CHEMICAL ENGINEERING

January
2011

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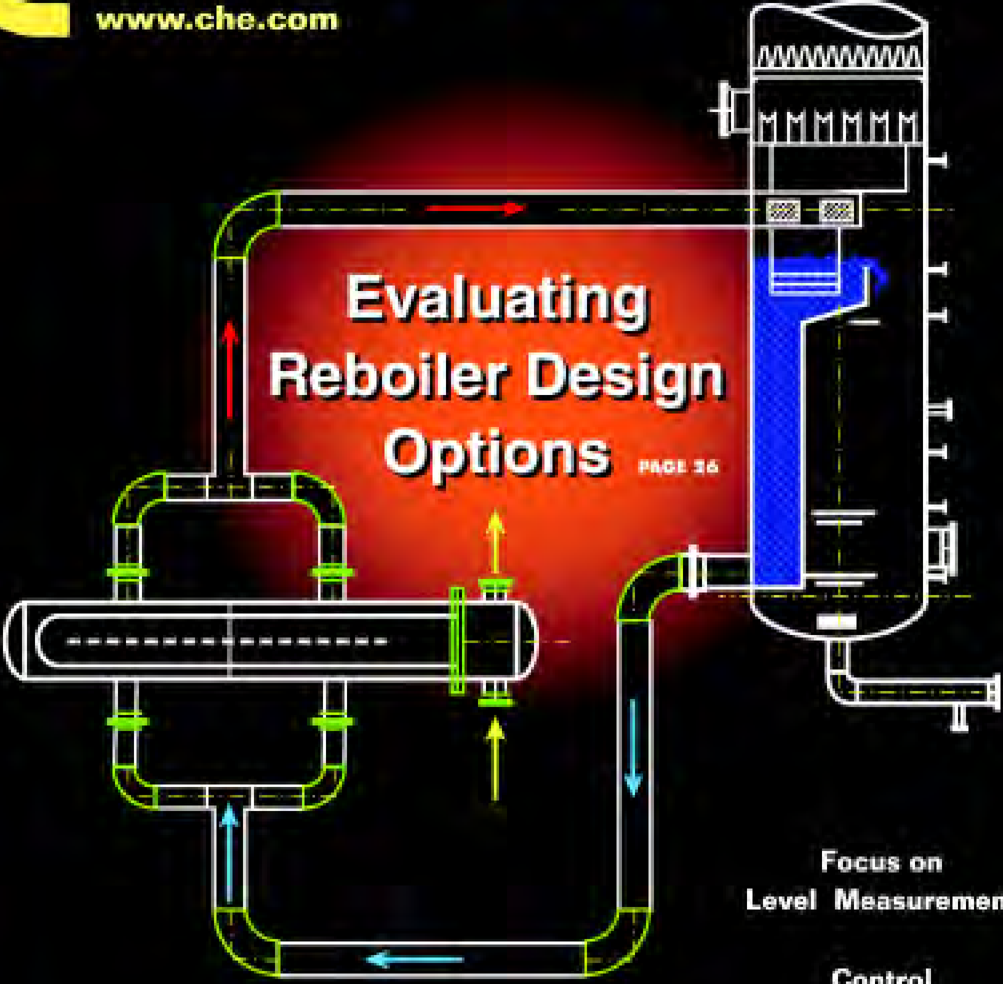

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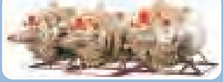
cGMP Reactors


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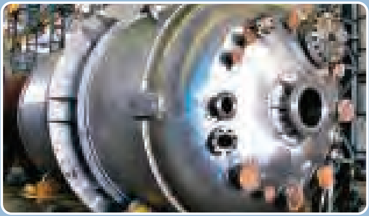
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Editor's Page

2011 Kirkpatrick Award: Call for Nominations

Many of you know of a company — perhaps your own employer — that has recently commercialized an innovative process, product, or other chemical-engineering development. If so, we would like to hear from you. Nominations are open for this magazine's 2011 Kirkpatrick Chemical Engineering Achievement Award. We aim to honor the most-noteworthy chemical engineering technology commercialized anywhere in the world during 2009 or 2010.

Chemical Engineering has awarded this biennial prize continuously since 1933. The 2011 winner will join a long and distinguished roster, studded with such milestones as Lucite's Alpha process for making methyl methacrylate (MMA; 2009), Chevron Phillips Chemical for significant advances in alpha-olefins technology (2005), The Dow Chemical Co.'s magnesium from seawater (1941) and Carbide & Carbon Chemical's petrochemical syntheses (1933).

How to nominate. Nominations may be submitted by any person or company, worldwide. The procedure consists simply of sending, by March 15, an unillustrated nominating brief of up to 500 words to kirkpatrick@che.com. In order to be considered, each nomination must:

- Summarize the achievement and novelty of the technology
- Describe the difficulty of the chemical-engineering problems solved
- Specify how, where and when the development first became commercial in 2009 or 2010

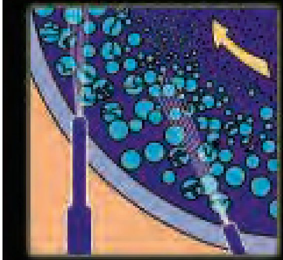
If you know of an achievement but do not have information to write a brief, contact the firm involved, either to get the information or to propose that the company itself submit a nomination. Firms are also welcome to nominate achievements of their own.

The path to the winner. After March 15, we will review the nominations to make sure they are valid — for instance, that the first commercialization did in fact take place during 2009–2010. Then we will submit copies to more than 100 senior professors who head accredited university chemical engineering departments and, accordingly, constitute the Committee of Award. Working independently of each other, each professor will vote for what he or she considers to be the five best achievements, without trying to rank them.

The five entries that collectively receive the most votes become the finalists in the competition. Each finalist company will then be asked to submit more-detailed information — for instance, a fuller description of the technology, performance data, exhibits of press coverage and a description of the teamwork that generated the achievement.

We will then send copies of these more-detailed packages to a Board of Judges, which, meanwhile, will have been chosen from within, and by, the Committee of Award. In late summer, the Board will inform the Secretary as to which one of the five finalist achievements it has judged the most noteworthy. The company that developed that achievement will be named the winner of the 2011 Kirkpatrick Chemical Engineering Achievement Award. The four other finalist companies will be designated to receive Honor Awards. Sculptures saluting the five achievements will be bestowed with appropriate ceremony in the fall at ChemInnovations 2011. ■

Rebekkah Marshall



Letters

Questions of CE history

I was digging through some old files in my office and came across a February 5, 1962 publication of *Chemical Engineering*. It's in good condition and I have now framed it and placed it on my wall in my office. Kinda neat. I was curious to know when was *Chemical Engineering's* first publication and which number the one I have might be.

David Naydyhor
ICL Performance Products, Lawrence, Kan.

CE's first issue was published in September 1902, under the original title Electrochemical Industry. The name changed five times since then, finally settling on the current title in August 1946. Therefore, this September we will celebrate our 109th birthday. The exact issue number is hard to judge. For a number of years, as some of you can personally attest, CE was published bimonthly. Since then, however, it has returned to a monthly frequency. In any case, this reader certainly has a relic on his hands.
— Ed.

Engineering yields diverse careers

Your editor's page in the November 2010 issue, "A passion for breakthroughs", struck a good nerve. I have been working this year with two local school districts in an advisory capacity for high school students considering pursuing an engineering education. Initially I simply shared as quick a view of my 40-year career as a class period would allow.

Then I discussed with some of our younger engineers at Stanley what advice they might share with high school students to improve the likelihood of success in getting an engineering degree. Their answers were basically keeping distractions under control; and maintaining balance of attention to mind, body, and spirit.

During recent opportunities to discuss career and college with individual high school students I found that some things don't change over even a 40+ year period. The student perception that he or she is facing a huge decision to devote themselves to a career they know painfully little about for the rest of their life makes for a pretty scary situation.

I found that they are greatly relieved to learn that being devoted to the task of getting an engineering degree does not paint them into the irreversible corner of actually having to be an engineer for the rest of their lives. Their eyes lit up when I shared that an engineering education and degree in fact opens doors to more opportunities, as opposed to narrowing the available path choices. Learning how an engineer thinks will make a person a better doctor, lawyer, financial analyst, college professor, product marketer and more [editor — Ed.], than he or she would otherwise be without the cause-and-effect understandings provided by the discipline of an engineering background.

I thought you might appreciate these thoughts in any outreach opportunities you may be afforded in the future. Giving back to the profession has been incredibly rewarding.

Charlie Meurer, P.E.
Stanley Consultants, Inc., Muscatine, Iowa

Bookshelf

Interpolation and Regression Models for the Chemical Engineer: Solving Numerical Problems. By Guido Buzzi-Ferraris and Flavio Manenti. Wiley-VCH. Boschstrasse 12, 69469 Wienheim, Germany. Web: wiley-vch.de. 2010. 442 pages. $130.00.

Reviewed by Francis McConville, Impact Technology Development, Lincoln, Mass.

Numerical analysis of data, mathematical modeling and statistical design of experiments are cornerstones of modern engineering. This book is part of a series that covers the range of modern numerical approaches. It deserves a place on the bookshelf of scientists and engineers looking for a deeper understanding of available methods and modern trends in data analysis and experimental design.

This volume focuses on methods that involve linear and non-linear regression and interpolation and statistical experimental design, with some emphasis on optimal model selection. The book is essentially a catalogue of algorithms, methods and programs for numerical analysis, and serves as something of a guidebook to the digital mathematical BzzMath library. This library was developed by author Buzzi-Ferraris and has been adopted by many researchers in academia and industry.

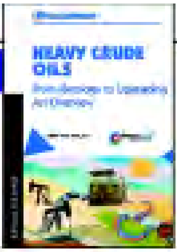
Both authors are distinguished faculty at the prestigious Polytecnico di Milano, Italy. They are widely recognized for their work in mathematical modeling and numerical methods, and they teach courses in these and related topics at the institute. Indeed, much of the material for the book has been drawn from this coursework.

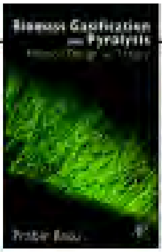
However, for that reason, the book sometimes lacks the cohesion of a text written from a more global perspective. Because of this, the book may be of limited value to the casual reader. Full appreciation of the book requires working through the many valuable examples and case histories, all of which are supplied as computer algorithms and datasets on the accompanying CD-ROM. The authors assume a strong background in statistics and numerical methods, and a working knowledge of the C++ programming language is imperative to work with the examples. Users also must have the requisite Windows- or Linux-based C++ compilers.

Introductory sections waste little time on basics. Chapter 1, on interpolation, presents the methods of Newton, Lagrange, Neville, Theile and Bulirsch-Stoer among others. Chapter 2, entitled “Fundamentals of Statistics” offers a few brief definitions and then delves quickly into advanced statistical-analysis principles.

The book’s strength lies firmly in the examples and case studies, which are drawn from a range of engineering disciplines. According to the authors, the book is intended not as a discourse on regression theory, but rather as a practical set of applied examples to help researchers select the best methods and algorithms to model the system of interest.

Bookshelf





Chapter 3 covers linear regression, beginning with a discussion of the least sum of squares method and moving on to advanced topics with a valuable list of caveats. Chapter 4 includes examples that highlight detection of outlying data points and gross experimental errors. Chapter 5 consists of a host of linear regression case studies. Chapters 6 and 7 cover non-linear regression methods and include another large set of associated case studies.

The text suffers from numerous odd grammatical constructs, dropped articles and other linguistic oversights that make a difficult read even more so. However, this does not detract from the value of the content and examples collected here.

Heavy Crude Oils From Geology to Upgrading: An Overview. Edited by Alain-Yves Huc. Editions Technip, 25 rue Ginoux, 75015 Paris, France. Web: editionstechnip.com. 2010. 432 pages. $115.00.

Chemical Sensors: Fundamentals of Sensing Materials, Vol. 1, General Approaches. Edited by Ghenadii Korotcenkov. Momentum Press LLC. 222 East 46th Street, New York, NY 10017. Web: momentumpress.net. 2010. 300 pages. $109.00.

Renewable Energy, 4th ed. By Bent Sorensen. Elsevier Inc., 30 Corporate Drive, 4th Floor, Burlington, MA 01803. Web: elsevier.com. 2010. 958 pages. $96.00.

Biomass Gasification and Pyrolysis: Practical Design and Theory. By Prabir Basu. Elsevier Inc., 30 Corporate Drive, 4th Floor, Burlinton, MA 01803. Web: elsevier.com. 2010. 376 pages. $108.00.

The Disassembly Line: Balancing and Modeling. By Seamus McGovern and Surendra Gupta. McGraw-Hill Professional, 1221 Sixth Ave., 45th Floor, New York, NY 10020. Web: mcgraw-hill.com. 2010. 398 pages. $130.00

Safety Critical Systems Handbook: A Straightforward Guide to Functional Safety, IEC 61508 (2010 ed.) and Related Standards. By David J. Smith. Elsevier Inc., 30 Corporate Drive, 4th Floor, Burlington, MA 01803. Web: elsevier.com. 2010. 288 pages. $81.20. ■

Scott Jenkins

CHEMENTATOR

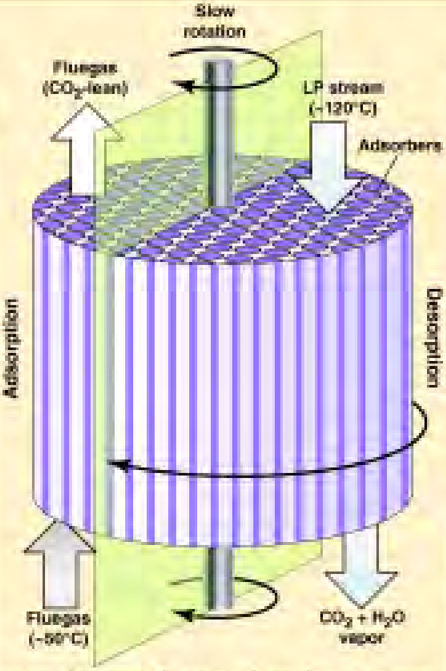
Edited by Gerald Ondrey

January 2011

This TSA process promises to slash costs for CO_2 separation

A post-combustion process capable of separating CO_2 from fluegas at one-third the cost of alternative separation processes has been developed by Inventys Thermal Technologies, Inc. (Burnaby, B.C., Canada; www.inventysinc.com). Tradenamed VeloxoTherm (VX), the patented process is now being tested together with a consortium of industrial partners — Mast Carbon International, BP, Suncor Energy Services and Doosan Babcock Energy — in a $1.9-million project funded by Sustainable Development Technology Canada (SDTC; Ottawa).

VX is an intensified temperature-swing adsorption (TSA) process that features structured, proprietary adsorbers (photo) instead of beaded adsorbents used in conventional packed-bed TSA processes. As a result, VX delivers enhanced heat and mass transfer at significantly lower pressure drop, says Darryl Wolanski, vice president of business development at Inventys. "The adsorption kinetics of the VX process is very fast — on the order of minutes to complete an entire adsorption-regeneration cycle, explains Wolanski. And because the regeneration temperature is lower than that required by conventional amine-based absorbants, energy penalties are also reduced — less than 1.5 GJ per metric ton (m.t.) of CO_2 versus approximately 4 GJ/m.t. to regenerate liquid solvents, he says.



In VeloxoTherm, the structured adsorbers are mounted inside a cylindrical vessel on a cassette that slowly rotates (diagram). The vessel is divided into two zones. Hot fluegas enters the first zone where CO_2 is adsorbed. As the cassette rotates, the loaded adsorbers enter the second zone where low-pressure (LP) steam is used to release the CO_2, which can then be separated by condensing the water vapor. Because the operations occur at low (near ambient) pressure, a simple sealing mechanism can be used to separate the two zones, says Wolanski.

The company has demonstrated the technology in a bench-top unit, which is capable of processing several hundred liters of gas per minute. Upon completion of the SDTC project in Fall 2012, Inventys will be deploying a 100 m.t./d VX process designed for process heaters in chemical plants and petroleum refineries. The company is targeting applications whereby the recovered CO_2 can be compressed for enhanced oil recovery or for CCS (carbon capture storage) projects.

Compressor offers improved efficiency with smaller footprint

A new rotary gas compressor technology designed by OsComp Systems (Cambridge, Mass.; www.oscomp-systems.com) incorporates advantages of reciprocating piston pumps into a hybrid rotor compressor. With a carefully optimized interior geometry, the new compressor can achieve near-isothermal compression with a large-volume liquid injection system for internal cooling. The compressor offers the sealing and efficiency of an API-618 standard piston compressor, says OsComp CEO Pedro Santos, but with the cooling effectiveness observed with a liquid-flooded, rotary-screw compressor.

"We were motivated to revolutionize technology in the area of natural gas compression," Santos says. He and his partners tinkered with the compressor design for several years, and tested many ideas before arriving at the final design, on which they have applied for three patents.

In addition to the optimized interior ge-

(Continues on p. 12)

Betaine production

A new process that produces natural betaine is being scaled up by Novasep Process (Pompey, France; www.novsasep.com) and Danisco (Copenhagen, Denmark; www.danisco.com). The plant will be the first to exploit a new extraction process that uses vinasse — a byproduct of sugar-beet-derived bioethanol. The process incorporates Danisco's proprietary NS2P chromatography technology with membrane and evaporation steps.

The plant will be built by De Smet Engineers and Contractors (Waterloo, Belgium), and Tereos (Lille, France) will supply the vinasse and operate the plant at its facility in Origny, France. Betaine is an animal feed ingredient, which Danisco will market as Betafin.

Ethylene tetramerization

Sasol (Johannesburg, South Africa; www.sasol.com) plans to build a 100,000-m.t./yr, combined 1-octene and 1-hexene production plant at its Lake Charles, La., site. The plant, scheduled to start up mid 2013, will be the first commercial ethylene tetramerization unit, and will utilize Sasol's proprietary technology for selectively converting ethylene into the alpha olefins.

(Continues on p. 12)

Note: For more information, circle the 3-digit number on p. 58, or use the website designation.

Streamlined terephthalic acid process lowers capital and operating costs

A simplified and streamlined new process for producing purified terephthalic acid (PTA), trademarked as Compress PTA and co-developed by The Dow Chemical Co. (Midland, Mich.; www.dow.com) and Davy Process Technology (DPT; London, U.K.; www.davyprotech.com), requires 15% lower capital spending, 20% lower utilities consumption and allows a 25% smaller processing space than conventiona processes.

While the process employs the same reaction chemistry as that found in conventional PTA plants, Dow and DPT have focused on technology improvements within the unit operations and a less equipment-intensive flowsheet to realize operating and cost benefits.

