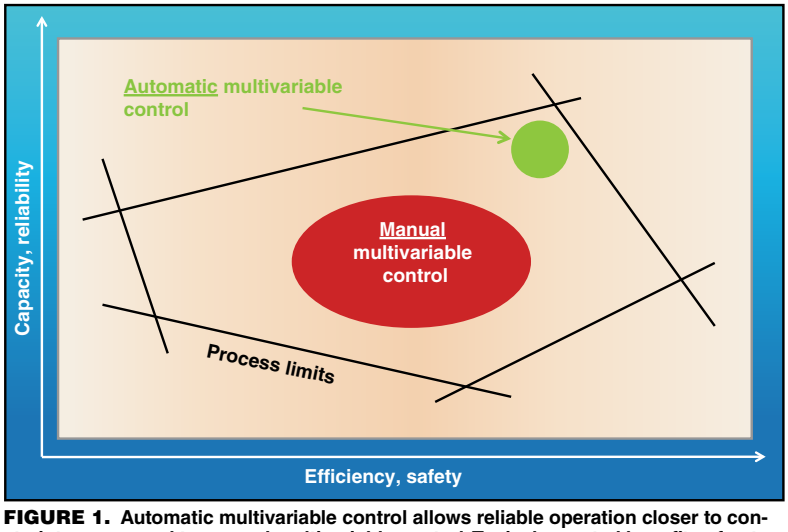


FIGURE 1. Automatic multivariable control allows reliable operation closer to constraints, compared to manual multivariable control. Typical reported benefits of automatic multivariable control are a 1–5% increase in overall economic performance for most process units, based on increased capacity, yield and efficiency

Background

Prior to the advent of computer-based process control systems, multivariable constraint control and optimization was accomplished manually. It was part of the operator's job to adjust the available controllers and valves to ensure that related process variables remained within limits, and secondarily to move the process toward better economic performance. However, due to a variety of factors — including the unwieldy nature of most large-scale industrial processes, their susceptibility to many sources of upset, the sometimes severe consequences of exceeding constraints and the absence of automatic constraint controls — the manual approach has always been challenging, and as a result, the process operating point was usually kept well away from critical constraints. However, operating away from constraints typically translates into decreased economic performance, such as reduced capacity, yield or efficiency. Balancing these two objectives — to stay within a safe and reliable operating window, while optimizing (or "push-

MULTIVARIABLE CONTROL CONCEPTS AND TERMINOLOGY

- The terms manipulated variable (MV), direct control variable (DCV), handle and independent variable are largely synonymous. Most often, MVs are the setpoints of existing base-layer, single-loop controllers. MVs are directly adjusted by the multivariable controller
- The terms controlled variable (CV), indirect control variable (ICV), constraint limit, and dependent variable are also largely synonymous terms. CVs are process variables that are controlled indirectly by the multivariable controller, by adjusting the MVs so that the CVs remain within constraint limits
- Each MV may affect multiple CVs, and each CV may be affected by multiple MVs — this comprises the multivariable nature of most continuous processes. Multivariable control means controlling the MVs and CVs in a coordinated manner, rather than individually
- An interaction refers to the effect of one MV on one CV. Detailed knowledge of the interaction, such as gain, response time and interim dynamics, constitutes a model of the interaction
- Model information is often arranged in a matrix of MV rows and CV columns. Where there are interactions, a graph or equation of the model is shown (Figure 2)
- Matrix size is expressed as the number of MVs (number of rows) by the number of CVs (number of columns). For example, Figure 2 shows a matrix with a size of 3×7. Size can also be classified as small (single-digit) or large (double-digit dimensions)
- Model-based predictive control (MPC) refers to using a model matrix for multivariable control, primarily in a feedforward (predictive) manner, to provide theoretically perfect multivariable control (subject to model accuracy), and also for optimization. That is, to find the most economical set of MV and CV target values. (Model-based control can be applied on a single-loop control basis, but MPC usually implies a multivariable application.)
- Degraded MPC performance refers to a common online condition of many MPC applications, characterized by "clamped" MVs (such that adjustment is partially or completely restricted), "detuned" movement (such that MV adjustment occurs very slowly), and out-of-service variables
- Transient error occurs when a CV limit is temporarily exceeded during a process disturbance or transition. It also refers to the time it takes to bring a CV or MV to its economically optimum target value
- Figure 2 shows a simplified representation of a small-matrix MPC. Each row of the model matrix can be thought of as a row of controlled variable (CV) override controllers, all cascaded via a "smart" (high, low, and/or target) override selector, to the row's manipulated variable (MV). And each column of the matrix basically represents feedforward of each MV that affects that column's CV. Inside a multivariable controller, you will not find a single DCS-like function block like this, but it can be thought of in this way ❑

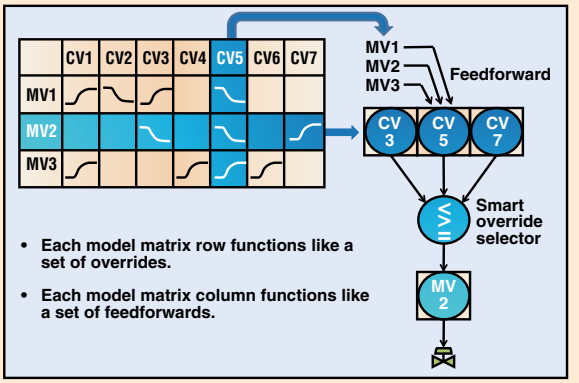


FIGURE 2. Multivariable control (model-based or model-less) can be envisioned as sets of override and feedforward controls, cascaded via smart high, low and target selectors to each MV

ing") economic performance — has always been an essential aspect of operating industrial processes.

With the advent of computer-based process control systems in the 1980s, and the development of suitable control algorithms, automatic multivariable control became established as a viable and often important part of process control. With automatic multivariable control, many processes can reliably operate closer to constraints, bringing significant benefits in product quality, capacity, yield, energy efficiency and so on. In many cases, the technology of choice has been multivariable model-based predictive control (MPC). Today, thousands of MPC applications have been deployed within the global CPI and are generally considered successful. Figure 1 shows a general depiction of the essential advantages of automatic over manual multivariable control.

Success notwithstanding, MPC technology has experienced some shortcomings. For instance, cost and complexity have continued to be high, life-cycle duration has proven to be limited, control performance is often poor, and the actual benefits of this approach often remain unclear. Industry has tried to address a series of supposed root causes, and MPC software tools have steadily improved, but the shortcomings have largely persisted and today "degraded" MPC performance has emerged as a key obstacle for users to consider going forward. It has also called into question the continued costs and difficulties.