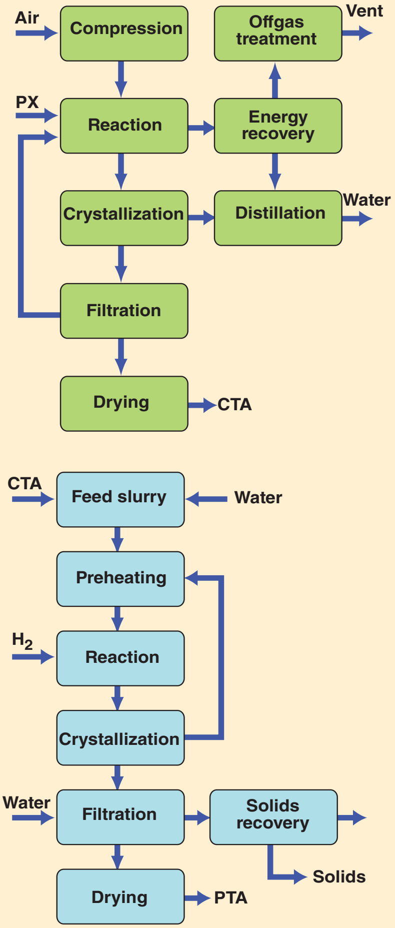
Conventional PTA production is complicated, and the technology can be difficult to operate and can suffer from reliability issues, explain Hugo Gonzalez, Dow global commercial manager for technology licensing and Julian Gray, DPT principal process engineer.

Now available for licensing, the Dow/DPT process requires 20% less utilities consumption, half as many pieces of rotating equipment, one-third fewer control valves and one-quarter fewer agitators. Less equipment means fewer constraints on plant layout, Gonzalez and Gray remark, which allows several areas of the plant to be integrated and improves water recycling and energy consumption.

In the first stage of the process (flowsheet), *p*-xylene (PX) is oxidized with air, using an acetic-acid based solvent and a cobalt-, manganese- and bromide-based catalyst to form crude terephthalic acid (CTA). The CTA then enters the purification stage, where an aqueous solution of the acid is subjected to a hydrogenation reaction to remove impurities. The PTA is recovered by crystallization, filtration and drying.

One key part of the process, used in both separation steps, is the use of pressure filtration, a technology that has demonstrated higher efficiency in filtering PTA crystals with less equipment. Compress PTA reduces overall energy consumption by using an improved binary distillation system and by additional heat integration in the purification plant.

PTA is the raw material for the production of polyethylene terephthalate (PET), a common thermoplastic polymer used to construct synthetic fibers, packaging, bottles, engineering resins and in other applications.



Oxalate-munching bacteria slash energy costs of alumina refining

A biological process for the destruction of sodium oxalate at Alcoa's Kwinana alumina refinery in Western Australia has proven to be an extremely robust technology. Alcoa's residue technical manager, David Cooling, says the plant has achieved an oxalate destruction rate of 40 metric tons per day (m.t./d), and the company plans to increase the destruction rate to 60 m.t./d.

The technology has been developed by scientists and engineers from Alcoa World Alumina's Technology Delivery Group (www.alcoa.com), the University of Western Australia (www.uwa.edu.au) and CSIRO (all Perth, Australia; www.csiro.au).

Naturally occurring oxalate sticks to bauxite and enters the alumina refining process. The oxalate must be removed because it has an adverse impact on alumina quality and refinery productivity. In some refineries, oxalate is removed by crystallization in a secondary process stream. The oxalate must then be disposed of properly. Alcoa used to burn the oxalate in a kiln, but this method generates carbon dioxide, volatile organic compounds (VOCs) and odors. It also requires expensive and energy-intensive emissions control equipment.

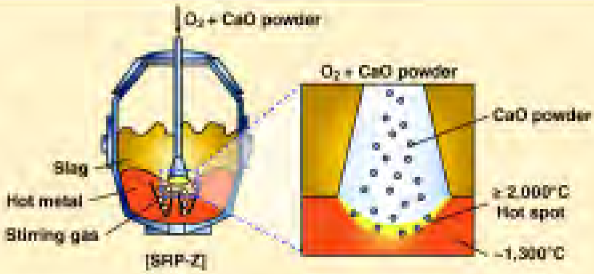
The new process, called "continuous biological oxalate destruction," is based on the scientists' discovery of naturally occurring bacteria that break down oxalate. Using DNA fingerprinting techniques, the scientists found a new genus of *Proteobacteria* and a new species of the genus *Halomonas* that are able to use the carbon in the oxalate to grow.

To maximize oxalate destruction, the process uses a series of tanks containing warm liquid and bacteria growing on strands of beads. O_2 and nutrients are added, and oxalate is introduced as a feed source, which the bacteria consumes. As a result, CO_2 emissions are reduced to less than half that of a kiln, and VOC emissions and odor are minimal. The researchers are now enhancing the removal efficiency by optimizing the conditions — pH, nutrient levels, temperature and oxygen — for growing the bacteria.

Alcoa says the Kwinana refinery is saving about $2 million/yr in energy costs compared with conventional technology. Cooling says rapid deployment of the process is now underway at a number of Alcoa's other refineries around the world.

A cleaner, more-efficient process for making high-grade steel

Phosphorous impurities in steel can lead to detrimental properties, such as reduced hardness and resistance to corrosion. Sumitomo Metal Industries, Ltd. (SMI; Tokyo and Osaka, Japan; www.sumitomometals.co.jp) has enhanced its SRP (simple refining process) for removing phosphorous from pig iron — a step necessary for making high-grade steels. The so-called SRP-Z process (diagram) involves blowing a dephosphorizing agent (calcined lime) as a powder in O_2 onto the surface of molten pig iron. Unlike the lumps of CaO used for fluxing in the SRP process, powdered CaO has a high surface area, which increases the reaction rate. As a result, the amount of calcined lime required and the time for dephosphorization are reduced by 15%, says the firm. In addition, the technology enables the use of so-called ladle slag that contains alumina. In conventional processes, Al_2O_3 causes problems due to foaming; with SRP-Z, the presence of Al_2O_3 actually enhances the efficiency because the top-blown powder breaks up the foam, says the company. As a result, the process enables the use of ladle slag that normally had to be recycled by other means.



SMI developed the O_2-injecting lance specifically for powder top blowing and has improved the operation to enable a near stoichiometric consumption of the calcined lime. This indirectly reduces CO_2 emissions generated by the production of calcined lime. In addition to dramatically improving the dephosphorization reaction efficiency, the SRP-Z process improves the quality of high-grade steel, enhances production efficiency, and lowers environmental load.

The SRP-Z process has been adopted for converters at Sumitomo Metals' Kashima Steel Works and Sumikin Iron & Steel Corp. in Wakayama, Japan. This process is also scheduled to be used at a new dephosphorization furnace due to begin operation this month at Sumitomo Metals (Kokura). Sumitomo Metals plans to adopt the technology at all steel works locations.

Direct ammonia synthesis at room temperature

Researchers at the University of Tokyo (Japan; park.itc.u-tokyo.ac.jp/nishiba/index.html) have developed a new catalyst that enables the direct synthesis of ammonia at ambient conditions. The breakthrough is a step toward an alternative to the energy-intensive, century-old Habar-Bosch process, which requires high temperatures (200–600°C) and high-pressure (200–400 atm) hydrogen from fossil-based resources.

Associate professor Yoshiaki Nishibashi and his research group have been developing a nitrogen fixation system using dinitrogen-bridged dimolybdenum complex bearing tridentate PNP (PNP = 2,6-bis(di-*tert*-butylphosphinomethyl)pyridine) pincer ligands as an effective catalyst (diagram). The catalyst was designed after a N_2-fixing enzyme and, despite its name, is easier to make than Mo-based, N_2-fixing catalysts developed by others, says Nishibashi. In the laboratory, the catalyst has been shown to produce small amounts of NH_3 after 20 h by reacting with N_2 at 1 atm pressure and room temperature. Nishibashi says the proof-of-concept is similar to or better than results achieved by other Mo-complexes, but that this new method is much simpler and uses a different mechanism, enabling the mild conditions. The researchers are now working to understand the reaction mechanism, and to further develop the process whereby water will be used as the proton source.

COMPRESSOR (*Continued from p. 9*)

ometry, the compressor also features cooling enhancements that allow improved fluid recovery, and design innovations in how the compressor is connected to the motor.

Santos comments that the hybrid rotor technology has achieved compression ratios of greater than 35 to 1, while keeping stage differential temperatures below 200°F. Also, he says the isentropic efficiency achieved by the compressor is around 87%, higher than that of existing process compressors (which is typically less than 80% under similar conditions). The hybrid rotor technology weighs less than one tenth of equivalent API piston compressors.

OsComp Systems has built a working prototype of the multiphase pump, and is talking with potential partners for field trials. In addition to natural gas, the compressor is also suitable for other applications in chemical processing where gas compression is needed.

(*Continued from p. 9*)

1-octene and 1-hexene are used as co-monomers in the manufacture of linear low density polyethylene, high density polypropylene and elastomers.

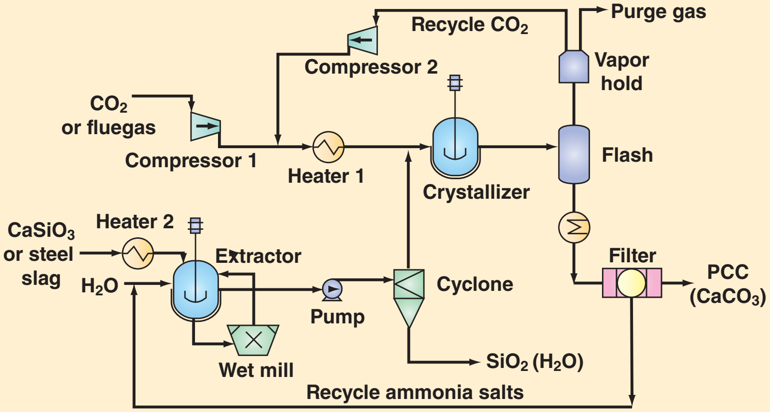
Pipe modeling

Last month at SPAR Europe (Amsterdam, the Netherlands; December 7–8, 2010), ClearEdge 3D, Inc. (Marshall, Va.; www.clearedge3d.com) launched EdgeWise Plant software, which incorporates a series of breakthrough algorithms that eliminate much of the manual tracing of pipes and other plant structures in a typical modeling workflow. The tool — used for modeling as-built pipe runs — is said to improve pipe-modeling pro-

(*Continues on p. 14*)


Uhde –
Engineering with ideas
ThyssenKrupp

Slag heaps: a new source of precipitated calcium carbonate



Two waste products — carbon dioxide and industrial wastes — are combined to obtain marketable mineral products in a process being developed by startup company CarbonX Inc. (Santa Barbara, Calif.; www.carbonxinc.com). The process produces precipitated calcium carbonate (PCC) and silica from such wastes as steel industry slag and flyash from lignite-fired power plants, cement kilns and municipal waste incinerators. PCC is a valuable product whose uses include paper coatings, paint and inks, says Michael Wyrsta, chief technology officer.

Wyrsta notes that steel slag, for example, contains 40–50 wt.% calcium as calcium silicate ($CaSiO_3$) in a metals complex. In CarbonX's process (flowsheet), an aqueous slurry of ground slag is fed to an extractor, where it is contacted with a solution of ammonium chloride salts. The salts leach calcium from the slag, then the leachate is separated from the rest of the slag by a cyclone and entrained in a stream of CO_2 or fluegas. CO_2 and Ca combine to form a precipitate of $CaCO_3$ in a reaction that takes place in a few seconds at less than 80°C and 45 psig. The $CaCO_3$ is crystallized and separated from the regenerated ammonium salt solution, which is recycled to the process. Meanwhile, the slag (mostly SiO_2, plus Fe) separated by the cyclone is recovered for use as a filler for roads or cement.

CarbonX has tested the process in a 10-gal unit, using slag supplied by a major U.S.-based steel company. Next, the company plans to build a pilot plant. Wyrsta estimates that a commercial plant would have a payback of 1.5–3 yr. He adds that the process does not necessarily require an onsite source of CO_2 for treating old slag heaps, so long as there is an industrial plant within an economical distance.

Fast results from this water toxin biosensor

A new system for detecting chemical or biological contaminants in water is made possible by analyzing the swimming pathways of one-celled protozoa that are introduced into the water sample. Alterations of the protozoa's swimming mechanics, relative to a clean water control, indicate the presence of toxins. The Swimming Behavioral Spectrophotometer (SBS) digitally records the movements of microscopic protozoa in water samples, then analyzes the motion with custom software that quickly evaluates 50 features of their swimming paths in three dimensions.

The system, invented by Woods Hole Oceanographic Institute (Woods Hole, Mass.; www.whoi.org) biologist Scott Gallager, allows virtually instantaneous feedback for only \$1–2 per test. Existing water tests require 24–72 h for results and cost \$50–250 per test. SBS has been licensed by Petrel Biosensors Inc. (Woods Hole, Mass.; www.petrelbiosensors.com), which is developing the system for commercial applications, such as monitoring industrial wastewater discharge, evaluating drinking water quality, and testing water sources associated with hydraulic fracturing (fracking) in the oil-and-gas industry.

A new pilot plant for CO_2 removal

Last month, Outotec Oyj (Espoo, Finland; www.outotec.com) commissioned a new CO_2-removal pilot plant at its R&D center in Frankfurt, Germany. The unit compliments the company's circulating, fluidized-bed pilot plant, which is used for cleaning process gas from direct reduction of iron ore as well as from coal and biomass gasification. The new pilot plant applies BASF SE's (Ludwigshafen, Germany; www.basf.com) licensed aMDEA (advanced methyldiethanolamine) technology for acid gas removal (primarily CO_2 and H_2S from metallurgical process gases). It also features integrated gas-cleaning steps allowing for the treatment of gases rich in dust and tars. ■

(*Continued from p. 12*)

ductivity by more than 50%.

EdgeWise Plant uses proprietary algorithms to find a pipe's centerline, determine its radius and automatically trace the precise geometry of the pipe run. The extracted pipes can be exported into any CAD (computer aided design) package for final modeling. The software can also identify and extract walls, ground surfaces and other critical structures within a facility. The commercial release is slated for January 15.

Cooling fans

Lubrication Systems Co. (Houston), a business of Colfax Corp. (Richmond, Va.; www.colfaxcorp.com), has launched a MistLock bearing and lubrication cartridge for air-cooled heat exchangers (ACHEs). Cooling fans of ACHEs have typically used grease to lubricate the bearings on the drive shaft that drives the ACHEs, but thermal degradation of such grease can lead to costly downtime and maintenance.

To overcomes the disadvantages of grease, MistLock continuously supplies a clean, cool oil mist that evenly coats the surface. Positive pressure in the cartridge prevents entry of external contaminants that could otherwise cause abrasive failure. Tests show that MistLock bearing life is nearly 10 yr compared to an average life of 2.5 yr for a grease bearing, says the manufacturer. ❑

FERMENTATION PROCESS DEVELOPMENT

Today's development depends on synthetic biology and efficient screening

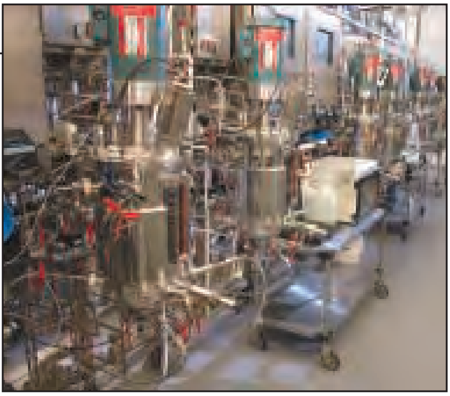


FIGURE 1. Pfenex evaluates top-performing strains in scaled-down bioreactors to optimize process parameters

The range of synthetic biology tools available for manipulating microbial metabolic pathways has expanded significantly in the past decade, opening new routes to chemical products. But the development challenges associated with strain development, as well as scaling up effective fermentation processes remain. Companies manufacturing biofuels, bio-based chemical intermediates, natural products and therapeutic proteins, are all capitalizing on powerful synthetic biology techniques to rationally engineer microbes, as well as seeking ways to use high-throughput screening systems that will expedite the development of robust and efficient cellular-production platforms and the effectiveness of process development and scaleup.

"We have seen a targeted emphasis in recent years on utilizing a wider range of synthetic biology tools to generate high-value products," says Mattheos Koffas, a chemical engineering professor at Rensselaer Polytechnic Institute (RPI; Troy, N.Y.; www.rpi.edu). "Many tools available to increase the efficiency with which microbial cells generate products simply did not exist 10 or 20 years ago."

But while today's understanding of biological systems is deeper and techniques are more sophisticated, the area is highly complicated, and predicting results is difficult. To address the challenges presented by the complexity of living systems, engineers are employing a number of strategies to generate high-quality data in an efficient manner to move their processes forward.

"It's important to have a clear picture of the metabolic activity of production strains and a good overall knowledge of your bug's physiology," says RPI's Koffas, because "such knowledge will elucidate bottlenecks that will have to be worked out for engineering an efficient and commercially viable process."

Small-scale screening

Optimizing a fermentation process involves orchestration of a wide range of variables, including introducing genetic modifications and identifying effective microbe strains, working out process conditions such as raw material substrate, aeration, agitation, and others. Whether a company is pursuing a therapeutic protein, intermediate chemical or biofuel, microbial strain development and fermentation process development require engineers to carry out a large number of experiments in a manageable format that reasonably mimics the process conditions of larger-scale operations. Simultaneously, engineers are seeking informative online process data to guide process-development decisions.

"An unfulfilled need in fermentation process development is small-scale, high-throughput experimental systems based on bioreactors, rather than culture flasks, where the conditions better resemble the production environment," says Neal Connors, founder of Phoenix Bioconsulting LLC, (Fanwood, N.J.; www.phoenixbioconsulting.com) and president-elect of the Society for Industrial Microbiology (SIM; Fairfax, Va.; www.simhq.org).

"There's definitely a need for small-scale laboratory capacity for process development," agrees industry consultant Bruce Zamost (Upstream BioSolutions LLC; Seattle, Wash.), and although much progress has been made in control and monitoring equipment for fermentation R&D, the ability to conduct a detailed analysis of fermentations at early stages is still lacking, he explains.

To meet the need, techniques and equipment associated with smaller-scale, high-throughput screening to aid microbial strain selection and process development have become important, and an active R&D area.

Fast evaluation in biopharma

In the biopharmaceuticals space, companies such as Applikon Biotechnology B.V. (Schiedam, the Netherlands; www.applikon-bio.com) and m2p-labs GmbH (Aachen, Germany; www.m2p-labs.com) are developing ways to help customers quickly generate useful data to support early process development.

"Industry is looking for improved screening methods and fermentation technologies," says m2p-labs managing director Frank Kensy. The company's BioLector technology is a tool for performing quantitative microfermentations under engineered reaction conditions. With this equipment, specific yields and rates can be directly deduced from online biomass and product concentrations. "The BioLector technology is designed to help people move to larger scales more quickly," Kensy explains.

m2p-labs recently launched a new, highly automated version of the technology known as RoboLector. The instrument (Figure 2) combines the abil-

FIGURE 2. RoboLector, from m2p-labs, combines the ability to perform parallel fermentations with pipetting robotics

ity to perform between 48 and 1,920 parallel fermentation experiments with the liquids-handling capability of pipetting robots. The company has also developed Flowerplates, which are intended to achieve the same mass transfer and mixing properties as larger-scale systems, while at the same time allowing online monitoring of relevant fermentation parameters, such as biomass concentration, pH and dissolved oxygen.

Kensy says his company is also working on specialized covers that seal the reactor chambers and, for the first time, allow high-throughput anaerobic fermentations with online monitoring.

Another company using high-throughput screening as a way to efficiently develop high-performance production strains is Pfenex Inc. (San Diego, Calif.; www.pfenex.com), a Dow Chemical Co. spinoff. Pfenex's platform technology is designed exclusively for rapidly identifying combinations of gene plasmids and host strains that express soluble and active target protein in high titers. Pfenex Expression Technology enables high-throughput, parallel analysis of up to 1,000 unique expression strains followed by a scalable, high-density fermentation process.

Pfenex bases its platform on *Pseudomonas fluorescens*, a bacterial host that offers significant advantages in both small- and large-scale protein expression. One is that the organism is an obligate aerobe, says Patrick Lucy, Pfenex vice-president of business development, which means it always grows aerobically and won't self-limit under certain conditions, as *Escherichia coli* can. Also, *P. fluorescens* can thrive on growth media that doesn't include animal components and doesn't require antibiotics, which reduces the regulatory risk.

"It's very difficult to predict beforehand which gene plasmid will work effectively with which phenotypically unique host strain," Lucy explains. So the Pfenex technology platform houses an extensive toolbox of both expression elements and unique *P. fluorescens* host strains that can be combined rapidly to generate 1,000 or more different strain/plasmid combinations. The combinations are tested in parallel using a high-throughput, robotic screening approach that enables Pfenex scientists to quickly identify a small subset of strains based on expression yield, protein quality and activity within five weeks.

The initial screening step for strain selection is followed by a later fermentation evaluation process, in which the best-performing strains are tested utilizing a design-of-experiments (DoE) approach in scaled-down, miniaturized bioreactors (Figure 1) to find the optimized operating parameters for the selected production strain.

"The Pfenex platform enables partners to avoid the opportunity cost associated with what can be a labor- and cost-intensive process," Lucy explains.

Synthetic biology to process

Synthetic biology and high-throughput screening also figure prominently in the process development and commercialization of a host of bio-chemicals and biofuels companies. A few examples are Amyris Inc. (Emeryville, Calif.; www.amyris.com), LS9 Inc. (San Francisco, Calif.; www.ls9.com), Genomatica Inc. (San Diego, Calif.; www.genomatica.com) and Mascoma Corp. (Lebanon, N.H.; www.mascoma.com).

Amyris is using synthetic biology tools to develop a metabolic pathway in yeast for manufacturing isoprenoid compounds, a class with applications in specialty chemicals and fuels. Its platform features proprietary high-throughput methods to create and test thousands of yeast strains per day to identify the most suitable ones. Amyris recently announced a joint venture with the Brazilian firm Cosan SA (Sao Paulo, Brazil; www.cosan.com.br) to use Amyris' genetically modified yeast to produce the isoprenoid molecule farnesene from sugarcane. The fermentation-produced farnesene is then finished chemically to create renewably sourced, high-end base oils as building blocks for a wide range of machinery lubricants.

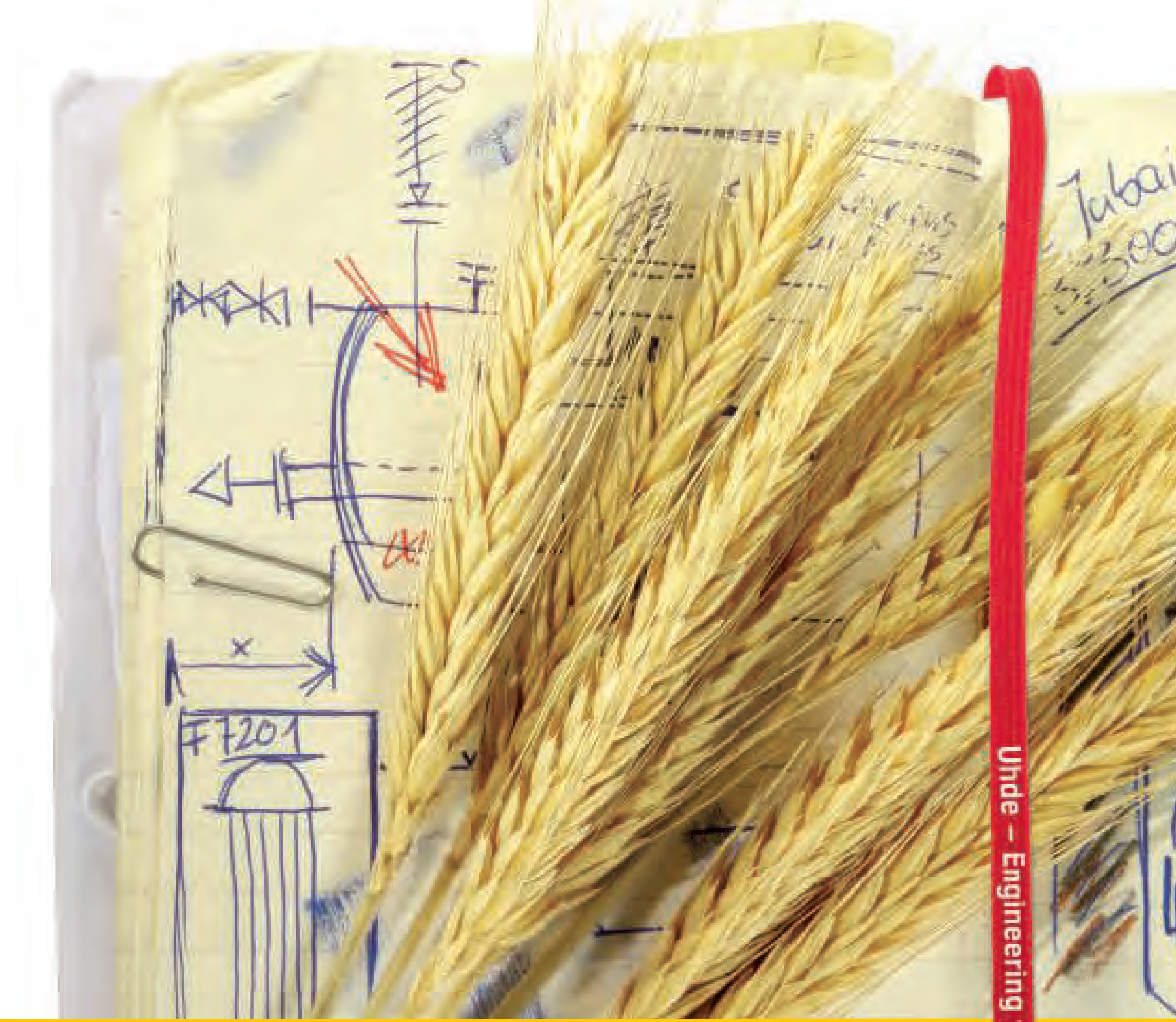
Focused squarely on a cheaper process for ethanol derived from cellulosic biomass, Mascoma is engineering microbes with genes from a variety of species that encode enzymes capable of breaking down biomass. "We're looking for the lowest-cost path for fermentation, which requires minimizing fermenter complexity," says Mascoma vice-president for external R&D David Hogsett. For example, in the biofuels arena, tight control of parameters such as pH, temperature and feedstock quality can become costly, potentially pushing the production cost of the biofuel out of the economically viable range. "We need our organisms to tolerate whatever conditions they encounter, rather than expending resources to control those problems to protect the organisms," he says.

Mascoma's consolidated bioprocessing approach has the enzymatic digestion of biomass and the fermentation of resulting sugars occurring together to lower costs. The company is placing considerable effort into resolving a key technical challenge — finding ways to allow microbes to access insoluble material, or liquefying biomass so that it is more accessible to the microbes.

The first commercial product pursued by Genomatica is a chemical building block, biologically sourced 1,4-butanediol (BDO) that the company now produces at 3,000-L scales. The BDO process was developed with a technology platform that stresses directed evolution of microbes and uses scaled-down microreactors to approximate fermentation reaction conditions. "We also have a computational modeling system that helps us understand the analytical data" that is obtained from the small-scale fermentation work, says Mark Burk, chief technology officer at Genomatica. The company is setting up partnerships now to establish a 10,000–20,000-L demonstration facility in 2011.

For more on synthetic biology and a discussion of other trends in fermentation-derived chemicals, see the expanded online version of this article at www.che.com. ■

Scott Jenkins



Uhde – Engineering with ideas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TIME CRUNCH

The new SO_2 standard will create engineering challenges for processors. Experts weigh in on how various technologies can help reduce the burden

Last June, the U.S. Environmental Protection Agency (EPA; Washington, D.C.) strengthened the primary National Ambient Air Quality Standard for sulfur dioxide by establishing a new one-hour standard at a level of 75 parts per billion (ppb). Previous primary standards permitted 140 ppb evaluated over 24 h. While the revised standard is expected to yield health benefits valued between $13 and 33 billion, pollution abatement experts anticipate a variety of challenges for chemical processors who will need to comply with this tighter standard once it makes its way into enforceable state regulations (see box, p. 20).

"A significant reduction of the time period for SO_2 emissions averaging could affect the type of technology a customer may need to use, as well as its capital and operating costs and the scrubber system's footprint in the plant," says Rich Staehle, vice president of business development and technology with Marsulex Environmental Technologies (Lebanon, Pa.).

For example, in the past, when a facility had a wet or semi-dry scrubber system, it was common to have three 50% or four 33% scrubber vessels so that a spare was available to quickly go into operation as needed. But due to the better equipment and technologies available and improved operating procedures in later years, the trend toward this vessel redundancy disappeared. "Many newer facilities may currently have only one scrubber vessel on any particular source," says Staehle. "But if we narrow the time averaging window we may, in some cases, ultimately have to revert back to redundancies to the extent that we had 30 years ago."

Maintenance might be another issue. "The configuration and type of equipment installed will determine how much of a challenge a facility might have in consistently achieving an acceptable one-hour average," Staehle notes. For example, technologies that employ reagent atomizers, which require cleaning, replacement and other periodic maintenance, may have some difficulty in meeting the narrower averaging periods. This type of online atomizer work has commonly been accommodated by operational procedures if the averaging period is sufficient. One of these methods, for example, is to over-scrub, (meaning more SO_2 is removed than normal) both before and after the atomizer maintenance, so that the overall SO_2 emission levels would remain at an acceptable value over the time averaging period.

"When you have a moderate time-

SOLVAir Solutions

FIGURE 1. Experts anticipate the new EPA standards regarding SO_2 will likely increase capital and engineering costs

REVISING THE MONITORING NETWORK

The EPA is revising the ambient air monitoring requirements for SO_2. States will need to make adjustments to the existing monitoring network in order to ensure that monitors meeting the network design regulations for the new one-hour SO_2 standard are sited and operational by January 1, 2013.

In the final rule, EPA is requiring fewer monitors than proposed because the agency plans to use a hybrid approach, combining air quality modeling and monitoring to determine compliance with the new SO_2 health standard.

For a short-term, one-hour SO_2 standard, EPA has deemed it more technically appropriate, efficient and effective to use modeling as the principal means of assessing compliance for medium to larger sources and to rely more on monitoring for groups of smaller sources and sources not as conducive to modeling.

EPA is setting specific minimum requirements that inform states on where they are required to place SO_2 monitors. Approximately 163 SO_2 monitoring sites nationwide are required by the new rule. The final monitoring regulations require monitors to be place in Core Based Statistical Areas (CBSAs) based on a population weighted emissions index for the area. The final rule requires the following:

- Three monitors in CBSAs with index values of 1 million or more
- Two monitors in CBSAs with index values less than 1 million but greater than 100,000
- One monitor in CBSAs with index values greater than 5,000

All newly sited SO_2 monitors must be in operation by January 1, 2013. EPA is also making changes to data reporting requirements for SO_2. State and local agencies are required to report two data values for every hour of monitoring conducted, including:

- The one-hour average SO_2 concentration
- The maximum five-minute block average SO_2 concentration for each hour

EPA authorities can require additional monitoring in certain circumstances, such as in areas with SO_2 sources that are not conducive to modeling, areas with multiple SO_2 sources with overlapping plumes or in areas with susceptible and vulnerable populations. ❑

SOLVAir Solutions

FIGURE 2. Coal-fired power plants, as well as chemical or other industrial facilities that produce SO_2 will be impacted by EPA's one-hour/75 ppb SO_2 standard

EPA'S ANTICIPATED APPROACH TO THE NEW SO_2 STANDARD

In addition to revising the SO_2 primary standard, the agency is providing guidance on its plan for implementing the new one-hour SO_2 standard.

EPA plans to use refined dispersion modeling to determine if areas with sources that have the potential to cause or contribute to a violation of the new SO_2 standard can comply with the standard. Dispersion modeling simulates how air pollutants spread throughout the atmosphere and is used to estimate the concentration of air pollutants from sources such as industrial plants. The resulting designations should be complete by June 2012.

The agency also anticipates initially designating areas based on 2008 to 2010 monitoring data, or refined dispersion modeling results if provided by the state. Areas that violate the standard would be designated as "non-attainment." Areas that have both monitoring data and appropriate, refined modeling results showing no violations would be designated as "attainment."

States with areas designated non-attainment in 2012 would need to submit state implementation plans to EPA by early 2014 outlining actions that will be taken to meet the standards by 2017. For all other areas, states will need to submit EPA "maintenance" or infrastructure state implementation plans by June 2013. The state plans should do the following:

- Demonstrate through refined air quality modeling that all sources contributing to monitored and modeled violations of the new standard, or that have the potential to cause or contribute to a violation, will be sufficiently controlled to ensure timely attainment and maintenance of the new SO_2 standard
- Account for SO_2 reductions that would result from compliance with national and regional regulations, including emissions controls for electric utilities and industrial boilers
- Include as necessary, enforceable emissions limitations, timetables for compliance and appropriate testing/reporting to assure compliance

EPA says these areas should plan to demonstrate attainment and maintenance of the standard no later than August 2017.

For more detailed information, a downloadable version of the final rule is available at www.epa.gov/air/sulfurdioxide. ❑

average period to meet, consistent compliance is very achievable because an atomizer can generally be pulled in and out of service within about an hour," says Staehle. "However, making compliance at the significantly narrower window may be difficult for many existing systems that were designed for the rules at the time of their original installation, and many such systems may require major upgrading or retrofits, or both, to meet one hour averaging. For systems yet to be installed, narrow time average windows will almost certainly compel people to re-evaluate the type of equipment they may be contemplating for SO_2 removal," he says.

Equipment selection

While all types of SO_2 abatement technology are capable of effectively removing SO_2 to acceptable levels, there are definite pros and cons associated with each method, according to the experts.

Dry sorbent injection technologies offer relatively low capital costs and quick installation that can be done off-line, but the cost of sorbents is high, says Mike Wood, business manager with Solvay Chemicals' SOLVAir Solutions (Houston). "The cost of the sorbents are higher than the operating costs of other technologies, but the capital investment is orders of magnitudes of difference, so there's a trade off," he says. There are, however, benefits that might outweigh the higher operating cost. For instance, Wood says dry injection achieves higher levels of removal, and there is a lot of flexibility. When higher levels of SO_2 are still acceptable, Solvay's Trona, a mined, natural mineral, can be used; but when lower levels of SO_2 are required, the systems can accommodate sodium bicarbonate, which is a manufactured product with a higher purity and a greater reactivity.

Another option would be to take the sorbent and grind or mill it to a very fine product. Smaller particles provide better distribution and faster reaction of product, so when you need more removal, the product can be milled down further or process improvements can be made by installing a mechanical milling operation right on the process.

"Performance can always be enhanced with dry injection technologies," says Wood. "When you're trying to get down to low, low levels, it's no longer chemistry, it's physics. You can always enhance this type of process instead of ripping it out," he says. "This provides the flexibility to do good enough now and better later, which is an attractive option for many processors."

Likewise, Tri-Mer Corp. (Owosso, Mich.) offers a dry technology that is suitable for high temperatures. The UltraTemp filtration technology uses a caustic calcium- or sodium-based sorbent that is impinged on a rigid ceramic filter that collects particulate and neutralizes SO_2 simultaneously, according to John Pardell, president of Tri-Mer. SO_2 removal is typically 90% or better with removal efficiencies as high as 97% for this system, which must have an operating temperature within 350–1,000°F for SO_2 removal.

Tri-Mer also offers wet technologies like a packed bed scrubber that scrubs SO_2 with sodium hydroxide. The device has a recirculation vessel built into the bottom as well as a packed section over which a caustic solution is circulated to neutralize the SO_2. Just as operation of a dry system can be tweaked to enhance performance, it is possible to make changes and adjustments to a wet system. "You can increase the concentration of the caustic, increase the depth of the packing in the media, increase the recirculation rate and modify the device to increase the performance beyond the original design," says Pardell.

Met Pro Environmental Air Solutions (Owosso, Mich.), a group that combines the resources and technology of the company's three operating units: Duall, Flex Kleen and Systems, also suggests wet scrubber technologies as the optimal solution to the one hour rule. "When levels need to be brought down lower, a second packed scrubber can be added in a series, or modifica-

Met-Pro

FIGURE 2. This installation includes a dust collector for ash and particulate matter, quench to cool combustion gases, a vertical packed tower for SO_2 removal and a stack and fan for ventilation. It represents a total solution for SO_2 and pollution abatement

SO_2 ABATEMENT SERVICE PROVIDERS

DuPont	www.dupont.com
Haldor Topsøe	www.topsoe.com
Marsulex Environmental Technologies	www.marsulex.com
Met Pro Environmental Air Solutions	www.met-pro.com
Pollution Systems	www.pollutionsystems.com
Solvay Chemical SOLVAir Solutions	www.solvair.us
Tri-Mer Corp.	ww.tri-mer.com

tions can be made to the operating parameters by increasing liquid rates, adding additional packing to the tower or changing to a more efficient packing design in the tower to enhance the performance as needed," says Steve George, industrial sales manager.