Nearly every industrial process is multivariable in that nearly every process has a handful of key variables that have multiple interactions with each other, and that are beneficial to control automatically in a coordinated manner. This makes automated multivariable control a core competency for the process industries, and it makes getting beyond the present limitations an essential challenge to be addressed.

Small-matrix practice

The rationale for small-matrix controller design is multi-faceted. In order of increasing significance, the key drivers to adopting small-matrix practice are are controlled-variable (CV) rationalization, practicality and general model inaccuracy.

CV rationalization. An important step that has been missing from traditional "big matrix" MPC prac-

tice is CV rationalization — that is, assessing each CV's type. Under traditional MPC practices, all CVs are created equal, in that each has a claim to (in other words, can override) the manipulated variable (MV). But from a process operation standpoint, there are at least three types of CVs — critical, managed and controlled — and each warrants its own type of control response.

Critical CVs. These are constraints for which potentially serious short-term consequences could occur as a result of a constraint violation. Critical CVs warrant reliable base-layer controls, but more often than one might expect, given well-known principles regarding the appropriate role of high-level versus base-layer control, critical constraints find their way into MPC.

Common examples are the control of level in a side stripper, and the control of outlet temperature in a hydrocracker bed. A useful guide is this: If MPC comes up during a process hazard analysis (PHA) or management of change (MOC) review, a base-layer treatment might be more appropriate. High-level control should be viewed as optimization, not as protection or as base-layer control.

Managed (or alerted) constraints. In contrast to critical CVs, which require a reliable short-term control response, managed constraints warrant only an operator alert, with no automatic control response. The alert is intended to bring the attention of the wider operating team, which may then jointly consider a range of responses, typically in a timeframe of hours or days. This review often involves high-level issues, such as production plans, equipment health and environmental limits. In these cases, an immediate, automatic control response is often unnecessary and may be highly disruptive to process operation. Many traditional CVs fall into this category, and this unwanted automatic control response is a leading cause of degraded performance.

A common example is provided by crude-distillation units. Many crude-unit MPCs include half a dozen or more CVs related to feed heater firing alone, such as high skin temperature and high valve position, any one of which can trigger a heater outlet temperature reduction (the MV). But reducing heater firing is usually the last thing to do from an operating standpoint, not the first.

The appropriate response to these conditions is usually to adjust field burners or, failing that, to carry out a comprehensive review of crude diet, production commitments, heater health and so on. On most crude units, the only CV that should lead to an automatic reduction of heater firing is high column pressure, but this override might not be available if the MV has been previously clamped due to an unwanted response to one of the other constraints. This illustrates the counter-productive impact of making every process interaction an automatically controlled constraint. In this example, half a dozen CVs could have been left out of the matrix, with the result that the process would be subject to fewer unnecessary upsets and result in greater reliability of the important column pressure CV.

Controlled constraints. Controlled constraints are the traditional CVs for which automatic control response is appropriate. Conducting CV rationalization (as defined above) during matrix design helps ensure that only appropriate controlled constraints remain in the matrix. It helps to avoid putting critical CVs into the matrix, where they will be subject to poor reliability, and it helps to avoid including managed CVs that are likely to cause unwanted control action, leading to MV clamping and other forms of performance degradation.

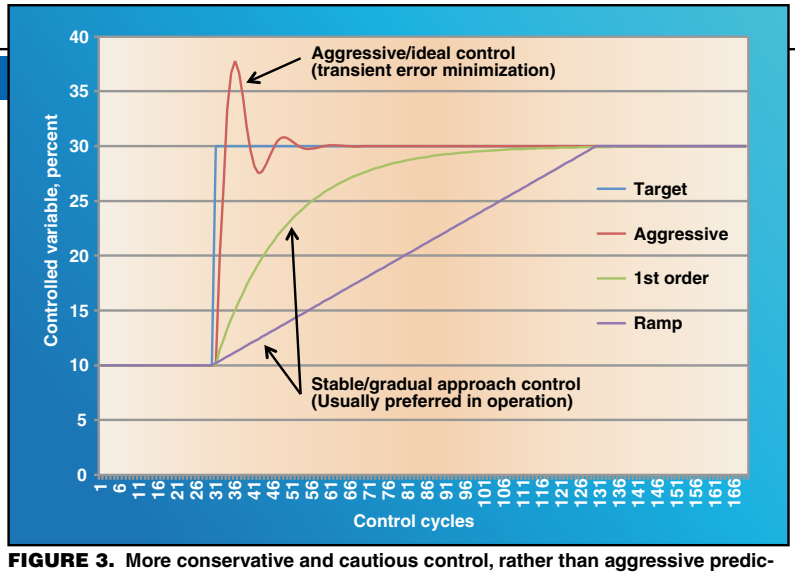


FIGURE 3. More conservative and cautious control, rather than aggressive predictive control and error minimization, is preferred for constraint control and optimization in most real process operation and automation contexts, to safeguard ongoing process stability. This type of control does not require detailed process models

Practical control and operation

If MPC had evolved into a more mature technology over the past two decades, such that the shortcomings had long since resolved themselves and the success of new MPC applications was more predictable and assured, then today's MPC software tools might be up to the task of *macro*-managing the hundreds of models that are typical of big matrix MPCs. But where performance troubleshooting and *micro*-management of individual models remains necessary, then having hundreds of models presents a practical problem.

The difficulty of "getting your head around" big-matrix MPC applications comprised of hundreds of models, from either an operating or engineering standpoint, has sustained a layer of abstraction that has prevented a practical working knowledge of MPC from emerging in industry (see sidebar). For many engineers and operators, basic MPC troubleshooting and operation skills remain underdeveloped.

TABLE 1. BIG MATRIX VS. SMALL MATRIX	
Big matrix, model-based	**Small matrix, model-less**
Double-digit matrix dimensions, for example 20 × 50	Single-digit matrix dimensions, e.g. 3 × 8
Hundreds of models	One or two dozen models
All process interactions are identified, most are included in the controller (and the models guide operation)	Interactions are selected based on practical criteria, that is, only key interactions are utilized in the controller
Depends on accurate models, which is usually not realistic	Does not require models

The use of a small-matrix multivariable control solution, if nothing more, constitutes a sensible "walk-before-run" approach to mastering multivariable control. A multivariable controller comprising one or two dozen models constitutes a highly valuable and respectable automation accomplishment.