However, Marsulex's Staehle suggests that an alternative semi-dry, multi-pollutant technology — a circulating fluid bed scrubber that has been widely used in China and Europe — might be a good way to meet stricter SO_2 guidelines for many sources. A version of this, marketed by MET as the CFB-FGD (circulating fluid-bed, fluegas-desulfurization) technology, employs multi-stage humidification, which injects humidification water at multiple levels, separate from the reagent, into the absorber vessel. This scrubbing approach does not make use of reagent atomizers, so it eliminates the issue of trying to maintain one-hour emission-averaging levels, says Staehle.

Another technological alternative might be DuPont's Lbbsorb Regenerative SO_2 Scrubbing System, which removes SO_2 from a gas flow for emission control, while minimizing the costs of wet scrubbing. It also nearly eliminates scrubber-water discharge normally associated with wet scrubbing systems.

With this process, the scrubbing reagent is regenerated for reuse, while at the same time recovering a high-concentration stream of SO_2 (90+%) as a byproduct for use in other processes. The recovered SO_2 can be used as an additional process feed for existing sulfur recovery units, as well as sulfuric acid plants. With further processing, it can be sold as commercial-grade liquid SO_2, sulfuric acid or elemental sulfur.

"With all the technologies available, processors have the ability to really do their homework and find the solution that will work best in their facility while meeting the tighter requirements," notes Staehle. "There is still time to figure out what you're doing with your plant and time to figure out how to do it in a way that works best for you." ■

Joy LePree

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Hansen Solubility Parameters (HSP)

In recent years, a number of factors have further emphasized the importance of solvent selection in the chemical process industries (CPI). These include the increasing regulatory scrutiny leveled on industrial solvents, and an effort by CPI companies to reduce the environmental, health and safety (EHS) impact of their solvent use. In addition, specialized, high-performance solvents are available for some applications [*1*].

Key tools for helping determine which solvents are suitable for particular applications have been predicated on the concept that thermodynamic affinity between solvent and solute can help predict solution behavior.

Conceptually, when assessing whether or not a molecule will dissolve in a solvent, engineers consider the difference between the energy cost of disrupting the intermolecular attractions of the solvent and solute molecules, compared to the energy gained through solute-solvent interactions. As Hansen and Abbott explain [*2*], to dissolve something, “you are essentially making a hole in the solvent, and that takes energy.” If the solute-solvent interactions are greater than the sum of the energy losses from the two substances, then solute will dissolve.

THE FOUNDATION OF HSP

Hildebrand [*3*] developed a thermodynamics-based, one-dimensional solubility parameter in 1936 as a tool for eliminating certain solvents from consideration in process development. The Hildebrand solubility parameter (represented by lower-case delta) for a pure liquid substance is defined as the square root of the cohesive energy density (the amount of energy needed to remove a volume of molecules from their neighbors to an infinite distance). The same energy needs to be overcome for molecules to separate from each other and be surrounded by solvent. Equation (1) represents the Hildebrand solubility parameter.

$$\delta = \left[\frac{\Delta H_v - RT}{V_m}\right]^{\frac{1}{2}} \qquad \textbf{(1)}$$

Where ΔH_v is the heat of vaporization, V_m is the molar volume and RT is the ideal gas term. The units are $(\text{MPa})^{1/2}$.

The Hildebrand method formed the foundation for a later multidimensional solubility parameter system that has been refined over time by Charles Hansen [*2*]. The resulting Hansen Solubility Parameters (HSP), have become a useful tool in selecting solvents for chemical processes.

THE HANSEN MODEL

HSP are a set of three values that describe the thermodynamics of dissolving one substance into another. Solvents with similar Hansen solubilities generally are miscible in most proportions, and Hansen values that are different mean limited solubility. As Hansen puts it, “The HSP describe whether things prefer to be near each other or not.”

HSP attempt to characterize the energies and assign values to them as a way to predict solution behavior. Hansen’s model essentially splits the Hildebrand solubility parameter into three components:

- Dispersion forces (Van der Waals interactions) are the attractions experienced by atoms placed at close distances
- Polar (dipole) interactions are electronic forces due to the positive-negative attraction of molecular dipoles
- Hydrogen bonding is a particular type of polar interaction, but can also be considered a form of electron exchange, according to Hansen and Abbott [*1*]

The three components of the HSP are respresented by Equation (2).

$$\delta^2 = \delta_d^2 + \delta_p^2 + \delta_h^2 \qquad \textbf{(2)}$$

The three terms (in units of pressure) comprising the HSP are calculated for each substance through empirical solubility experiments of various types, depending on the material being measured. The HSP values are known for a large number of solutes. Also, molecular dynamics methods exist that can estimate HSP without the need for experimental data [*4*].

Once determined, the values are then treated as coordinate points in a three-dimensional space, called Hansen space, (see Figure 1), with axes corresponding to each of the three HSP components. The nearer to each other that two molecules are in this three-dimensional space, the more likely they are to dissolve into each other. To calculate the distance between the HSP of two substances (R_a), the following equation is used:

$$(R_a)^2 = 4(\delta_{d2} - \delta_{d1})^2 + (\delta_{p2} - \delta_{p1})^2 + (\delta_{h2} - \delta_{h1})^2 \qquad \textbf{(3)}$$

Equation (3) was developed by plotting experimental data, and represents solubility data as a sphere, where solvents inside the sphere are effective at dissolving a given substance, and those outside are progressively less so.

Polymer solubilities

For solubilities of polymers, Hansen introduced a concept called the interaction radius (R_0). Solubility data determined experimentally on a given polymer for a range of solvents allow engineers to estimate a “volume of solubility” in the three-dimensional Hansen space. For most polymers, this volume of solubility is spherical in shape if the scale of the dispersion axis relative to the other axes is doubled. Solvents whose data values lie within the sphere will generally dissolve the polymer, while those lying outside the sphere will not.

Once an R_0 value is established, the ratio of R_a to R_0 can be determined. This ratio has been called the relative energy distance (RED) number.

- Systems with RED values less than one are sufficiently alike and will dissolve
- RED values equal to one mean the system will partially dissolve
- RED greater than one means the system will not dissolve

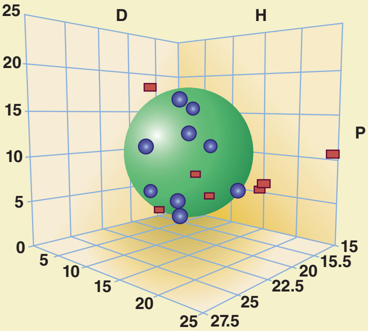

FIGURE 1. HSP values for dispersion (*D*), polar (*P*) and hydrogen bonding (*H*) factors are plotted within a 3D space

Applications of HSP

HSP are useful in selecting process solvents, additives in formulations, for the blending of polymers, and for the control of kinetics and monomer-sequence distributions in co-polymers. HSP have been used as the basis for solvent selection models and computerized methods, but they can also be used in manual calculations. The following represent some of the applications in which HSP have been used:

- Predicting effective solvents for polymers
- Studying dispersion of pigments
- Determining solubility properties of carbon nanotubes
- Finding solvent blends that are cheaper, perform better or that have smaller negative environmental impact

Limitations of HSP

HSP are often best used for screening purposes, with experimental data then used to validate (or not) the predictions. Limitations of the HSP that are discussed by Hansen include the following:

- The parameters can be difficult to measure
- Molecular size plays a significant role in whether a substance dissolves within a given time period
- The HSP are an approximation
- Parameters vary with temperature

Ongoing work by Hansen, discussed in [2] has begun to address HSP limitations. ■

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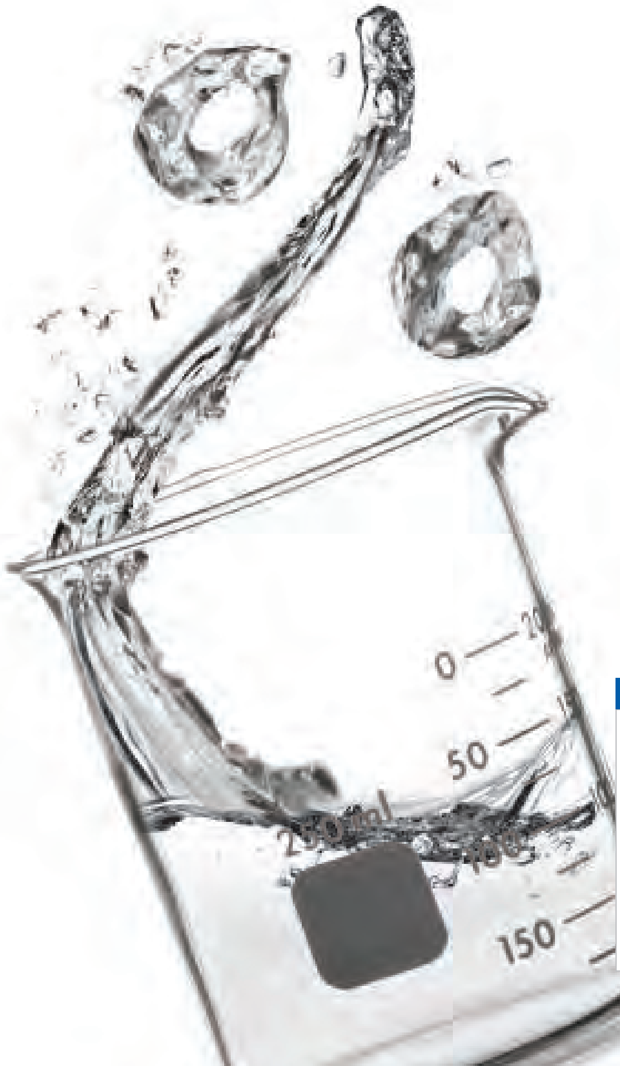

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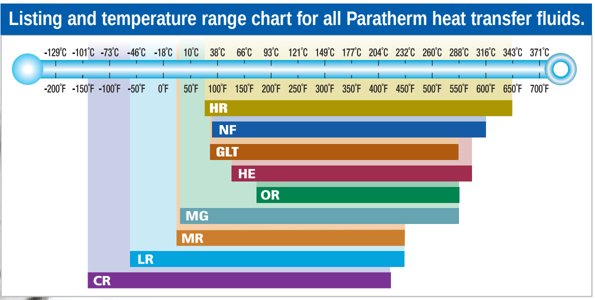

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Earthquake fractionation

Some columns sway with the wind; some columns sway with the waves. In fact, hundreds of columns now reside offshore, on platforms and on barges. Most dry and sweeten gases. Some distill. The trays and packing distributors of such columns are regularly, appreciably out of level. Sloshing occurs. The packings are regularly, appreciably off vertical. Some of what we know about the design of such columns originated with work that was performed at Heriot-Watt University. Other universities and companies performed levelness and swaying research of their own.

In 1985, following the lead of Dr. Mike Lockett, of Praxair (and a winner of this magazine's Personal Achievement Award), the company I worked for decided to use the University of Buffalo (UB) Earthquake Table to simulate a swaying distillation column. A 4-ft dia. Plexiglas test column was built and was placed on a skid along with a pump to circulate water and a blower to drive air through three test trays. The pump pulled water from the column's sump and delivered it to the top of the column via a 12-ft tall 3-in. dia. pipe.

A customer was considering building a methanol plant on a barge in the Persian Gulf. That plant would have required distillation columns. The customer asked to witness the testing of specifically designed trays subjected to swaying/rocking motion.

In 1989, the UB Table was rented for one week. On day one, a forklift placed the skid-mounted column (with the pump and blower) onto the table. Eight 500-W spotlights were aimed at the column as were two film cameras. Surrounding the table were computers that were used by UB civil engineering students who studied building destructions. On days two and three, two technicians and I collected data from the column as the table was swayed from side to side. A technician sat in a control room and adjusted tilt angle and swaying speed per requests.

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

On day four, three client engineers joined the team. First, the pump and blower were turned on, and water and air were circulated through the column. Then, a technician flipped the switches to initiate the column's swaying. Very unfortunately, the technician flipped the wrong switches. The pistons beneath the concrete table went immediately into earthquake simulation mode. The concrete table slammed the test column up-down-up-down-up-down about three times, until the weak link in the test column was clearly identified — the connection between the water pump and the water line. The bad news: The connection broke. The worse news: The pump kept pumping. A water spout 20-ft tall sprayed the entire laboratory. When the water hit the spotlights, they exploded. Technicians and engineers ran everywhere, none of whom knew exactly what had just transpired. Luckily, there was only enough water in the sump of the test column to allow the geyser to spout for about 2 min. Unfortunately, that was sufficient to cover every computer in water. Broken light bulb pieces were everywhere. Every engineer and technician was drenched. One client engineer looked like he had been swimming underwater in his three-piece suit. And that was my most embarrassing career moment.

Thereafter, several global companies initiated and completed research work on off-shore columns. Now, such columns are designed regularly — and easily — by the people who have experience with them. ■

Mike Resetarits
resetarits@fri.org

WHO'S WHO

Yeghnazar

Hubbard

Allard

Dalton

Way

Clifford Johnson, formerly of NACE International, is now president of the **Pipeline Research Council International** (Falls Church, Va.).

Andrew Yeghnazar is named president of **Blacoh Fluid Control** (Riverside, Calif.).

John Harrower is named chief operating officer of the offshore division for **Universal Pegasus International** (Houston), which provides engineering, project and construction management in the energy industry.

James Hubbard becomes vice-president of commercial development for toll chemical manufacturer **InChem Corp.** (Rock Hill, S.C.). He will also serve as vice-president of technology for InChem's new subsidiary, Toll Solutions LLC (Duncan, S.C.)

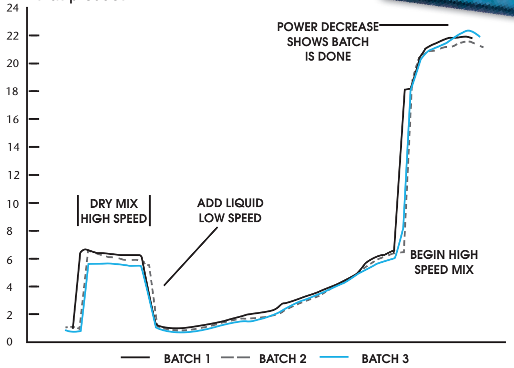
Plastic-tubing manufacturer **New Age Industries** (Southhampton, Pa.) appoints *Michael Allard* global distribution sales manager.

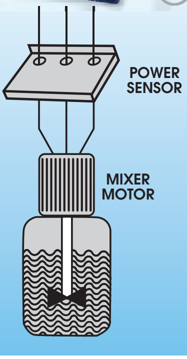
Jarkko Sairanen has been appointed executive vice-president of engineering company **Pöyry PLC** (Vantaa, Finland) and president of the company's management consulting group.

John Dalton, Sr., executive vice-president of engineering-and-construction company **Mustang** (Houston) is inducted into the National Academy of Construction.

Andrew Way has been appointed vice-president of services for **GE Oil & Gas** (Florence, Italy). ■

Suzanne Shelley





Reboiler Circuits For Trayed Columns

These vetted recommendations are key to efficient and troublefree separations

Design Practices Committee
Fractionation Research Inc.

The reboiler generally supplies most of the energy required to effect component separation. If too much heat is supplied, the tower may flood; conversely, if too little heat is available, separation performance may decrease via poor reflux ratio (pinching), excessive weeping or poor tray action. Proper design of reboiling systems involves coordinating aspects both outside and inside the tower. This article focuses on both of these aspects to ensure proper operation of the overall reboiler system. Important literature discussing these topics is also cited.

The objectives of reboilers

The design of tower reboiler circuits and bottom sections can be broken into several parts: fluid flow systems, exchanger types, liquid sumps and associated baffling, and drawoff and return arrangements.

Although these are not generally studied as much as the mass transfer equipment above, tower bottom sections should be considered key tower internals. A number of fractionator problems can be attributed to either improper bottom-section design or poor reboiler-circuit layout; taken together, they are thought to be the second-most common cause of tower problems [*1*]. To better illustrate this, consider the objectives that a properly designed tower bottom and reboiler system must accomplish:

- Provide adequate hydraulics for the reboiler circuit
- Separate and distribute the incoming vapor and liquid phases properly
- Absorb fluid momentum and prevent mechanical damage to surrounding internals
- Prevent entrainment of bottom-tray overflow liquid or bottom-pool liquid by reboiler return fluids
- Provide adequate liquid inventory for startup and step changes in reboiler duty
- Provide sufficient liquid-residence and degassing time for downstream equipment
- Provide adequate net-positive-suction head (NPSH) for any bottoms pumps
- Maximize mass transfer capabilities of the reboiler (nearly one theoretical stage can be obtained via use of a staging baffle)
- Maximize available temperature driving force in the reboiler
- Accommodate transients in the concentration of heavy components in the feed
- Allow removal of fouling material from the tower bottom
- Allow safe column shutdown in the event of a process upset
- Minimize overall column height

Consequently, many factors come into play in designing a successful reboiler and tower bottom arrangement. The available literature does not address the subject in depth, and, especially with regard to multipass trayed towers. This paper is intended to clarify the design process and extend coverage to multipass tray towers.

Preliminary design work

The design process begins by definition of the design basis and selection of the reboiler type that best suits the particular application. "Reboiler type" refers to exchanger and circulation mode, such as vertical thermosyphon, kettle, internal, horizontal forced circulation, and so on. The designers proceed through the following steps:

1. Run tower simulation(s)
2. Determine reboiler type and method of process liquid circulation, using criteria from the next section (Selection of reboiler type) and Tables 1 and 2
3. Select tower bottom configuration (such as once-through, constant head recirculating, and so on) using criteria from the Tower bottom arrangements section and Table 3
4. Choose limiting case(s) for duty and bottoms product rate to be used in detailed design

After this, the designer would be ready to begin developing details of the tower bottom and reboiler circuit.

Selection of reboiler type

As noted above, selecting a reboiler type means determining the method of fluid circulation (thermosyphon, forced or none) and selecting an exchanger type (vertical, horizontal, kettle or internal). These decisions need to be made before any tower bottom internals can be designed, since internals vary substantially for different reboiler types. To aid in the selection process, considerations are discussed below starting with general rules of thumb and progressing to more specific issues. Simple conceptual examples of common reboiler types are shown in Figure 1, and a comparative summary of reboiler types is given in Table 1.

Thermosyphon reboilers are the most widely used type in distillation

TABLE 1. COMPARISON OF REBOILER TYPES (ADAPTED FROM REF. *3*)

	Vertical Thermosyphon (Figure 1A)	**Horizontal Thermosyphon (Figure 1B)**	**Kettle (Figures 1E and 1F)**	**Forced Circulation (Figure 1C)**	**Internal Reboiler**
Boiling side	Typically tube	Typically shell	Shell	Typically tube	Shell
Heat transfer rate	High	Moderately high	Low to moderate	High	Low to moderate
Plot space requirement	Small	Large	Large	Vertical: small Horizontal: large	Minimal to small
Process piping	Small quantity and simple to design	Standard quantity, two-phase return	Standard quantity, single phase only	Extra piping with two-phase and controls	None
Pump required	No	No	No	Yes	No
Extra column skirt height requirement (if bottoms product is not pumped)	Yes – to accommodate vertical exchanger	Yes – to drive thermosyphon flow (but less than vertical thermosyphon)	Small	Yes – to provide reboiler circulation pump NPSH	No
ΔT requirement	High	Moderate	Low	High	Moderate to high
Residence time in heated zone	Low	Low	High	Low	High
Process side fouling tendency	Low	Moderate	High	Very low	Moderate
Performance with high viscosity liquids	Poor	Poor (but better than vertical thermosyphon)	Poor	Good	Poor
Ability to handle large surface area	Modest: approximately four medium shells maximum	Good, if multiple large shells used	Very good: large areas handled in a single shell	Good, if multiple large shells used	Poor, unless tower bottom swaged out for larger bundles
Maintenance and cleaning	Can be difficult, depending on congestion	Relatively easy	Relatively easy	If vertical, can be difficult depending on congestion (easy if horizontal)	Next to impossible while on-stream, but easy during shutdowns
Susceptibility to instability	High, but moderate for constant head	High, but moderate for constant head	Low	Low	Low
Design data	Readily available	Some available	Readily available	Readily available	Readily available
Capital cost	Low	Moderate	High	Moderate	Very low, unless tower swaged out for larger bundles
Operating cost, excluding heating medium	None	None	None	Pumping cost, and occasional pump maintenance cost	None
Safety issues	Normal	Normal	Normal; kettle exchanger can hold liquid inventory to help in emergency shutdown	Pump seal leakage is important for flammables or toxics	Flange leakage is a major concern especially for flammables or toxics

TABLE 2. REBOILER EXCHANGER COMPARISON: HORIZONTAL VERSUS VERTICAL

	Advantages	**Disadvantages**
Vertical	Minimal plot space requirement	Exchanger area is limited
	Return piping typically short to very short	Greater skirt height requirement
	Relatively small capital cost	Requires relatively high ΔT driving force
	Fouling process side	Fouling heating medium
	High pressure process side	High pressure heating medium
Horizontal	Good for large heat-exchanger area requirement	Occupies moderate-to-large plot space
	Requires moderate ΔT driving force	Higher capital cost than vertical
	Better access for maintenance	Return piping design must avoid slug flow
	Often requires less tower or skirt height	

systems and are usually considered first. A "thermosyphon" reboiler utilizes the density difference between the liquid in the tower bottom and the mixed-phase fluid in the reboiler and return line to drive reboiler process flow. Thermosyphon reboilers are gravity-flow systems. To summarize their advantages, they are relatively compact and economical, require no pumps, and offer relatively high heat-transfer rates (for small exchanger size) with relatively low residence times in the heated zone.

Of course, thermosyphon systems are not applicable in all circumstances. They are not recommended for the following conditions:

- High liquid viscosity (viscous-liquids friction loss dampens fluid circulation)
- Fouling systems (pumped systems achieve higher velocities that help mitigate fouling)
- Adequate driving head cannot be attained economically (instead, consider a kettle system)
- Large operating load variations or turndown ratios are required (instead, consider a pumped system)
- High reliability is a key factor (kettle or forced circulation systems are preferred for this)

Sometimes thermosyphon reboilers can be troublesome with vacuum systems because even a small liquid head has a large impact on the boiling point, leading to large and head-dependent preheat zones in the exchanger [2]. This is especially true for services where the liquid boiling range or circulation driving-head varies routinely. However, if the driving head is kept steady, a reliable vaporization curve is available and care is taken in modeling the hydraulics, thermosyphon reboilers can be successfully used in vacuum service. Most existing vacuum thermosyphon systems tend to use vertical heat exchangers.

If one of the above thermosyphon limitations applies, a kettle or forced circulation system is generally preferred. For towers in clean services, an internal reboiler may sometimes be considered.

If a thermosyphon system is selected, the next decisions are to determine the flow and exchanger type.

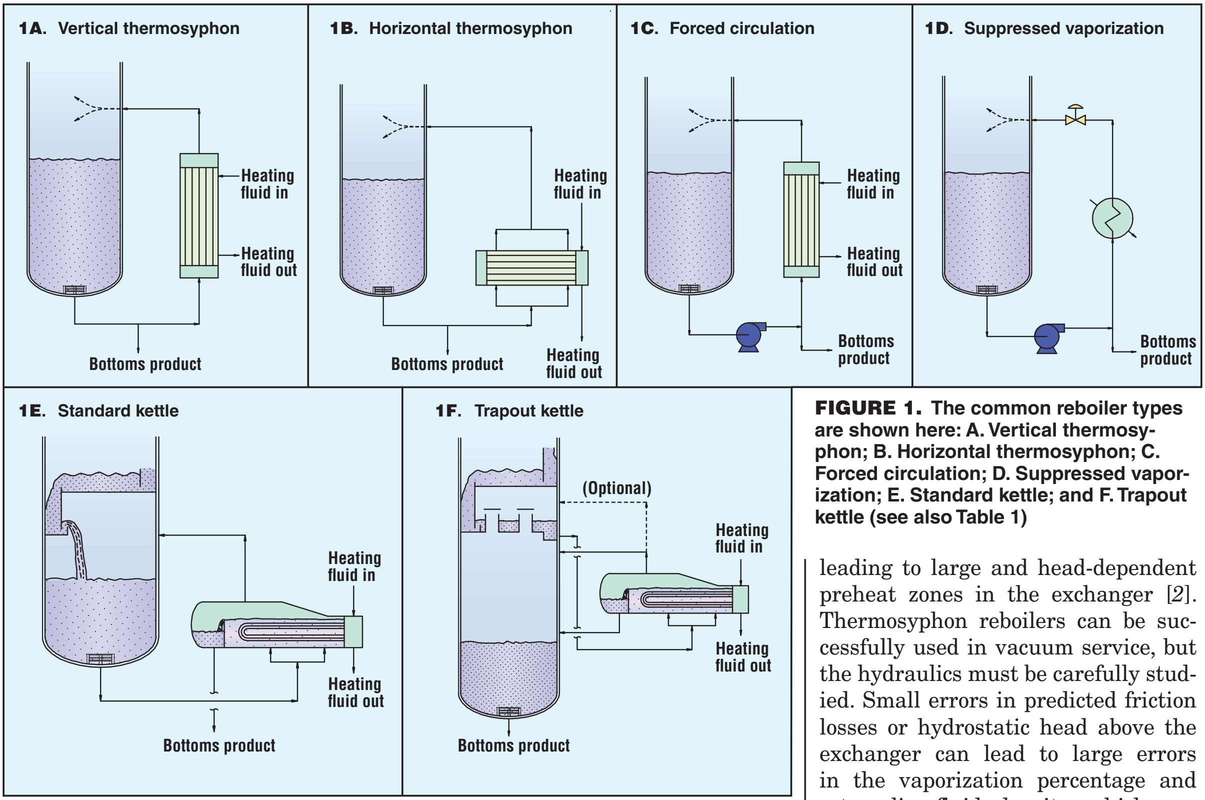


FIGURE 1. The common reboiler types are shown here: A. Vertical thermosyphon; B. Horizontal thermosyphon; C. Forced circulation; D. Suppressed vaporization; E. Standard kettle; and F. Trapout kettle (see also Table 1)

The choices for flow type are once-through and recirculating; the choices for exchanger type are vertical and horizontal.

Once-through flow is useful for strippers and other low-boilup services where the mass flowrate of vapor in the reboiler return is less than about 40% of the bottoms-product mass flowrate [*4*]. ***Recirculating*** flow is required in services where reflux rates are high compared to product rates, such as splitters. More information about once-through versus recirculating reboilers is given in the Tower bottom arrangements section below.

Selection of a ***vertical*** or ***horizontal*** exchanger can be made based on each option's advantages and disadvantages as given in Table 2. The published literature gives conflicting accounts about vertical versus horizontal exchangers [*5–7*], leading to some confusion about selection practices. Sloley [*8*] provides a detailed discussion of factors affecting this decision, and explains that vertical exchangers predominate in chemical applications, while horizontal exchangers are prevalent in petroleum-refining applications.

Selection by process issues

Fouling service (process side). Fouling service, as used herein, refers to a fouling tendency of process fluid in the tower bottom rather than the heating medium. The preferred bottoms arrangement for fouling service is forced circulation. Forced circulation systems (using a pump) can achieve much larger reboiler-circuit velocities than thermosyphon systems, which aids in keeping exchanger tubes clean. The forced circulation reboiler can be vertical or horizontal, as long as the fouling fluid is on the tube side (this is more typical of vertical exchangers). If a forced system is not suitable, the next best alternative is generally a vertical thermosyphon system. Kettle and internal reboilers should be avoided due to long residence times in the heated zone and high vaporization rates.

Vacuum systems. These can be a problem for thermosyphon systems because even a small liquid head has a large impact on the boiling point, leading to large and head-dependent preheat zones in the exchanger [*2*]. Thermosyphon reboilers can be successfully used in vacuum service, but the hydraulics must be carefully studied. Small errors in predicted friction losses or hydrostatic head above the exchanger can lead to large errors in the vaporization percentage and return-line-fluid density, which can adversely affect their hydraulics and heat transfer.

Forced circulation systems are easier to design for vacuum services. One particular forced circulation setup for vacuum service is the suppressed-vaporization system (Figure 1D), where the flow control valve is placed downstream from the reboiler [*9*]. No vaporization occurs in the exchanger itself (sensible heat transfer only), so the heated liquid flashes as it traverses the downstream valve. Another way to suppress vaporization in forced circulation systems is to use an orifice at the column return nozzle. Note that these valves or orifices can experience erosion as the liquid flashes across them under vacuum conditions, producing high exit velocities. For this reason, some practitioners recommend the use of control valves having contoured plugs, and some completely avoid suppressed vaporization systems. Also, the high fluid velocities produced by a valve or orifice at the tower inlet can cause fluid distribution problems or mechanical damage inside the tower unless specific provisions are made to handle these.

TABLE 3. COMPARISON OF TOWER BOTTOM ARRANGEMENTS

Type	Primary advantages	Primary disadvantages
Once-through trapout	Full theoretical stage. No bottoms recontact with hot reboiler tubes	Boilup ratio limited to 40% of the bottoms rate. Gives highest reboiler outlet temperature. Incompatible with forced circulation. Leakage from trapout or trapout tray can restrict heat transfer, even make system inoperable
Once-through collector	Full theoretical stage. No bottoms recontact with hot reboiler tubes. Compatible with forced circulation	Boilup ratio limited to 40% of the boilup rate (thermosyphon reboilers) Produces high reboiler outlet temperature. Chimney tray: fewer active tray(s). Partition baffle: reduction of bottoms product residence time
Constant head	Thermosyphon flow stability during upsets. Does not limit boilup ratios	Partial theoretical stage only. Constant head compartment(s) must be leak tight. Increased likelihood of reboiler fouling. Baffle unnecessary and can be troublesome at high boilup ratios [*17*]. Complicated baffles can breed hydraulic bottlenecks [*18*]
Standard kettle	Simple bottom configuration with vapor only return. Full theoretical stage	High cost. Long residence time of bottoms material in heated zone. Precise exchanger elevation required
Trapout kettle	More product residence time available than standard kettle	Product spends more time at maximum temperature than standard kettle. May require more height than standard kettle
Unbaffled	Simple, low cost. Good for high boilup ratios	For recirculating systems, gives lowest separation efficiency. For thermosyphon systems, operating perturbations can affect reboiler flow, prolonging upsets
Internal pool	Low cost	On-stream cleaning nearly impossible. Bottom liquid level difficult to assess. Long residence time of bottoms material in heated zone
Internal bath	Low cost. Nearly full theoretical stage	On-stream cleaning nearly impossible. Boilup ratios limited, similar to once through. Long residence time of bottoms material in heated zone

With *clean* process fluids, the designer of a vacuum system may wish to consider a falling film reboiler (which is outside the scope of this paper).

Safety. Forced circulation systems require pumps and often pump seals. The hazards of a seal leak should be considered, especially for flammable or toxic fluids. Thermosyphon systems avoid the pump and the seal leakage problems. Internal reboilers have large flange connections that may have substantial moment arms applied by the heavy tube bundles, if they are not supported properly. The flanges are prone to leak and have been known to cause fires.

Ease of maintenance. During shutdowns, access space (rather than reboiler type) is generally the prime factor for ease of maintenance, but the reboiler TEMA (Tubular Exchanger Manufacturers Assn.) type is also important. The designer can specify exchanger inlet and outlet heads that allow the tubes to be inspected and cleaned without requiring removal of external piping. The reboiler can also be designed for easy tube bundle removal to facilitate inspection and mechanical cleaning or hydroblasting [*10*]. Selection of the correct shell type is also very important to ensure proper fluid circulation, minimize fouling potential and maximize on-stream time. In services where online cleaning is necessary, internal reboilers should be avoided. In fouling services, a spare exchanger is often provided, but this is not practical with internal reboilers.

If the process side is dirtier than the heating medium, a design that allocates process fluid to the tube side is often preferred. Conversely, if the heating medium is dirtier, it is preferred to allocate it to the tube side.

Typically, vertical exchangers have the process fluid on the tubeside, and horizontal exchangers have the process fluid on the shell side — although these are not absolute rules. For kettle and internal reboilers, however, process fluid is always on the shell side.

Reliability. From a process standpoint, well-designed kettle reboilers are considered the most reliable, although vertical thermosyphon systems are also considered to be quite good. Forced circulation systems can be robust, but this depends on the reliability of the pump. Horizontal thermosyphon systems and internal reboilers are considered average in terms of reliability.

Stability when perturbed. When subjected to tower swings, the most stable systems are forced circulation systems with flow control upstream of the exchanger, followed by kettle systems. Vertical and horizontal thermosyphon systems are more sensitive to operating perturbations; however, use of a constant head baffle in the tower bottom design may greatly improve their stability.

Approach temperature. For a given heating medium, once-through systems give the largest cool-end "approach temperature," or thermal driving force, in the reboiler exchanger. This is because the process side feed to the reboiler is comprised solely of liquid from the bottom tray, which is the coolest possible reboiler feed. Conversely, recirculating systems with high tower reflux ratios provide the smallest driving force because a large percentage of the reboiler feed is material from the reboiler effluent.

As for exchanger types, vertical exchangers require the greatest driving forces, while kettle types require the least. Forced circulation systems allow for the greatest driving forces without concern for process side fouling because they can be designed with high process-fluid velocities.

Required heat transfer area. Vertical reboilers are limited in tube length (see below) and are also limited to about four shells per tower [*11*], so the heat exchange areas they can provide are limited. Horizontal and kettle reboilers are greatly preferred when large area is required. Internal reboilers can also limit available heat-transfer area unless the tower is increased in height or swaged out to accommodate more or larger bundles.

Capital cost. Internal reboilers are typically the least expensive because they eliminate external process piping and reboiler exchanger shell(s), although in some cases this advantage is negated by bottom section height or diameter increases to accommodate larger heat-transfer bundles. Vertical thermosyphon systems generally rank second lowest in cost because the return piping is usually very short. Horizontal thermosyphon and forced circulation systems are considered moderately expensive. Kettle systems are typically the most capital intensive due to exchanger shell size and foundation requirements.

Operating cost. Other than the cost of the heating utility, thermosyphon systems have no operating costs due to the use of gravity acting on density differences to drive reboiler fluid flow. Forced circulation systems are more expensive to operate due to pumping and associated pump-maintenance costs.

Plot space requirement. Internal

reboilers occupy very little (if any) plot space, followed by vertical exchangers, which generally require small plot spaces. Horizontal exchangers and kettle systems require relatively large plot spaces, especially if removable bundles are desired. Proper exchanger-head selection can help minimize plot space requirements.

It is beyond the scope of this article to cover actual design of the reboiler circuit piping and exchanger(s). For thermosyphon and kettle systems, the flow through the reboiler must be calculated from a pressure balance. It is essential that accurate assessments be made of fluid densities, extent of vaporization and friction losses so that the correct flow driving force and resistances are used in the pressure balance. An article by Kern [*12*] describes the pressure balance particularly well and gives criteria for piping design. A comprehensive review of design correlations for vertical, horizontal and kettle exchangers is given by Fair [*13*]. A detailed description of kettle force balances from field data is given by Kister and Chaves [*14*]. Additional information about horizontal and vertical reboiler systems is contained in articles by Collins [*15*] and Orrell [*16*].

Tower bottom arrangements

This section discusses the relative merits and weaknesses of various tower-bottom arrangements that feed the reboiler and provide residence time. The descriptions here pertain to internal features, such as baffles or drawoff configurations, which comprise the tower bottom design. A summary of this information is given in Table 3.

Flow classifications. Bottom arrangements are classified into once-through and circulating. In **once-through** systems, liquid from the bottom tray traverses the reboiler only once. The liquid portion of the reboiler effluent is collected as net product and is kept separate from bottom tray liquid. **Recirculating** systems allow a portion of the reboiler effluent liquid to remix into the reboiler feed, thus permitting some of the liquid to traverse the reboiler two or more times. There are two main differences in these flow modes: once-through systems achieve a full stage of mass transfer in the reboiler, but their boilup ratios are limited by the maximum vaporization rate in the reboiler. Conversely, recirculating systems provide only a partial stage of mass transfer in the reboiler, but allow unlimited boilup ratios.

Because liquid leaving the bottom tray is the coolest stream possible for reboiler feed, once-through arrangements also give the greatest cold-end approach temperature in the reboiler exchanger. When their outlet temperatures are not excessive, they are also good for thermally degradable or fouling materials, where it is desirable to avoid repeated contact with hot reboiler tubes.

Unbaffled tower bottoms are the most common type of tower bottom arrangement. Note that there are several different reboiler types that lack baffle(s) in the tower bottom:

1. Once-through trapouts (sump liquid is reboiler return material, unmixed with bottom tray liquid)
2. Kettle systems (sump may hold liquid for residence time, but pre and post reboiler liquids do not mix)
3. Recirculating systems (bottom tray overflow mixes with reboiler return liquid)

Further descriptions of the first two cases can be found in the respective sections below. The third item, unbaffled recirculating systems, is the primary subject of this subsection.

Unbaffled recirculating systems are simple and inexpensive, which are the main reasons they are so widely employed. They are compatible with both thermosyphon and forced circulation reboilers. Figures 1A through 1D show simplified examples of unbaffled recirculating systems.

Advantages: Simple design requires no baffle inspection or maintenance. Reboiler and product draws may be combined in a single draw nozzle. Like all recirculating systems, it allows unlimited boilup ratios in the tower.