A controller comprised of hundreds of models may at first appear that much better, but the additional variables often have diminishing returns and experience shows they are likely to compromise, rather than augment, the benefits derived from automatic control of the core variables. This benefit loss is due to unwanted control action, potential process instability that can result from control actions based on incorrect models, ill-conditioned matrix behavior (that is, a lot of MV movement for a small amount of optimization gain, something operations people instinctively avoid), and other symptoms. All of this can lead to MPC performance degradation and loss of the original benefits.

Moreover, from a process-operation standpoint, larger matrices and aggressive constraint control are usually simply unnecessary. In only very rare instances is it desirable from an operation standpoint to control any one CV with more than three MVs, or to control more than three CVs with any one MV. In the vast majority of cases, it is only one or two. As a guideline, if there are multiple instances of three or more models in any one row or column of the matrix, then further CV rationalization is probably indicated.

Debunking old myths

The root cause of most limitations of traditional big-matrix, model-based multivariable control, and the most important factor driving the adoption of small-matrix, model-less practice, is widespread model inaccuracy, which is unavoidable. Process gains change, not just over the long term, but day to day, based on feed rate, feedstock quality, product grade, and many other factors. The working assumption has often been that modern model-identification software solves this, but process modeling turns out to be a rapidly shifting target — even if you remodel today, the models may be inaccurate tomorrow. When tuning loops or troubleshooting models, one notices many sources of model variability. Where general model inaccuracy is the case, then limiting the size of the control problem to key variables can make the overall multivariable control problem more manageable and better behaved.

This perspective — that more models can be part of the problem, rather than part of the solution — runs counter to MPC orthodoxy, but in retrospect it isn't necessarily surprising. Single-loop performance has always been limited by the changing nature of process gains and interactions. That's why loop tuning has always been an ongoing activity, rather than a one-time activity.

MPC is subject to the same problem, perhaps even more so, due to the extensive and aggressive manner in which MPC uses the models for control. The several shortcomings of traditional big-matrix MPC that have very slowly emerged in industry are actually well-explained as the consequences of unavoidable model inaccuracy [*1*].

Just as inherent model inaccuracy is a common limitation of both single-loop and multivariable control performance, so the remedy is similar in both cases, too. In the single-loop world, model uncertainty is addressed by conservative tuning (sometimes called detuning). This is natural because maintaining process stability is always a top priority and conservative control action is almost always more prudent, especially in the face of unknown or changing process gain. In the multivariable context, this equates to small-matrix, model-less multivariable control, where priority is given to conservative control of a handful of the most important variables, potentially at the cost of increased transient error that theoretically could be reduced by using a larger set of perfect models.

Aggressive constraint control, path optimization and transient error minimization are often cited as advantages of MPC, but they are actually inappropriate in most industrial process-control contexts. From a process operation standpoint, conservative control action and ongoing process stability assurance are higher priorities, while transient error is usually negligible or a distant second priority.

Figure 3 shows the difference between aggressive model-based and conservative model-less control methods. In this figure, a controlled-variable target value undergoes a step change, and three different control responses are shown: error minimization, first order and ramp. In error minimization, the response is fast, with some overshoot and cycling, but total integrated error is small compared to the two conservative cases. That is often presented as a positive outcome, but actual operation of industrial processes almost always favors the more conservative approaches, so that ongoing process stability can be reliably monitored and assured.

Another important difference between the aggressive and conservative cases is that aggressive control requires precise and reliable model or tuning data, whereas conservative control requires only more qualitative information, such as the sign (positive or negative) of the interaction, approximate settling time, and a safe rate of change, all of which are commonly known by process operators and engineers. This opens the door to simpler, model-less control algorithms and bypasses the source of most costs and difficulties

associated with traditional big matrix model-based control — that is, models and model inaccuracy.

Closing thoughts

The power, elegance and rigor of model-based multivariable control should not be overlooked. For a perfectly behaved process (such as a simulation, where the process response is back-calculated from the models themselves), model-based multivariable control has the theoretical potential to affect perfect real time dynamic control, limited only by the speed of the process itself. However, model-based control fundamentally depends upon accurate models, which cannot realistically be assured for most real-world industrial processes. In real process-plant operation, careful and conservative-control action remains the order of the day. This leaves a critical gap in process automation, because most processes are multivariable and a simple, effective multivariable-control solution is needed to fill this important competency.

CV rationalization, practical considerations and model-inaccuracy issues, drive the trend from traditional big-matrix, model-based multivariable control practice, toward small matrix model-less practice. Moreover, the nature of industrial process operation means that conservative model-less control response is preferred in most process automation contexts. Small-matrix, model-less multivariable control practice offers a path forward that overcomes the limitations that have persisted with traditional big matrix model-based practice, and potentially offers a multivariable-control solution that is much more accessible to industry. Small-matrix approaches can help fill this essential multivariable-control competency gap, in that they provide a less costly, less complicated and more easily managed solution. ■

Edited by Suzanne Shelley

References

1. Kern, A., MPC: Beyond the glass ceiling, InTech Web Exclusive, June 2013, accessed http://www.isa.org/InTechTemplate.cfm?template=/contentmanagement/contentdisplay.cfm&contentID=93409

Author

Allan Kern is an independent consultant (allan.kern@apcperformance.com) with more than 35 years of process control experience. He has authored numerous papers on multivariable control performance, and served as automation lead at a major Middle Eastern Refinery, where his responsibilities included deployment and performance of multivariable control technology. In 2012, Kern founded APCperformance.com and began working as an independent industry process-control consultant. He has professional engineering licenses in control systems and chemical engineering, is a senior member of ISA, and is a chemical engineering graduate of the University of Wyoming.

Is there a university-industry disconnect?

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

I felt somewhat insulted when he said, "At universities, we do the difficult work and we leave the easy work for industry." I had asked a question of a speaker at the November 2013 AIChE meeting. The speaker answered the question. Then, a gentleman in the first row chimed in with his "difficult/easy comment." For most of my career, I have performed research and development work for industry. Maybe that was is why I was taken aback by the gentleman's statement.

Over the last ten years, there have been relatively few CO_2-related presentations at AIChE meetings. At the November 2013 meeting, however, there was a tsunami of CO_2-related abstract submittals. Several sessions had to be added to the program, especially on the last days of the meeting, which are typically time-to-go-home days. In fact, ultimately, there were 22 sessions with "CO_2" or "carbon dioxide" in the title; 130 presentations comprised those sessions (not counting the poster papers).