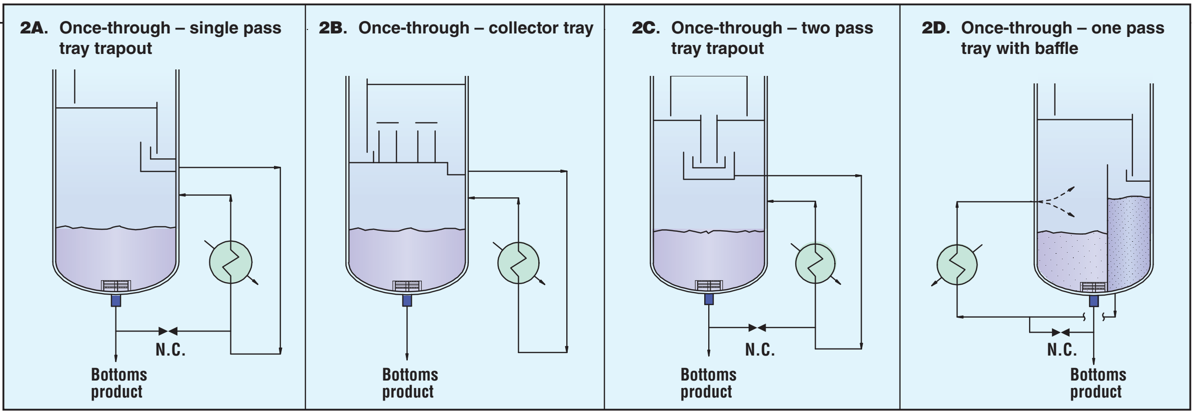
Weaknesses: It forfeits a fraction of a mass transfer stage; the reboiler simply becomes an enthalpy addition point. In thermosyphon applications, swings in the tower bottom liquid level can affect the reboiler circulation rate and duty, sometimes prolonging tower upsets. These swings can be at least partially countered by more-responsive heating fluid controls. These duty and control considerations apply more to exchangers with bare or low-fin tubes; exchangers with nucleate-boiling enhanced tubes provide much-more stable heat-transfer rates as circulation varies.

Once-through trapout arrangements involve a total draw via either a downcomer trapout or a collector tray, per Figures 2A and 2C, to capture all of the liquid leaving the bottom tray and feed it directly to the reboiler. The reboiler return is directed to an unbaffled tower bottom, and its liquid drawn as bottoms product. None of the bottoms liquid is recycled back to the reboiler, hence the name once-through. Trapout arrangements are generally limited to simple, single-draw configurations; multi-draw configurations, such as dual draws from two or four pass trays, are better handled with chimney trays (see below). Trapouts are used mainly with thermosyphon flow systems because they provide insufficient residence time for a pump.

Advantages: They can achieve one full theoretical stage of separation, if the trapout draw does not leak. The high elevation of the trapout draw generally provides good driving force for thermosyphon flow.

Limitations: With a thermosyphon system, reboil vapor is limited to about 40 wt.% of the bottoms product rate, due to the normal limitation of 30 wt.% maximum vaporization in thermosyphon exchangers [*19*]. This makes once-through thermosyphon systems appropriate only for low-boilup systems such as strippers. Although use of forced flow could increase the boilup rate, trapout draw systems suffer from a lack of liquid inventory to prevent pump cavitation. Thus a once-through *collector* system (see below) would be preferred for forced flow. Finally, in cases where the desired vapor-boilup rate *exceeds* the bottoms product rate, a recirculating reboiler should be used instead.

Weaknesses: The trapout draw box and bottom tray must be carefully designed and constructed to avoid leakage. Even then, leakage may occur during turndown and startup. A recent malfunction survey [*1*] found that leakage issues render


2A. Once-through – single pass tray trapout

2B. Once-through – collector tray

2C. Once-through – two pass tray trapout

2D. Once-through – one pass tray with baffle

FIGURE 2. Once-through arrangements are shown here: A. Single pass tray trapout; B. Collector tray; C. Two pass tray trapout; and D. One pass tray with baffle (N.C. = normally closed)

once-through trapout thermosyphons one of the most troublesome reboiler types. As the trapout affords little degassing time, rundown lines from once-through thermosyphons must be sized for self-venting flow [*20*]. Thermosyphon flow is not compatible with high viscosity liquids.

Once-through collector systems remove the limitation of low liquid inventory inherent in once-through trapout systems (see above). Well-designed collectors provide enough degassing time to overcome rundown line bottlenecks when the lines are slightly under sized from the recommended self-venting flow. The collector smoothes out variations in flow to the reboiler caused by perturbations in tower operation. Once-through collector arrangements are compatible with both thermosyphon and forced flow systems. In forced flow applications, additional residence time is needed for liquid level control. As with once-through trapout systems, reboil vapor is limited to about 40% of the bottoms rate for thermosyphon driven flow and equal to the bottoms rate for pump driven flow. For vapor boilup ratios greater than these, a recirculating reboiler should be used.

There are two variations of the once-through collector system:

- Chimney tray collector (Figure 2B)
- Partitioned bottom (Figure 2D)

Both of these options have advantages and weaknesses. Chimney tray arrangements can provide plenty of residence time, but they take up height, so fewer active trays can be installed in a fixed tower height. Partitioned bottom arrangements can increase reboiler feed inventory without reducing tray counts as long as sufficient bottoms residence time is available on the product side of the baffle. But they provide less liquid-flow driving head than trapout or chimney tray arrangements, and care must be exercised to ensure the baffle is leak tight and mechanically strong.

Preferential baffle arrangements are recirculating systems that utilize a baffle in the tower bottom to segregate bottom-tray overflow liquid from reboiler return liquid. An opening in the baffle allows some reboiler return liquid to flow into and mix with bottom tray liquid. Thus the reboiler draw *preferentially* contains bottom tray liquid, but also contains recirculated liquid to make up the additional reboiler flow demand. The liquid level on each side of the baffle is equal, except for a small differential from liquid flowing through the hole. Preferential baffles are also known in the literature as **baffles with a large hole** or **baffles with underflow**. They may be used with thermosyphon or forced circulation systems.

Figures 4A and 4B show two configurations for single pass and multipass trayed towers. For multipass trays, extra spacing should be provided between the bottom tray and seal pans to accommodate liquid backup caused by the short overflow notches on the seal pan weirs. Note that some companies do not believe the added complexity and expense of preferential baffles are justified by their performance benefits, and omit these baffles entirely.

Advantages: The internal baffle does not need to be liquid tight. It gives more separation than an unbaffled arrangement, but less than a full mass transfer stage. Like all recirculating systems, it allows unlimited reflux ratios in the tower.

Limitations: Preferential baffle systems do not develop a full equilibrium stage for the reboiler. As the tower reflux ratio increases, the ratio of recirculated material to bottom tray liquid in the reboiler feed also increases, and the usefulness of the reboiler as a separation stage steadily drops. When the ratio of tower bottoms product to reboiler draw rate falls below 20% (for example, splitting close-boiling components), a preferential baffle is considered no longer useful, and it should be omitted to provide an unbaffled bottom arrangement. An additional limitation for thermosyphon driven systems is that they cannot handle high viscosity liquids.

Weaknesses: The weaknesses of preferential baffle systems are similar to those for unbaffled towers. For a thermosyphon, a change in the bottoms liquid level will affect the reboiler circulation rate, and thus the reboiler duty. Some preferential thermosyphon systems have been known to work well only at one particular liquid level. It can be seen that all of these issues are related to duty control, and preferential baffle arrangements may therefore require responsive control schemes on the heating medium. As mentioned previously for unbaffled tower arrangements, use of nucleate-boiling enhanced reboiler tubes can mitigate these control issues.

Constant head arrangements are recirculating systems that maintain a constant-depth liquid pool above the reboiler draw. The most common configuration has a partition baffle, which separates the tower bottom into product- and reboiler-draw compartments (Figures 3A and 3B). Many other design arrangements are also available. Liquid from the bottom tray is directed into the reboiler draw side, as is liquid from the reboiler return. Then, return liquid in excess of the reboiler draw requirement spills over a weir to the product side, where the level can be varied to provide rate control to downstream equipment. Constant head partition baffles are also referred to in the literature as **baffles with overflow**. Other constant-head configurations include chimney tray and collector box configurations, where an inventory of liquid is kept inside the tower above the bottom liquid pool, using a tray or box with an overspill weir. These alternative arrangements generally provide less liquid holdup than the partition baffle, although they may be less expensive to build.

The tower bottom should be designed to make the bottom tray liquid pass through the reboiler at least once before proceeding to the product compartment. Constant head arrangements are used only with thermosyphon circulating systems. Extra height should be provided between the bottom tray and the seal pans in certain multipass versions to accommodate liquid backup caused by short overflow notches on the seal pan weirs.

Advantages: Changes in product rate or level do not affect the reboiler circulation rate and duty, thus uncoupling the tower from minor downstream events. Like all recirculating systems, unlimited reflux ratios are allowed in the tower.

Limitations: Baffle, tray or box leakage must be less than bottoms product rate, becoming more important as the tower reflux ratio increases. Thermosyphon circulation is not compatible with high viscosity liquids.

Weaknesses: Constant head systems generally require more internal pieces and increase complexity than other bottom arrangements. They also often require more tower height than other options. Because the bottom tray and reboiler return liquids are both directed to the reboiler feed compartment(s), constant head systems can collect fouling products or nonvolatile components in the reboiler loop. The reboiler feed piping should have means to drain these materials at low points.

Constant head systems are troublesome and should be avoided in high reflux ratio systems such as C3 splitters. In these systems the baffle overflow becomes a tiny fraction of the total liquid rate, and the overflow baffle becomes unsuitable to provide a steady flow. One troublesome case was reported [*17*].

Sometimes the baffle arrangement gets complicated, especially with multipass trays. Complicated baffle designs breed hydraulic bottlenecks. The simpler the baffle geometry, the less likely it is to generate such bottleneck. One case study of a baffle design causing a hydraulic bottleneck was described [*18*].

Kettle arrangements appear deceptively simple from a process standpoint. Liquid from the bottom tray of the tower is drawn and directed to a kettle reboiler. The kettle is an exchanger that has a tube bundle immersed in a liquid bath, with substantial vapor disengaging space above the bundle. Vapor and liquid are separated in the reboiler's disengaging space, so the return line carries essentially vapor. Kettle arrangements are once-through systems; reboiler effluent liquid does neither recirculate nor backmix with bottom tray liquid.

Kettle reboilers are typically designed with an overflow weir, which creates a separate product compartment within the exchanger shell. Kettle designs with overflow weirs must have removable tube bundles (U-tube bundles or TEMA "S" or "T" type return heads). Some alternative kettle designs do not have overflow weirs; in this case the liquid bath is maintained via level control. Fixed tubesheets (non-removable tube bundles) may be used in this type of exchanger.

There are three types of kettle arrangements. The standard arrangement is most prevalent (Figure 1E). It collects bottom tray liquid in the tower bottom and feeds a kettle exchanger having an internal weir. No level control is needed on the tower bottom because the liquid level in the tower is governed by the weir elevation in the kettle exchanger. Level control is required on the bottoms product compartment of the exchanger.

The trapout kettle arrangement utilizes a trapout draw from the bottom tray, or a chimney collector tray, to feed a kettle exchanger with an internal weir (Figure 1F). Product overflowing the kettle weir drains back to the tower bottom where it is collected for residence time purposes. In this case, level control is placed on the tower bottom rather than the kettle product compartment. The trapout type typically requires more tower height in the bottom section because liquid must flow back from the exchanger to the tower sump. The kettle reboiler elevation also tends to be higher for these systems.

This trapout kettle arrangement can be very troublesome unless using a chimney tray with adequate degassing time as the trapout. Leakage or weep from a trapout tray, especially at startup or low rates, can prevent liquid from reaching the kettle reboiler, stopping its action altogether. This leakage can be avoided with a well-designed chimney tray trapout. Unless the trapout chimney tray provides adequate degassing time, the lines from the trapout to the kettle reboiler need to be designed for self-venting flow [*20*].

Figure 1F also shows two options for returning vapor from the kettle exchanger: above or below the collector tray. Note that the chimney riser area and riser vapor velocity are very different for these two options. In the case where the return vapor is introduced above the chimney tray, the risers act basically as vents, and very little riser area is required. When the return vapor is introduced *below* the chimney tray, the riser area must be substantially greater to handle the full process vapor rate.

The third type of kettle arrangement is basically a variation of the first arrangement. The overspill weir inside the kettle exchanger is eliminated, and the entire liquid inventory of the exchanger is placed on level control. Not only does this reduce the buildup of fouling material in the exchanger, it also permits manipulation of the fluid level to affect liquid entrainment into the return line. However, sensing the liquid level in a boiling liquid pool can be difficult, as mentioned below for internal reboilers.

Advantages: A kettle achieves a full theoretical stage of separation. The tower bottom configuration requires no baffles. The tower internals do not need

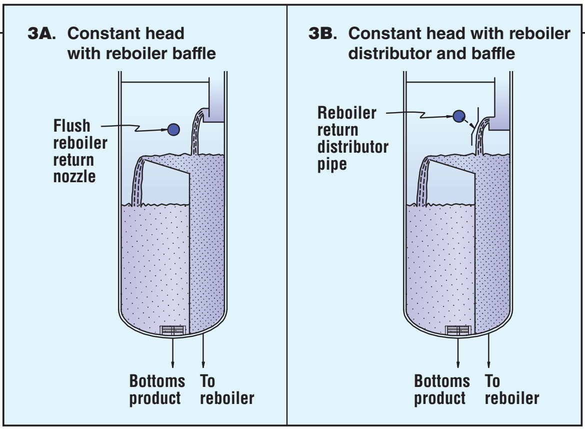


FIGURE 3. Constant head baffle arrangements are recirculating systems that maintain a constant depth liquid pool above the reboiler draw: A. Constant head with reboiler baffle and B. Constant head with reboiler distributor and baffle

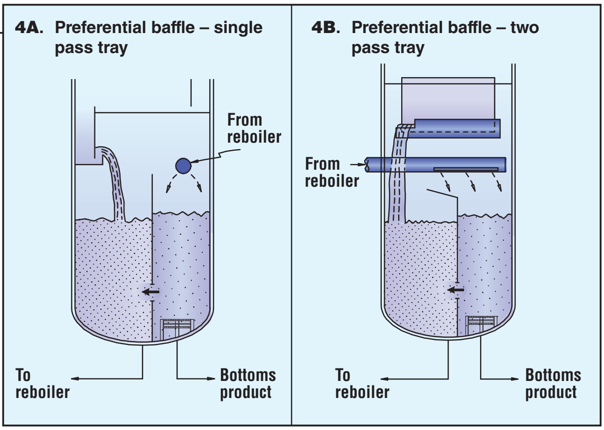


FIGURE 4. Preferential baffle configurations for single and multipass trayed towers: A. Preferential baffle, single pass tray; and B. Preferential baffle, two pass tray

to separate mixed phase fluids nor absorb large fluid forces. Kettle reboilers with removable tube bundles are relatively easy to inspect and clean.

Weaknesses: Kettle reboilers are expensive. They have a long residence time at maximum temperature in the exchanger, and perform poorly with thermally degradable or chemically fouling materials. In addition, they are improperly designed more often than other types of reboilers because they appear so simple. A recent tower malfunction survey [*1*] found kettle reboilers to be the most troublesome reboiler type. Almost all kettle-reboiler failures have been due to an improper force balance. Therefore it is imperative to focus the utmost attention to the kettle pressure balance (described in detail elsewhere [*14*]). The survey found that kettles whose force balance is adequate are usually not troublesome. The kettle force balance gives the liquid head required to drive flow from the tower to the exchanger and back through the vapor return piping. Sufficient disengaging space must be allotted in the kettle exchanger. Any entrainment increases the static head in the reboiler vapor return lines. Also, the entrainment is knocked out in the tower bottom, and from there it is returned to the reboiler, increasing the friction pressure drop at the tower inlet and outlet lines. In the extreme case, the entrainment can become so high that the kettle begins to thermosyphon, as demonstrated by field measurements [*14*]. Practices for minimizing entrainment from kettles were described elsewhere [*14*].

As system pressure increases, kettle entrainment may become more important due to the decreasing rate of vapor/liquid phase separation at higher operating pressures, which is caused by lower surface tension and smaller phase density differences.

Internal reboilers, also known as stab-in reboilers or stab-in bundles, are reboiler exchanger bundles, which are inserted directly into the tower shell below the bottom tray. The bundle is submerged either in the tower bottom liquid pool or in a bath of liquid formed by damming the bottom tray overflow liquid per Figure 5A. With a bath arrangement, lighter materials boil off from the bath and the remaining liquid overflows to the sump as bottoms product, where it is collected for residence time purposes. In some cases, the bathtub arrangement is used further up in the tower as a side reboiler. Note that the Design Practice Committee generally recommends against using internal reboilers because they are known to have caused numerous operating and capacity problems in previous applications.

Advantages: A properly designed internal reboiler can achieve nearly a full theoretical stage of separation (similar to kettle types). Internal reboilers can be inexpensive in cases where they eliminate exchanger shells and associated process piping without substantially increasing the tower shell cost.

Limitations: Internal reboilers are limited to small diameter towers or special applications because tube-bundle heat-transfer area cannot grow as fast as tower cross-sectional area with increasing tower diameter. Multiple bundles may increase tower height, offsetting any cost advantage. The bath type arrangement is similar to a once-through reboiler and may limit the boilup ratio.

Weaknesses: On-stream cleaning is nearly impossible; the tower must be shut down for exchanger maintenance. Similar to kettle reboilers, performance is poor with fouling materials. Internal reboilers require extra tower shell height and incorporate large flange connections, which can leak, especially if the bundle is not supported properly inside the vessel. For the bottom pool arrangement, the tower bottom liquid level can be difficult to assess because of froth generated by the internal exchanger [*22*]. The lower liquid level tap must also be located well below the tube bundle to ensure that two-phase material cannot reach it and cause a false low-level reading. False level readings can mislead operators about the true froth height in the tower, and result in flooding by entrainment of froth to the tray above the reboiler bundle. For the bath arrangement, excessive frothing and hydraulic restrictions, caused by improper design of the bath basin, often bottleneck towers.

Reboilers and tower elevation

To minimize tower and foundation capital costs, it is generally desired to minimize the overall tower height. Typically this means designing the tower (including the reboiler type and bottom section) first, based on process requirements, then selecting the minimum tower skirt height that provides adequate head for all of the following purposes:

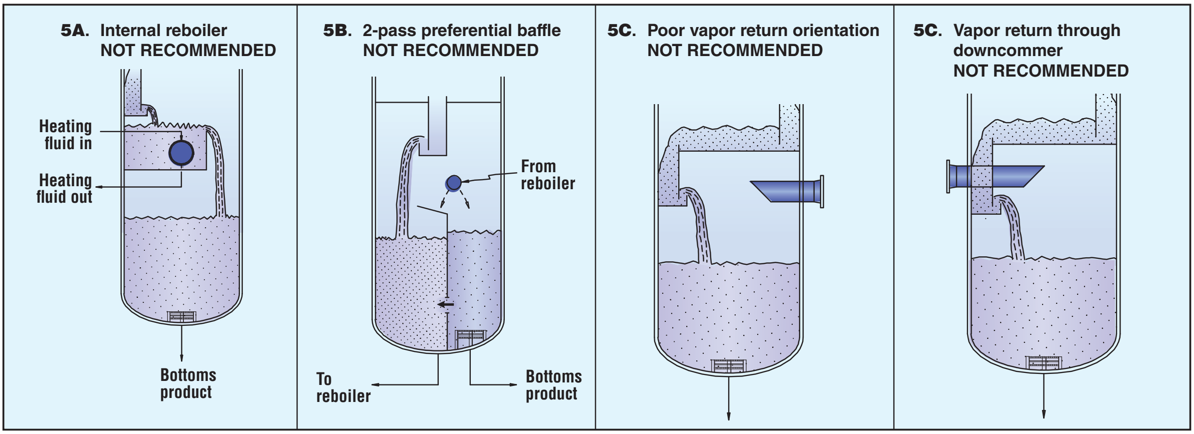


FIGURE 5. These four configurations are NOT RECOMMENDED: A. Insert reboiler; B. Two-pass preferential baffle; C. Poor vapor return orientation; and D. Vapor return through downcomer

- Reboiler circulation (thermosyphon driving force or pump NPSH)
- Bottoms product pump NPSH
- Tower or reboiler drainage to downstream equipment, if required

The sections below discuss head considerations for various reboiler types in more detail to allow an assessment of their contribution to required tower skirt height. Note that when an unbaffled bottoms arrangement is specified, the liquid head used in the reboiler flow calculations should be based on the lowest operating liquid level allowed (typically designated LLL). But the thermal and hydraulic design of the reboiler circuit should comprehend both HLL (highest operating liquid level allowed) and LLL process limits, and the reboiler inlet and outlet lines should be sized to handle circulation rates at HLL operating conditions. If a constant-head baffle arrangement is used for a thermosyphon system, there will be different liquid levels to consider on the reboiler and product sides of the baffle, and the designer should use LLL on the product side for all product hydraulic calculations.

Vertical thermosyphon systems. Generally this type of exchanger is hung off the tower itself, and the height of the system is determined by the selected length of the exchanger tubes. Common tube lengths are from 6 to 20 ft (2 to 6 m), with the longer lengths applicable to designs that require large heat transfer areas [*11*]. Reboiler tube length is often shorter at lower column process pressure (for example, near atmospheric pressure) to minimize liquid hydrostatic head, which maximizes LMTD (log mean temperature difference) because vaporization can start at a lower temperature. If the reboiler feed piping enters the exchanger channel from below, additional skirt height may be required for this as well.

Horizontal thermosyphon systems. In this case, the reboiler exchanger is typically located at a minimum practical distance above grade to allow for piping clearances, ease of maintenance, or condensate drainage if necessary (the reboiler tubeside outlet nozzle is usually located above the top of the condensate drum for this purpose). Then a pressure balance calculation is performed for the reboiler cir-

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cuit (including return piping), which gives the required liquid height above the exchanger necessary to drive the desired reboiler flow.

Kettle systems. Properly designed kettle systems do not usually require significant liquid head for reboiler flow, so the skirt height is typically governed by another factor such as bottoms-pump NPSH requirement. The elevation, however, must be high enough to satisfy the force balance without having the liquid level in the sump approach the reboiler return inlet. In the case of a trapout, the trapout must be at an elevation high enough so that the force balance does not lead to liquid overflow into the chimneys [*23*]. In the case of a tower whose pressure is sufficiently above downstream equipment to drive bottoms product onward without a pump, the skirt height may be quite low. Conversely, if bottoms evacuation or drainage requirements dictate a significant skirt height, and it is not desirable to have the liquid level in the kettle inlet pipe, the kettle exchanger itself may need to be situated on a high foundation because of the elevation relationship between kettle overspill weir elevation and tower bottom liquid level. This elevation difference is given by the kettle pressure balance as described previously.

Forced circulation systems. The liquid head necessary for a forced circulation system is based on the NPSH requirement of the reboiler circulation pump. Typically, the tower bottom tangent line is elevated about 15 ft (4.5 m) [*11*] to provide sufficient NPSH. If a separate product pump is used, its NPSH requirement may govern.

Things to avoid

In Figure 5A, we have an internal reboiler. Note that the Design Practice Committee generally recommends against using internal reboilers because they are known to have caused numerous operating and capacity problems in previous applications.

In Figure 5B, this two pass arrangement is not recommended because the reboiler vapor must pass through the downcomer's liquid curtain in an attempt to distribute itself evenly to both passes. The bottom tray should have two side downcomers in this case.

In Figure 5C, the reboiler return fluid is directed toward the bottom tray downcomer and/or seal pan. This design can fail in a number of ways, including: (1) backup of the bottom tray downcomer; (2) entrainment of seal pan overflow liquid by the returning vapor; (3) mechanical failure of the bottom tray downcomer from fluid impingement; or (4) heat transfer from reboiler return fluid to the liquid in the downcomer, causing vaporization and choking inside the downcomer.

In Figure 5D, the reboiler return pipe has been routed through the downcomer. Again, this can fail by vaporizing liquid in the downcomer and choking it. Also, if the bottom section trays are heavily liquid loaded, this design might block enough downcomer area to cause backup flooding. ■

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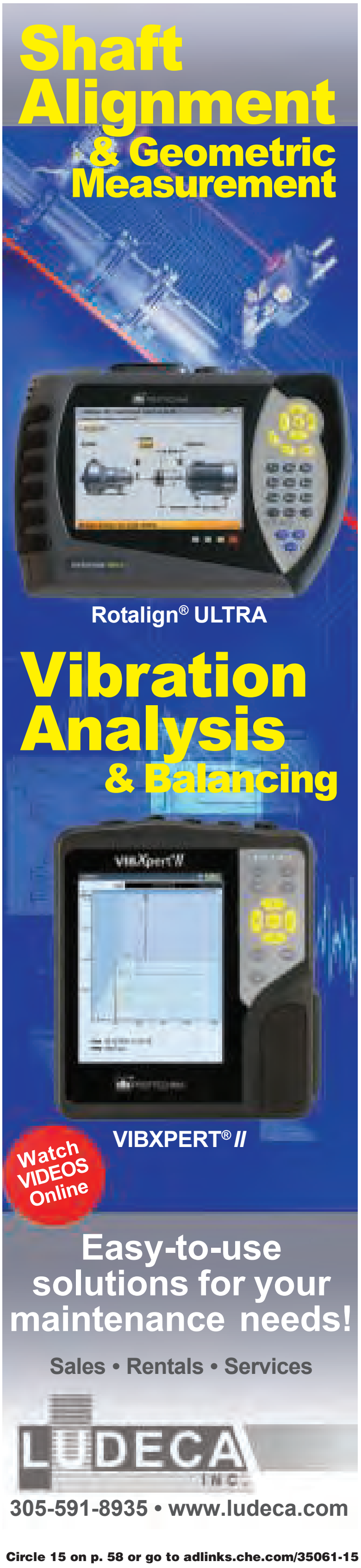

Get the Most out of Vibration Analysis

By listening to the messages your components are sending, you will be better able to assess the status of your machinery and take action to address problems

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With productivity, growth and reliability as constant drivers, the proactive evaluation of all machinery is critically important. In order to gain useful insight, the maintenance team must capture comprehensive data related to machinery operation and carry out a logical interpretation of the data.

The conventional language of equipment components — vibration — transmits relevant information that varies based on the type of machinery or asset system and the conditions these components are experiencing. Learning to decipher vibration data properly can help operators to properly assess the condition of their machinery, gauge equipment performance and plan for whatever actions are needed to address problems that may have arisen.

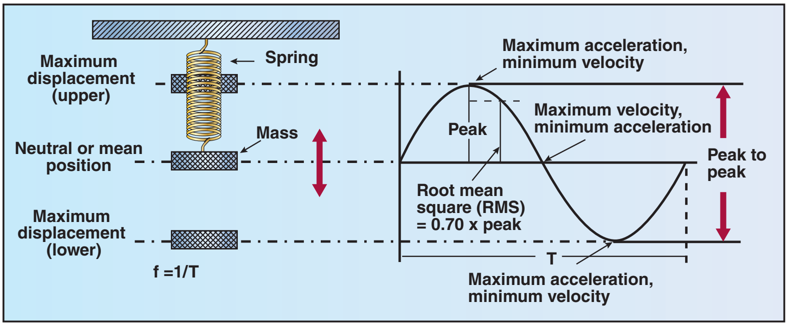


FIGURE 1. This graphical representation shows the simple harmonic motion for an excited spring-and-mass system

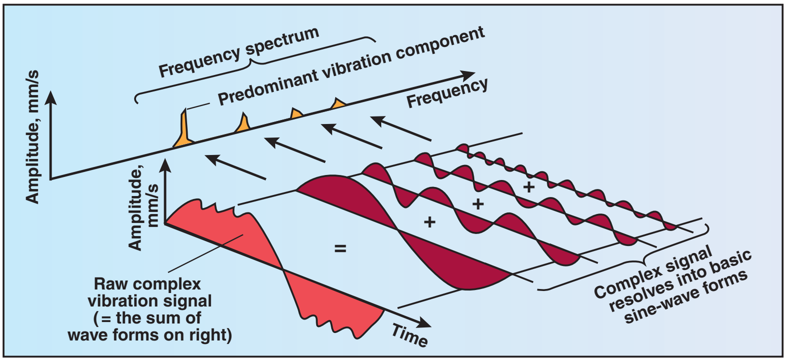


FIGURE 2. Complex vibration signals can be resolved into multiple sinusoidal time-wave signals, which can then be converted into frequency-domain signals using Fast Fourier Transformation (FFT) analysis

Vibration basics

Technically, vibration occurs in response to excitation forces acting on an operating machinery system. Vibration is often an indication of construction-related defects of the machine or machine parts, assembly problems, improperly installed systems, electromagnetic forces and other factors.

As an elastic body in a non-equilibrium condition experiences excitation forces, it creates vibratory sinusoidal motion (Figure 1). As the internal forces within the displaced body (in the form of strain energy) are converted into kinetic energy, the body moves in a "to-and-fro" vibratory motion about a fixed position. Hence, the most corroborative parameters that can represent the vibration signal are the following:

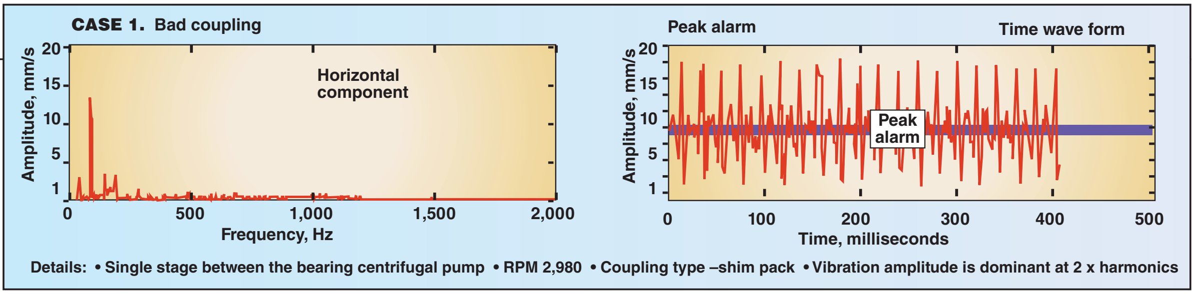
- Displacement from the mean position or amplitude
- Repetition of cyclic motion in unit time or frequency
- Angular position of the mass in the cycle with respect to a specified reference or phase

To assess these key parameters, the most important measurable, detectable signals of vibration are:

- Amplitude
- Frequency
- Phase

From these primary parameters, the mechanical vibration movement must then be converted into a signal with respect to time, so that it can be measured and analyzed.

Amplitude. As shown in Figure 1, *amplitude* refers to the magnitude of vibration present in a measured signal. In vibration analysis, amplitude is measured in units of displacement, velocity or acceleration, and is typically plotted on the vertical axis of any graphic representation of the signal. Normal units are microns (one thou-



Details: • Single stage between the bearing centrifugal pump • RPM 2,980 • Coupling type –shim pack • Vibration amplitude is dominant at 2 x harmonics

FIGURE 3. In this example, the engineer observed a broken shim and misaligned coupling with a loose coupling hub. In the left-side plot, vibration amplitude is plotted against frequency (Hz). In the time-wave form (right), amplitude is plotted against time. For this case, repeated spiking in the time-wave form within a short span confirmed misalignment, compounded by mechanical looseness of the rotor component

sandth of a millimeter) or mils peak-to-peak.

Velocity is the rate at which displacement changes. The unit for velocity measurement is mm/s of peak or RMS value, where RMS is the root mean square value of the vibration amplitude. This is the speed of the vibration.

Acceleration is the rate of change in velocity with respect to time. Acceleration is normally expressed either in terms of gravitational units or in m/s^2 unit of the measured peak or RMS value. This is proportional to the force of the vibration.

The following discussion shows how the simple harmonic motions of the three measurable amplitudes (which have three different characteristics of vibratory propagation with different measurement units) are related mathematically. For a pure sine wave, displacement at time *t* from the mean position or origin is:

$$x(t) = X \sin(2\pi ft) \qquad (1)$$

Where:

x = the magnitude of displacement of the mass at time t after it starts moving from the mean position or origin

X = the maximum magnitude displacement from the origin

f = the frequency of vibration, cycles/s

t = the reference time interval from the start at origin

Amplitude can be expressed in terms of the rate of change of displacement, or rate of change of velocity.

$$\text{Velocity: } V(t) = dx/dt = V\cos(2\pi ft) \qquad (2)$$

Where:

$V = 2\pi fX$

$$\text{Acceleration: } A(t) = dv/dt = d^2x/dt^2 = -Z\sin(2\pi ft) \qquad (3)$$

Where:

$Z = 2\pi fV = (2\pi f)^2 X$

x = the displacement at time t, microns

X = the peak displacement, microns

f = the frequency of vibration, cycles/s or Hertz (Hz)

If displacement — the maximum excursion of the object — is held constant and frequency is doubled, then the velocity must also double, because the mass has to travel twice the distance in the same increment of time. Since the object must reverse direction twice during every cycle, the maximum acceleration experienced at the object's reversal in direction increases by the increase in frequency squared.

Variation in velocity and acceleration with frequency forms the basis for vibration-severity criteria, provides guidelines for selecting the variable that will be most representative for detecting and analyzing a particular fault, and explains how failures can occur without warning if the wrong variable is measured. It is evident from the discussion above that displacement can appropriately represent the amplitude of low-frequency signals, but as the frequency goes up, velocity and acceleration become the more-accurate variable to use to express the magnitude of vibration.

Frequency. Frequency is a measure of the cyclic period of repetitive amplitude changes that the vibrating object experiences with respect to time. The period of vibration *T* is the time taken to complete one cycle of motion (in other words, the motion is seen to repeat itself after time *T* seconds).

The number of cycles that occur in the unit time (the frequency) is denoted by the letter *f*, and may be expressed in several ways: cycles per minute (CPM); cycles per second (Hz); revolutions per minute (RPM); or orders of running speed (where the rotational speed of the machine is the first-order running speed, twice the rotational speed is the second-order running speed, and so on). Because certain types of faults typically occur at certain frequencies, the ability to identify the frequency at which the vibration occurs can provide a good indicator of the type of fault at hand.

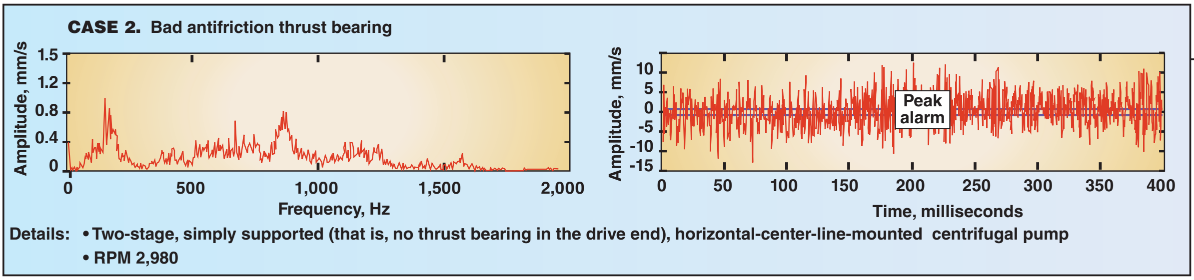
Phase. Phase is the state of the sinusoidal signal with reference to either time or a fixed reference point. For instance, the angular distance traveled within a given time represents the measure of phase in terms of the angle domain. Alternatively, the time required to arrive at a given angular position is a measure of phase in terms of the time domain.

The phase difference is either the time difference between two signals arriving at a given angular postion, or it is the angular difference between two signals at a given time. Note that while the phase can be expressed in these two ways, during vibration analysis, only the angular phase difference is used. In time-displacement curves, the phase of velocity is $\pi/2$ or 90 deg ahead of displacement, while acceleration is π or 180 deg ahead.

In numerous methods of determining the phase relationship between two signals, there must be a common denominator — time. (Figure 2). One approach is to use time-based waveform comparisons (that is, graphical waveform represenations of the vibration amplitude with respect to time) for signals generated by two displacement probes mounted 90 deg apart on the vibrating body. (Note: To measure the phase difference, two signals are required). In a single-signal channel probe, the reference pulse may be generated with a strobe light, infrared or photo tacho-pulse system.

Multi-channel measurement

Expanding on the earlier definition, cross-channel phase measurement (using two sensor probes mounted on the upper half of the body, 90 deg apart) simplifies and expedites the



CASE 2. Bad antifriction thrust bearing

Details:
- Two-stage, simply supported (that is, no thrust bearing in the drive end), horizontal-center-line-mounted centrifugal pump
- RPM 2,980

FIGURE 4. These plots of vibration signature and time-wave-form distribution were produced as a result of a bad anti-friction bearing. The raised spectrum floor spread (from low order to very high order of operating harmonics) suggested a damaged bearing, helping the operators to locate a broken bearing cage

acquisition of phase data. Of all cross-channel measurements, cross-channel phase is the most sensitive vibration parameter because errors in mounting positions for the sensors can lead to erroneous conclusions.

Some multi-channel Fast Fourier Transformatiom (FFT) analyzers require a specific input channel (FFT analysis is a mathematical operation that extracts the frequency information from a time-domain signal and transforms it to the frequency domain). This allows one sensor to be configured as a reference input during phase-difference checking.