Being semi-obsessed with the gentleman's comment, I flipped through the meeting program book, and did some tallying regarding the employers of the authors and co-authors who presented CO_2-related papers. I found the following: 38 were from "think tanks" like NETL (The National Energy Technology Laboratory; www.netl.doe.gov), SwRI (Southwest Research Institute; www.swri.org) and EPRI (Electric Power Research Institute; www.epri.com); 24 were from industry including companies such as Petrobras (www.petrobras.com), Fluor (www.fluor.com), Alstom (www.alstom.com) and others; and 125 were from universities! Why was there such an industry-university mismatch? People who regularly attend both the Fall and Spring AIChE Meetings know that the fall meeting is generally regarded as the "academia meeting" and the spring meeting is generally regarded as the "industry meeting." This dichotomy is particularly true in the very large Separations Division.

The academic CO_2-related presentations at the fall meeting were relevant, interesting and covered a very broad range of topics including the following: solvents, blended solvents, activators, passivators, flue gas treating, solvent degradation, environmental impacts, column internals, operating costs, capital costs, bench tests, pilot plants, membranes, adsorption and more. The huge amount of ongoing global university research work regarding carbon dioxide removal is understandable, but shocking nevertheless.

It will be interesting to see how many CO_2-related abstracts will be presented by authors from industry and academia at the upcoming spring meeting. Will there be a second tsunami of CO_2-related presentations? If so, will more academics attend the spring "industry" meeting?

I am worried about a massive disconnect. Do the universities know what industry truly needs? Does industry know what the universities are working on, and why? Clearly, both parties are simply following the money. Wouldn't it be better if universities and industry communicated more and followed each other? ■

Mike Resetarits

RECRUITMENT

Tech Service Manager

Tanner Industries, a leading distributor of ammonia, has an immediate opening for a Tech Service Manager. Position will be located in Southampton, PA. Candidates should be highly motivated with excellent problem solving, organizational and customer service skills. Experience with compressed gases and/or ammonia properties required along with good mechanical and technical aptitude. Individual will interact with both internal and external customers to provide technical support on storage, handling and delivery processes of both anhydrous ammonia and aqua ammonia systems. Some travel will be required.

Full benefit package.
Submit resumes to:
mtanner@tannerind.com
or fax: 215-526-7812

SOFTWARE

NEW & USED EQUIPMENT

SOFTWARE

CONSULTING

CHEMICAL ENGINEERING New Product Information

February 2014

JustFAXit! or go to www.che.com/adlinks

Fill out the form and circle or write in the number(s) below, cut it out, and fax it to 800-571-7730.

Go on the Web and fill out the online reader service card.

Name ______________________ Title ______________________

Company ______________________

Address ______________________

City ______________ State/Province ______________ Zip/Postal Code ______________

Country\ ______________ Telephone ______________ Fax ______________

Email | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

FREE PRODUCT INFO
(please answer all the questions)

YOUR INDUSTRY

01 Food & Beverages
02 Wood, Pulp & Paper
03 Inorganic Chemicals
04 Plastics, Synthetic Resins
05 Drugs & Cosmetics
06 Soaps & Detergents
07 Paints & Allied Products
08 Organic Chemicals
09 Agricultural Chemicals
10 Petroleum Refining, Coal Products
11 Rubber & Misc. Plastics
12 Stone, Clay, Glass, Ceramics
13 Metallurgical & Metal Products
14 Engineering, Design & Construction Firms
15 Engineering/Environmental Services
16 Equipment Manufacturer
17 Energy incl. Co-generation
18 Other______________

JOB FUNCTION

20 Corporate Management
21 Plant Operations incl. Maintenance
22 Engineering
23 Research & Development
24 Safety & Environmental
26 Other______________

EMPLOYEE SIZE

28 Less than 10 Employees
29 10 to 49 Employees
30 50 to 99 Employees
31 100 to 249 Employees
32 250 to 499 Employees
33 500 to 999 Employees
34 1,000 or more Employees

YOU RECOMMEND, SPECIFY, PURCHASE
(please circle all that apply)

40 Drying Equipment
41 Filtration/Separation Equipment
42 Heat Transfer/Energy Conservation Equipment
43 Instrumentation & Control Systems
44 Mixing, Blending Equipment
45 Motors, Motor Controls
46 Piping, Tubing, Fittings
47 Pollution Control Equipment & Systems
48 Pumps
49 Safety Equipment & Services
50 Size Reduction & Agglomeration Equipment
51 Solids Handling Equipment
52 Tanks, Vessels, Reactors
53 Valves
54 Engineering Computers/Software/Peripherals
55 Water Treatment Chemicals & Equipment
56 Hazardous Waste Management Systems
57 Chemicals & Raw Materials
58 Materials of Construction
59 Compressors

1	16	31	46	61	76	91	106	121	136	151	166	181	196	211	226	241	256	271	286	301	316	331	346	361	376	391	406	421	436	451	466	481	496	511	526	541	556	571	586
2	17	32	47	62	77	92	107	122	137	152	167	182	197	212	227	242	257	272	287	302	317	332	347	362	377	392	407	422	437	452	467	482	497	512	527	542	557	572	587
3	18	33	48	63	78	93	108	123	138	153	168	183	198	213	228	243	258	273	288	303	318	333	348	363	378	393	408	423	438	453	468	483	498	513	528	543	558	573	588
4	19	34	49	64	79	94	109	124	139	154	169	184	199	214	229	244	259	274	289	304	319	334	349	364	379	394	409	424	439	454	469	484	499	514	529	544	559	574	589
5	20	35	50	65	80	95	110	125	140	155	170	185	200	215	230	245	260	275	290	305	320	335	350	365	380	395	410	425	440	455	470	485	500	515	530	545	560	575	590
6	21	36	51	66	81	96	111	126	141	156	171	186	201	216	231	246	261	276	291	306	321	336	351	366	381	396	411	426	441	456	471	486	501	516	531	546	561	576	591
7	22	37	52	67	82	97	112	127	142	157	172	187	202	217	232	247	262	277	292	307	322	337	352	367	382	397	412	427	442	457	472	487	502	517	532	547	562	577	592
8	23	38	53	68	83	98	113	128	143	158	173	188	203	218	233	248	263	278	293	308	323	338	353	368	383	398	413	428	443	458	473	488	503	518	533	548	563	578	593
9	24	39	54	69	84	99	114	129	144	159	174	189	204	219	234	249	264	279	294	309	324	339	354	369	384	399	414	429	444	459	474	489	504	519	534	549	564	579	594
10	25	40	55	70	85	100	115	130	145	160	175	190	205	220	235	250	265	280	295	310	325	340	355	370	385	400	415	430	445	460	475	490	505	520	535	550	565	580	595
11	26	41	56	71	86	101	116	131	146	161	176	191	206	221	236	251	266	281	296	311	326	341	356	371	386	401	416	431	446	461	476	491	506	521	536	551	566	581	596
12	27	42	57	72	87	102	117	132	147	162	177	192	207	222	237	252	267	282	297	312	327	342	357	372	387	402	417	432	447	462	477	492	507	522	537	552	567	582	597
13	28	43	58	73	88	103	118	133	148	163	178	193	208	223	238	253	268	283	298	313	328	343	358	373	388	403	418	433	448	463	478	493	508	523	538	553	568	583	598
14	29	44	59	74	89	104	119	134	149	164	179	194	209	224	239	254	269	284	299	314	329	344	359	374	389	404	419	434	449	464	479	494	509	524	539	554	569	584	599
15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345	360	375	390	405	420	435	450	465	480	495	510	525	540	555	570	585	600

If number(s) do not appear above, please write them here and circle: ______________

Fax this page back to 800-571-7730

ADVERTISING SALES REPRESENTATIVES

North America

Terry Davis
Sales Director
Chemical Engineering
2276 Eastway Rd., Decatur, GA 30033
Tel: 404-634-5123; Fax: 832-201-8823 E-mail: tdavis@che.com
Alabama, Canada, Connecticut, Delaware, Georgia, Idaho, Kentucky, Latin America, Maine, Maryland, Massachusetts, Mississippi, Montana, Nebraska, New Hampshire, New Jersey, New York, North and South Carolina, North and South Dakota, Ohio, Oregon, Pennsylvania, Rhode Island, Tennessee, Utah, Vermont, Virginia, Washington D.C., West Virginia, Wyoming

Jason Bullock,
District Sales Manager
Chemical Engineering
8325 Broadway, Ste. 202/PMB 261
Pearland, TX 77581
Tel: 281-485-4077; Fax: 281-485-1285
E-mail: jbullock@che.com
Arizona, Arkansas, California, Colorado, Florida, Kansas, Louisiana, Missouri, Nevada, New Mexico, Oklahoma, Texas, Washington

Dan Gentile
District Sales Manager
Tel: 512-918-8075
E-mail: dgentile@che.com
Alaska, Hawaii, Illinois, Indiana, Iowa, Michigan, Minnesota, Wisconsin,

Diane Burleson
Inside Sales Manager
Chemical Engineering;
11000 Richmond Ave, Suite 690,
Houston, TX 77042
Tel: 512-337-7890
E-mail: dburleson@che.com
Product Showcase, Literature Reviews, Classified Display Advertising

International

Petra Trautes
Chemical Engineering
Zeilweg 44
D-60439 Frankfurt am Main
Germany
Phone: +49-69-58604760
Fax: +49-69-5700-2484
Email: ptrautes@che.com
Austria, Czech Republic, Benelux, Eastern Europe, Germany, Scandinavia, Switzerland, United Kingdom

Dipali Dhar
Chemical Engineering
88 Pine Street, 5th floor, New York, NY 10005
Tel: 718-263-1162
E-mail: ddhar@accessintel.com
India

Katshuhiro Ishii
Chemical Engineering
Ace Media Service Inc., 12-6, 4-chome
Nishiiko, Adachi-ku, Tokyo 121, Japan
Tel: 81-3-5691-3335; Fax: 81-3-5691-3336
E-mail: amskatsu@dream.com
Japan

Ferruccio Silvera
Chemical Engineering
Silvera Pubblicita
Viale Monza, 24 Milano 20127, Italy
Tel: 39-02-284-6716;
Fax: 39-02-289-3849
E-mail: ferruccio@silvera.it/www.silvera.it
Andorra, France, Gibraltar, Greece, Israel, Italy, Portugal, Spain

Rudy Teng
Sales Representative
Chemical Engineering;
8F-1 #181 Wulin Road
Hsinchu 30055 Taiwan
Tel: +86 13818181202, (China),
+886 921322428 (Taiwan)
Fax: +86 21 54183567
E-mail: rudy.teng@gmail.com
Asia-Pacific, Hong Kong, People's Republic of China, Taiwan

Advertisers' Index

Advertiser *Phone number*	Page number *Reader Service #*
3P Prinz *adlinks.che.com/50973-01*	**9**
Abbe, Paul O. *1-800-524-2188* *adlinks.che.com/50973-03*	**6**
*** Bronkhorst High-Tech BV** *adlinks.che.com/50973-04*	**6**
Brookfield Engineering *1-800-628-8139* *adlinks.che.com/50973-05*	**24**
Buss-SMS-Canzler GmbH *49 60 33-85-0* *adlinks.che.com/50973-06*	**25**
Check-All Valve Mfg. Co. *1-515-224-2301* *adlinks.che.com/50973-07*	**29**
Chemineer *1-800-643-0641* *adlinks.che.com/50973-26*	**40**
Chemstations *adlinks.che.com/50973-08*	**15**
Corzan Piping Systems *1-855-735-1431* *adlinks.che.com/50973-19*	**18**
Eastman Chemical Company *1-800-426-2463* *adlinks.che.com/50973-09*	**3**
Endress + Hauser *1-888-ENDRESS* *adlinks.che.com/50973-10*	**7**
Expoquimia - Fira de Barcelona *adlinks.che.com/50973-11*	**8**
Flexicon Corporation *1-888-FLEXICON* *adlinks.che.com/50973-12*	**FOURTH COVER**
Flexim GmbH *adlinks.che.com/50973-13*	**6**
Fluid Metering, Inc. *1-800-223-3388* *adlinks.che.com/50973-14*	**9**
GIG Karasek GmbH *43 2662 42780* *adlinks.che.com/50973-15*	**23**
Interphex 2014 *adlinks.che.com/50973-16*	**16**
Kral AG *43/5577/86644-0* *adlinks.che.com/50973-17*	**41**
Load Controls *1-888-600-3247* *adlinks.che.com/50973-18*	**56**
Magnetrol *1-800-624-8765* *adlinks.che.com/50973-20*	**4**
PNC Financial Services Group *1-855-762-2361* *adlinks.che.com/50973-21*	**21**
Quest Integrity Group *1-253-893-7070* *adlinks.che.com/50973-22*	**43**
RedGuard *1-855-REDGUARD* *adlinks.che.com/50973-02*	**SECOND COVER**
Ross, Charles & Son Company *1-800-243-ROSS* *adlinks.che.com/50973-23*	**10**
Samson AG *49 69 4009-0 adlinks.che.com/50973-24*	**13**
ThyssenKrupp Industrial Solutions AG *adlinks.che.com/50973-25*	**19**

*** International Edition**

See bottom of opposite page for advertising sales representatives' contact information

Classified Index February 2014

Advertiser *Phone number*	Page number *Reader Service #*
Amandus Kahl Hamburg *adlinks.che.com/50973-201*	**58**
Applied e-Simulators Software *adlinks.che.com/50973-241*	**59**
Heat Transfer Research, Inc. *adlinks.che.com/50973-242*	**58**
HFP Acoustical Consultants *1-713-789-9400* *adlinks.che.com/50973-243*	**59**
Indeck Power Equipment Co. *1-847-541-8300* *adlinks.che.com/50973-244*	**59**
Ross, Charles & Son Company *1-800-243-ROSS* *adlinks.che.com/50973-245*	**59**
Tanner Industries *adlinks.che.com/50973-246*	**58**
Vesconite Bearings *27 11 616 11 11* *adlinks.che.com/50973-247*	**59**
Wabash Power Equipment Co. *1-800-704-2002* *adlinks.che.com/50973-248*	**59**
Xchanger, Inc. *1-952-933-2559* *adlinks.che.com/50973-249*	**59**

Send Advertisements and Box replies to: Diane Burleson

***Chemical Engineering*, 11000 Richmond Ave, Houston, TX 77042**

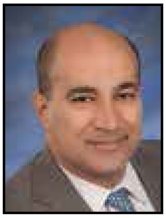
E-mail: dburleson@che.com Tel: 512-337-7890

FEBRUARY WHO'S WHO


Batz


Schaefer


Selby


Said


Brandmeier

Brad Batz becomes president of **Fike Corp.** (Blue Springs, Mo.), a leader in fire, explosion and over-pressurization solutions.

Bernd-Josef Schaefer becomes managing director of flowmeter maker **Endress+Hauser Flowtec AG** (Reinach, Switzerland).

Rod Selby becomes director of Asia Pacific business development for **Intelligrated** (Cincinnati, Ohio), a provider of automated material-handling solutions.

Polymer producer **Bioformix** (Cincinnati, Ohio) makes the following promotions: *Jeff Uhrig* is now CEO, *Kousay Said* is now chief commercial officer, and *Adam Malofsky* is now chief innovation officer.

Toray Plastics (North Kingstown, R.I.) announces several promotions: *Michael Brandmeier* becomes executive vice president for the company's three divisions (Torayfan propylene film, Lumirror polyester film and Toraypef polyolefin foam); *Scott Van Winter* becomes senior vice president and general manager of the Lumirror Div.; *Christopher Roy* becomes general manager of the Torayfan Div.; and *Lisa Ahart* becomes vice president, U.S. corporate human resources and environmental health and safety.

Burkhard Zoller becomes chief financial officer of specialty chemicals company **Evonik Corp.** (Parsippany, N.J.), a subsidiary of Evonik industries AG. ■

Suzanne Shelley

BUSINESS NEWS

PLANT WATCH

Arkema to double production capacity for organic peroxides in China
January 9, 2014 — Arkema (Colombes, France; www.arkema.com) has announced the construction of a new organic peroxide plant on its Changshu site in China. This investment will double the site's production capacity. The new Changshu plant is due to start up in early 2016.

Foster Wheeler awarded PMC contract for grassroots refinery in Turkey
January 8, 2014 — A subsidiary of Foster Wheeler AG (Zug, Switzerland; www.fwc.com) was awarded a contract by STAR Rafineri A.S. for project management consultancy (PMC) services for its grassroots Aegean Refinery to be built in Turkey. The refinery is designed to process 10 million metric tons per year (m.t./yr) of crude oil and is expected to start operations in 2017.

Outotec to deliver technology and services to Turkey's Cengiz Group
December 28, 2013 — Outotec (Espoo, Finland; www.outotec.com) will deliver technology and services worth over €100 million to Cengiz Group for their operations in Turkey. The contract includes a roasting plant for pyrite concentrates, leaching and solvent-extraction plants, copper-smelter modernization, as well as gas cleaning and sulfuric acid plants. The deliveries will take place from late 2014 until 2016.

Axiall selects Louisiana as site for proposed U.S. ethylene cracker
December 20, 2013 — Axiall Corp. (Atlanta, Ga.; www.axiall.com) has selected Louisiana as the location of a possible ethylene cracker to be built in conjunction with a related derivatives plant. Axiall proposes to construct the facility with a soon-to-be-named partner. Axiall's capital investment would be approximately $1 billion, with an additional $2 billion from a partner. If construction goes forward, operations could begin in 2018.

Sibur expands production capacity for butyl rubber
December 19, 2013 — Tolyattikauchuk, a subsidiary of Sibur (Moscow, Russia; www.sibur.com), has commissioned a third solution-polymerization line for butyl rubber separation, expanding its production capacity from 48,000 m.t./yr to 53,000 m.t./yr.

KBR ammonia technology selected for new fertilizer facility in Indiana
December 19, 2013 — KBR (Houston; www.kbr.com) has announced that its Purifier process technology for ammonia was selected by Midwest Fertilizer Corp. for a new fertilizer manufacturing plant in Mt. Vernon, Ind. The plant's ammonia capacity will be 2,200 m.t./d.

BASF to build new plastics compounding plant in Korea
December 17, 2013 — BASF SE (Ludwigshafen, Germany; www.basf.com) will build a compounding plant for the engineering plastics Ultramid (polyamide) and Ultradur (polybutylene terephthalate) in Yesan, Chung Nam Province, Korea. Construction is expected to begin by the first half of 2014 and commence operations by the end of 2015. With an initial capacity of 36,000 m.t./yr, the new plant will more than double the total compounding capacity of BASF's engineering plastics in Korea.

Haldor Topsøe builds plant in China to produce automotive catalysts
December 13, 2013 — Haldor Topsøe A/S (Lyngby, Denmark; www.topsoe.com) will establish a new automotive-catalyst plant in China's Tianjin Economic Technological Development Area. Construction has already begun and will consist of two primary phases, to be completed by April 2015, and early 2016, respectively. The total capital investment is around DDK 900 million ($180 million).

Honeywell to expand refrigerant production in Louisiana
December 11, 2013 — Honeywell (Morristown, N.J.; www.honeywell.com) will invest approximately $300 million to increase production capacity for HFO-1234yf, a new refrigerant for automobiles. With these investments, Honeywell will construct a high-volume manufacturing plant using new process technology at the company's Geismar, La. refrigerants manufacturing site, which is expected to be fully operational in 2016.

MERGERS AND ACQUISITIONS

AkzoNobel completes sale of primary amides business to PMC Group
January 7, 2014 — AkzoNobel (Amsterdam, The Netherlands; www.akzonobel.com) completed the sale of its primary amides chemicals business to chemicals and plastics company PMC Group Inc. (Mt. Laurel, N.J.; www.pmc-group.com). Financial details were not disclosed.

Jacobs acquires telecommunications provider FMHC
January 7, 2014 — Jacobs Engineering Group Inc. (Pasadena, Calif.; www.jacobs.com) has announced the acquisition of FMHC Corp. (Chicago, Ill.; www.fmhc.com). FMHC provides turnkey wireless communications site development, design, network deployment, construction and related services to clients who operate in the wireless-telecommunications industry.

Rosneft, Pirelli and Oil Techno collaborate on synthetic rubber JV in Armenia
December 30, 2013 — Rosneft, LLC (Moscow, Russia; www.rosneft.com), Pirelli Tyre Russia and Oil Techno have signed a memorandum of understanding to establish a styrene-butadiene rubber production joint venture (JV) in Armenia. The JV will focus primarily on research and development.

Sika acquires cementitious powder producers in Singapore and Malaysia
December 17, 2013 — Sika AG (Baar, Switzerland; www.sika.com) has agreed to acquire LCS Optiroc Pte Ltd. of Singapore and LCS Optiroc SDN. BHD of Malaysia. Both acquired companies are manufacturers of cementitious powder products. With these acquisitions, Sika gains established factories in Singapore and Malaysia.

Clariant to acquire Indian masterbatch producer
December 17, 2013 — Clariant (Muttenz, Switzerland; www.clariant.com) intends to acquire Plastichemix Industries, a masterbatch business in India. Plastichemix Industries supplies black, white, filler and color masterbatches, additive masterbatches, flushed pigments and mono-concentrates as well as engineering plastics.

Arkema to divest coatings businesses in South Africa
December 13, 2013 — Arkema plans to divest its two South African subsidiaries, Arkema Resins Pty Ltd. and Harveys Composites Pty Ltd. to Ferro Industrial Products Pty Ltd. (Brakpan, South Africa; www.ferro-sa.co.za), a company specializing in coatings and materials for composite markets. ■

Mary Page Bailey

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

February 2014; VOL. 121; NO. 2

FOR MORE ECONOMIC INDICATORS, SEE NEXT PAGE

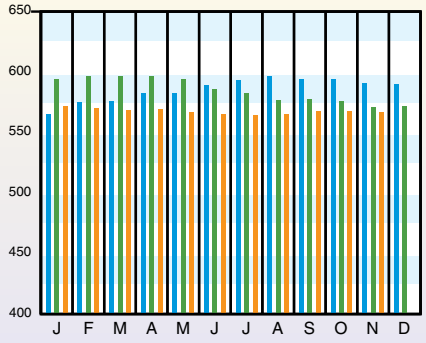
DOWNLOAD THE *CEPCI* TWO WEEKS SOONER AT WWW.CHE.COM/PCI

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Nov.'13 Prelim.	Oct.'13 Final	Nov.'12 Final
***CE* Index**	566.8	567.5	570.6
Equipment	686.7	686.6	691.7
Heat exchangers & tanks	620.7	620.0	634.0
Process machinery	653.1	655.7	656.7
Pipes, valves & fittings	873.9	874.5	890.4
Process instruments	411.5	411.8	420.7
Pumps & compressors	924.3	924.7	895.8
Electrical equipment	514.1	513.8	511.2
Structural supports & misc	746.3	744.1	726.0
Construction labor	318.3	321.6	321.6
Buildings	533.3	533.7	525.0
Engineering & supervision	323.9	324.4	327.3

Annual Index:

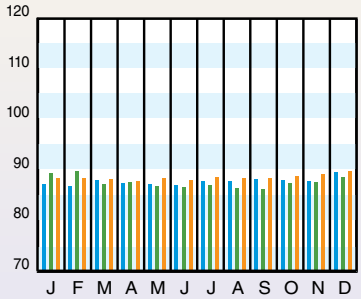
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6



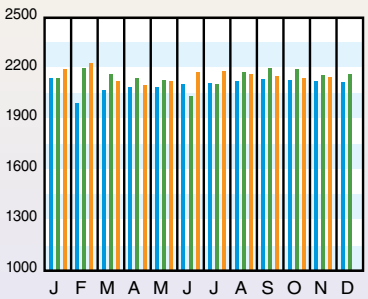
CURRENT BUSINESS INDICATORS*

	LATEST		PREVIOUS		YEAR AGO	
CPI output index (2007 = 100)	Dec.'13 =	89.6	Nov.'13 =	89.0	Oct.'13 =	88.7	Dec.'12 =	88.4
CPI value of output, $ billions	Nov.'13 =	2,148.5	Oct.'13 =	2,140.7	Sep.'13 =	2,152.1	Nov.'12 =	2,159.8
CPI operating rate, %	Dec.'13 =	75.5	Nov.'13 =	75.1	Oct.'13 =	75.0	Dec.'12 =	75.2
Producer prices, industrial chemicals (1982 = 100)	Dec.'13 =	294.2	Nov.'13 =	291.5	Oct.'13 =	296.3	Dec.'12 =	297.1
Industrial Production in Manufacturing (2007 = 100)	Dec.'13 =	97.8	Nov.'13 =	97.4	Oct.'13 =	96.8	Dec.'12 =	95.3
Hourly earnings index, chemical & allied products (1992 = 100)	Dec.'13 =	160.3	Nov.'13 =	156.3	Oct.'13 =	156.6	Dec.'12 =	153.6
Productivity index, chemicals & allied products (1992 = 100)	Dec.'13 =	107.6	Nov.'13 =	107.2	Oct.'13 =	107.3	Dec.'12 =	106.5

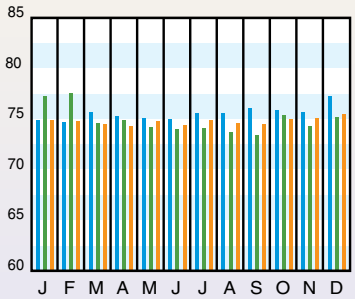
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



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

HIGHLIGHTS FROM RECENT ACC WEEKLY REPORTS

The S&P index for chemical companies rose by 4.2% in December 2013, outpacing the overall S&P 500 index, which rose 2.4%. The numbers were included in the Weekly Chemistry and Economic Report from the American Chemistry Council (ACC; Washington, D.C.; www.americanchemistry.com) for the week of January 10. Over the entirety of 2013, the S&P chemical index rose by 29.6%, its largest annual gain since 1997, the ACC report says. The S&P 500 rose 29.0% in 2013.

In the report for the week of January 3, the ACC indicated that the JP Morgan Global Manufacturing purchasing managers' index (PMI) rose 0.2 points in December 2013, to a level of 53.3. The gain is the 12th consecutive monthly rise, and the highest level for the index in 32 months.

"Output growth was again led by the G7 developed nations in December, as robust expansions in the U.S., Japan, Germany, the U.K. (which registered the highest Output PMI reading of all countries) and Italy offset the ongoing contraction in France and a sharp growth slowdown in Canada," says the ACC report.

In other data discussed in the report, U.S. specialty-chemical market volumes rose 0.8% in November 2013. "The 2013 slowdown in manufacturing affected these business segments, but recovery in specialty chemicals appears to be broadening," the ACC says.

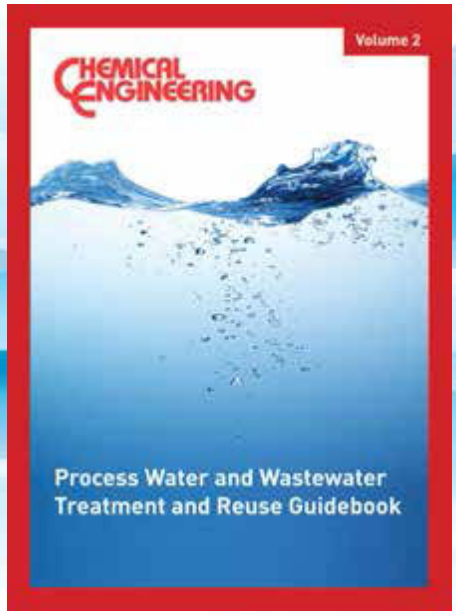
Of the 28 specialty chemical segments monitored by ACC, 24 expanded in November, while the remaining four experienced decline. Large gains (1.0% or greater) were noted in 13 segments, the ACC noted, including the following: adhesives and sealants; antioxidants; biocides; catalysts; coatings; cosmetic additives; electronic chemicals; flavors and fragrances; foundry chemicals; oilfield chemicals; paint additives; rubber processing chemicals; and textile specialties. ❑

CURRENT TRENDS

Preliminary data for the November 2013 *CE* Plant Cost Index (CEPCI; top; the most recent available) show a small decrease (0.12%) in the overall index compared to the October index value. The decrease reverses the trend direction for the three previous months, which all saw increases in the PCI. The decrease in the overall index was mostly due to decreases in the index subcategories for Process Machinery and Construction Labor. The current CEPCI value stands at 0.67% lower than the value from a year ago. Meanwhile, updated values for the Current Business Indicators from IHS Global Insight (middle) saw the numbers for each category increase compared to the previous month's values. ❑

Now Available in the *Chemical Engineering* Store:

Process Water and Wastewater Treatment and Reuse Guidebook- Volume 2



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

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

Table of Contents

Order your copy today by visiting store.che.com

CONVEY

FLEXI-DISC™ Tubular Cable Conveyors gently slide fragile foods and non-foods through smooth stainless steel tubing routed horizontally, vertically or at any angle, over short or long distances, dust-free. Single or multiple inlets and outlets.

DUMP

FLEXICON® Manual Dumping Stations allow dust-free dumping of bulk material from bags and other containers. Automatic reverse-pulse filter cleaning allows continuous, efficient operation. Available with integral bag compactors for total dust containment.

UNLOAD

BULK-OUT® Bulk Bag Dischargers unload free- and non-free-flowing solids from bulk bags automatically. Allows untying, discharging, retying and collapsing of bulk bags—all dust-free. Available with weigh batching controls.

USDA ACCEPTED

CONDITION

BLOCK-BUSTER® Bulk Bag Conditioners loosen bulk materials that have solidified during storage and shipment. Variable height turntable positions bag for hydraulic rams with contoured conditioning plates to press bag on all sides at all heights.

FILL

SWING-DOWN®, REAR-POST and TWIN-CENTERPOST™ Bulk Bag Fillers can fill one bulk bag per week or 20 per hour at the lowest cost per bag. Numerous performance options. Available to industrial or sanitary standards.

USDA ACCEPTED

CONVEY

FLEXICON® Flexible Screw Conveyors transport free- and non-free-flowing bulk solid materials from large pellets to sub-micron powders, including products that pack, cake or smear, with no separation of blends, dust-free at low cost. No bearings contact material. Easy to clean quickly, thoroughly.

USDA ACCEPTED

3-A CERTIFIED

CONVEY

PNEUMATI-CON® Pneumatic Conveying Systems move a broad range of bulk materials over short or long distances, between single or multiple inlet and discharge points in low to high capacities. Available as dilute-phase vacuum or positive pressure systems, fully integrated with your process.

DUMP

TIP-TITE® Container Dumpers dump bulk material from drums (shown), boxes or other containers into vessels up to 10 ft (3m) high. Dust-tight (shown) or open chute models improve efficiency and safety of an age-old task.

SUCCEED

The FLEXICON® Lifetime Performance Guarantee* assures you of a successful result, whether you purchase one piece of equipment or an engineered, automated plant-wide system. From initial testing in large-scale laboratories, to single-source project management, to after-sale support by a worldwide network of factory experts, you can trust your process—and your reputation—to Flexicon.

USA
sales@flexicon.com
1 888 FLEXICON

CHILE +56 2 2415 1286
UK +44 (0)1227 374710
AUSTRALIA +61 (0)7 3879 4180
SOUTH AFRICA +27 (0)41 453 1871

flexicon® .com

BB-1295

Circle 12 on p. 60 or go to adlinks.che.com/50973-12