If the channel is set up incorrectly, cable changes will be required. One way to sidestep this problem is to take the orientation into account and add 180 deg. Other multi-channel FFT analyzers provide the ability to determine which input signal can be the reference without changing cable connections. Listed next are some basic considerations that must be taken into account when acquiring multi-channel phase data:

- An accelerometer is the only true phase transducer
- The multi-channel FFT analyzers have no internal phase shift between channels
- Depending on the type of fault, a machine's structure will either be moving as one unit (in phase) or not as one unit (out of phase)

Vibration excitation

For vibration excitation to happen, two types of forces — namely the exciting forces and the restraining forces — are at work. In general:

Exciting force = Stiffness force + Damping force + Inertial force

This can be expressed as:

$$F(t) = Kx(t) + Cv(t) + ma(t)$$

or

$$F(t) = Kx(t) + C\cdot dx/dt(t) + m\cdot d^2x/dt^2(t) \quad (4)$$

where:

$F(t)$ = a measure of the exciting force

K = stiffness constant (depends upon physical and dimensional properties of component)

C = dampening force per unit velocity (depends upon dampening system engaged)

m = Mass of the component subjected to the exciting force

All the forces are expressed as a function of time. (The equations shown are for illustrative purposes, so showing specific units here is not relevant. During the actual calculations, units are required.)

The static deflection is controlled by the stiffness force alone. At a low-speed frequency range, the response (that is, the vibration) is dominated by the spring force and is in phase with the excitation force.

As frequency increases, the inertial force of the mass has an increasing influence [because by definition, *force* = (*mass*)(*acceleration*)]. At a particular frequency (called the undampened natural frequency,) the mass and spring terms cancel each other out. The system is easily excited into motion and the response is controlled only by the dampening.

At the natural frequency, the response lags the excitation by 90 deg. At frequencies greater than the natural frequency, the mass term exerts increasing control and the system begins to behave as a moving mass; in these situations, the response lags the excitation by 180 deg.

The general rule of thumb is that for any rotating mass, the stiffness of the system (imparted by physical properties of material and dimensional geometry) counters the frequency of vibration, and the amplitude of any vibration that does occur is controlled by any dampening device in the system (such as the dampening provided by the foundation and any supports).

Direction of measurement

To be of greatest utility, vibration data must be collected at the right place, under the right conditions, using the right procedure. For relatively large (Class IV and above) machines, online vibration data are typically collected using an integrated monitoring and display system that captures radial displacement data using sensor probes mounted close to the rotating body through the support housing.

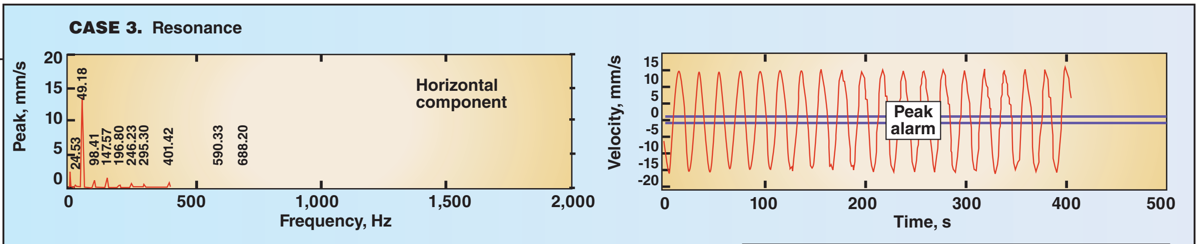
For smaller units, vibration data are typically collected off line at a preset frequency using portable vibration-monitoring devices. Care must be taken during the manual collection of vibration data to reduce the chance of error and ensure the most comprehensive data set.

The three directions of vibration amplitude to be monitored are defined here (and discussed further below):

- *Axial* — Parallel to the machine's axis of rotation (x-axis)
- *Vertical or longitudinal* — Perpendicular to the machine's axis rotation (y-axis)
- *Lateral or horizontal* — Perpendicular to the axial direction at the same plane (z-axis)

The following points should be strictly observed when measuring vibration using handheld sensors:

- Vibration data for rotating machines should be collected as close to the bearings as possible
- Readings should be taken at precisely the same spot every time to ensure consistent data for comparison over time. Operators should mark these spots with permanent marker or create a shallow conical hole (45-deg counter shank) with a drill point
- The sensor angle should always be perpendicular to the surface (that is, 90 deg ±10 deg)
- The hand pressure should be even and consistent (not too loose or too firm, as that would dampen the vibration signal)



Details: • Horizontal rotary screw pump, having RPM 2,980, with rigid coupling

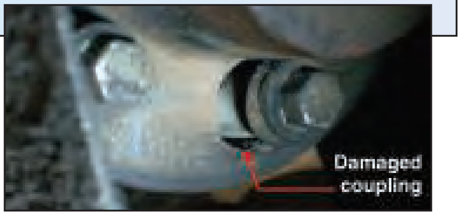


FIGURE 5. This case shows vibration results from resonance in a rotating equipment system. The phase difference between the horizontal and vertical components at the same bearing is close to zero. As seen in the photo, the hole in the coupling hub bolt became oblong-shaped due to persistent vibration damage. The time waveform for the axial direction shows periodic spacing with two humps at each peak. This situation can be addressed by modifying the piping and support systems

- Magnetic mounts can help to ensure measurement consistency from episode to episode, while stud-mounted are even better, and permanently mounted sensors are the best for consistency in data collection

If possible, it is best to avoid collecting vibration data from these sources:

- Painted surfaces
- Unloaded zones (that is, any part that is separated from the vibrating part by an isolator such as a flexible bellows joint)
- Housing splits (that is, the joint area of a component's split bearing case)
- Structural gaps

Directional significance

Lateral or horizontal. Measurements in this direction typically show the most vibration due to the machine being most flexible in the horizontal plane. Excessive horizontal vibration is often an indicator of imbalance.

Vertical or longitudinal. Measurements typically show less vibration in the vertical direction than in the horizontal direction because of stiffness created by the mounting and the force of gravity under ideal conditions.

Axial or parallel to the axis of rotation. Measurements in this direction should show very little vibration, as most forces in dynamic machinery are generated perpendicular to the shaft. However, misalignment and bent shaft problems can create vibration along the z-axis. Note that equipment that is vertically mounted or over-hung may show different responses.

For best results, the measurements should be gathered when the machine is operating under normal conditions, has reached its normal steady operating temperature, and is running under its normal rated conditions for flow, pressure, voltage and load.

Analyzing the results

Several different analytical techniques are described here.

Amplitude-based analysis. Such an approach provides a good, first-hand indication of vibration severity levels and provides a useful diagnostic profile. Amplitude data are typically collected using either offline accelerometers or online displacement probes.

Signature analysis. Using this approach, time-based signals are transformed to a frequency-based spectrum via FFT. The resulting plot of frequency versus amplitude indicates the dominant sources of major exciting forces.

Waveform analysis. This time-based distribution profile of vibration amplitude is mainly used for severity assessment and identification of probable fault locations. The data are typically plotted as time versus amplitude.

Phase analysis. This validation process helps to pinpoint probable fault locations that are identified by signature and waveform analysis. A dual-channel sensor or a reference signal for a single channel is used to capture the phase shift between two reference locations vibrating under the influence of the same excitation sources.

Coast-down testing. This confirmation test can help to identify the source of a fault between the driver and the driven equipment, and will indicate the presence of a low-frequency resonance zone.

Bump test. This test is used for identification of resonant vibration and pinpoint its source.

Bode plot. This is a run-away test with combined measurement of amplitude and phase to confirm the presence of resonance and its frequency zone. It produces plots of speed versus phase and speed versus amplitude.

Orbit analysis. This is a useful diagnostic analysis for machines with forced-feed, lubricated, hydrodynamic bearings, where the nature of the dominant excitation source can be inferred from the profile of journal-bearing loading. The important diagnostic parameter is the shape of the orbit plot, not the amplitude. Data are collected by two sensors mounted 90 deg apart on the bearing in radial locations. A two-dimensional plot (x- and y-axes) of data is produced. On this plot, a circular orbit distribution over a larger diameter indicates imbalance. An oval-shaped distribution of the plot may be due to resonance, while a "figure-eight" distribution of the plot is often an indication of misalignment.

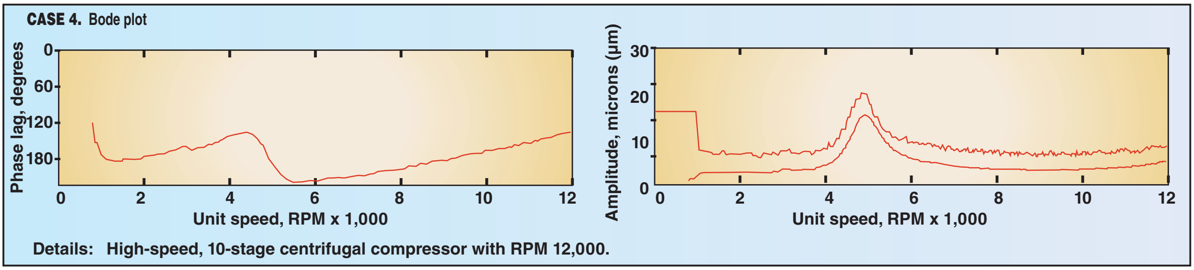
Current-signature analysis. Using this technique, an online spectrum analysis is created by capturing a motor's current and voltage signals and analyzing them to detect various faults. The graphical plot shows the distribution of electromagnetic flux magnitude versus time.

Figures 3 through 9 show useful vibration analyses for several different case-history scenarios.

Electrical-signature analysis

Experts are always looking for new methods for identifying and predicting equipment failures. Analysis of electrical signals (also called current-signature analysis) is a relatively new technique that extracts information from the line current that is supplied to the motor. It entails capturing a motor's current and voltage signals and analyzing them to detect various faults in induction motors, and can provide insight into both the electrical and mechanical health of the components.

Just like a vibration signal, electrical power supply (alternating current) is not a pure sine wave. Many fluctua-


CASE 4. Bode plot

Details: High-speed, 10-stage centrifugal compressor with RPM 12,000.

FIGURE 6. This graphical plot of vibration amplitude profile and phase change during resonance shows the special diagnostic features for a high-speed compressor with hydrodynamic bearings. The measurement during this runaway test shows the phase of vibration signal changes close to 180 deg with a rise in vibration amplitude at the first critical speed (4,922 RPM)

tions of different harmonics appear in both voltage and current signals. By performing FFT analysis, frequency information from a time-domain signal can be extracted, transforming it to a frequency-domain signal or current spectrum (that is, a graph of the amplitude of a signal at a given frequency domain). In the frequency domain, the height of the peak represents the amplitude of the signal.

All electrical and mechanical faults change the flux distribution inside the motor and thus generate harmonics in the current. Analysis of the frequency spectrum enables the user to see all the harmonic components of voltage and current. Superimposing the current and voltage spectra enables us to distinguish between the supply harmonics and the fault harmonics. The harmonics generated by each fault will produce a different, distinctive signature that can be evaluated. Studying the distribution of these fault harmonics then allows the operator to better identify the fault.

To capture voltage and current signature, clamp-on probes are placed around the supply cable for low-tension (LT; also called low-voltage) motors (below 440-V supply), and around the measuring or protection current-transformer secondary coil. LT meters and the lead for the motor-protection relay can be directly connected to the supply cables, whereas for high-tension (HT) motors (also called high-voltage motors; above 440-V supply), this cannot be done. In such cases, a step-down transformer must be used, which then becomes the input for various meters and protection systems. The meters are calibrated in accordance with the transformer primary or secondary coil-turn ratio so as to display the actual supply current voltage for the HT motors. All testing is done at the motor- control panel so there is no need to approach the motor.

Electrical-signature analysis, especially when used in conjunction with vibration analysis, allows the user to identify electrical and mechanical disorders, such as rotor-bar damage, misalignment or imbalance, static and dynamic eccentricity, bearing faults, foundation looseness, air-gap eccentricity, stator mechanical and electrical faults, and more. The following are some advantages of this technique:

- It can be conducted online, so no downtime is required
- Monitoring can be carried out remotely, so there is no need to approach the motor
- It provides accurate detection of electrical and mechanical problems

To carry out current-signature analyses, these parameters must be known:

- Electrical line/supply frequency (f), Hz
- 50 Hz = 3,000 RPM
- Number of electromagnetic poles (motor-P)
- Rotor-bar pass frequency (fb) = Number of rotor bars times rotor RPM
- Synchronous speed (Ns) = $2f$
- Slip frequency (S) = Synchronous speed minus rotor RPM
- Pole pass frequency, (fp) = Slip frequency times number of poles

Signature interpretation

Discussed below are some rules of thumb for reading and interpreting the current-signature spectrum (a graph of amplitude versus frequency) to identify faults in the electrical motor.

Rotor bar and end-ring faults. Every individual rotor bar can be considered to form a short-pitched, single-turn, single-phase winding. The air-gap field produced by a slip-frequency current flowing in a rotor bar will have both a fundamental component rotating at a slip speed in the forward direction with respect to rotor, and one of equal magnitude that rotates at the same speed in the backward direction. With symmetrical rotors, the resultant sum of the backward component becomes zero. For a broken bar rotor, however, the resultant component sum will be non-zero.

The field, which rotates at slip frequency backward with respect to the rotor, will induce an electromagnetic field (EMF) on the stator side that modulates the main frequency component at twice the slip frequency. The side-band components around the fundamental of the line current spectrum are usually measured, indicating broken bar faults.

Rotor bars and end-ring failures give rise to a sequence of side bands given by:

- $fb = (1 \pm 2s)f$, where f = supply frequency
- S = slip
- Frequency-domain analysis of the stator current

Motor-current slip ratio:

- 20 log (A/B)

where:

A = Slip frequency amplitude

B = Line frequency amplitude (or fundamental frequency of rotation)

- Ratio > 45 db: No fault exists
- 40<Ratio<45 db: Fault is developing
- Ratio<40 db: Fault exists

Bearing faults. Anti-friction bearings have a set of unique defect frequencies that can be utilized to evaluate the health of a bearing. These signature

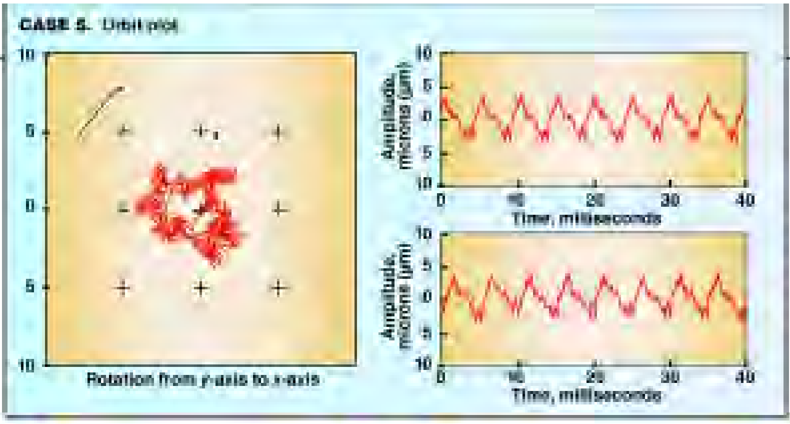


FIGURE 7A (top). This orbit plot of the bearing of the non-driven end of a compressor (top; a plot of sleeve-bearing clearance around the shaft and time-wave distribution), shows an unsymmetrical pattern, indicating unstable lubrication and uneven journal loading (The two wave forms come from two sensors). The time wave forms show repetitive spacing with time, with random spiking revealing irregular loading

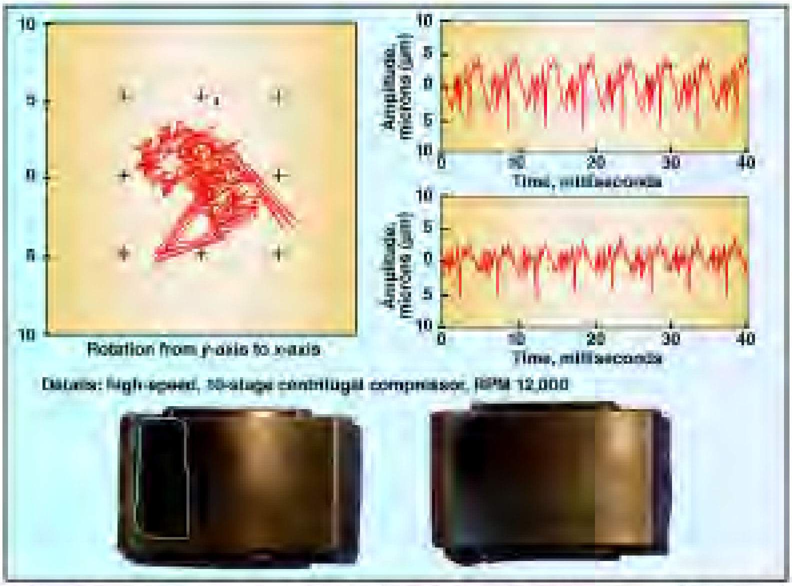


FIGURE 7B (bottom). This orbit plot of the bearing at the compressor drive end shows no formed orbit. This indicates a breach in the lube oil film and possible rubbing of the shaft journal with baring-pad high spots. The highly disturbed time wave form (with sharp spiking) substantiates the beasing and profile irregularities. In the photo, bearing load pads show the mark of oxidized oil and surface score

frequencies, are based on the size and design of the bearing, and can be monitored for possible defects in the inner race, outer race, ball (roller) and cage of the bearing.

Specific bearing defects will cause variation in the magnetic flux at a frequency that can be corroborated to the bearing defect and appear in a current-signature plot as the dominant frequency zone.

Eccentricity faults. When there is an unequal air gap between the stator and rotor, this condition leads to the formation of a phenomenon called static-air-gap eccentricity (f_{ecc}). This can create an imbalanced magnetic pull, which tends to increase vibration and wear, or can lead to a rotor-to-stator rub and consequential damage to the stator core and winding. Such eccentricity gives rise to a sequence of frequency components, given by:

$$f_{ecc} = f\,[(R \pm nd)(1-s)/p \pm n] \qquad (5)$$

Where:

n = 1,3,5: The harmonics index or order of harmonics, depends on motor-stator winding pattern

nd = Dynamic eccentricity index = 1, Static eccentricity = 0

R = number of rotor bars

P = number of poles

S = slip (the difference between line frequency and motor rotating frequency), Hz

This eccentricity also gives rise to the frequency-component side bands, which are given by

$$f_{ecc} = f \pm fr \qquad (6)$$

Where:

f = line frequency, Hz

fr = rotor speed, Hz

Eccentricity-related frequencies are generated from a combination of static and dynamic eccentricity, with the magnitudes increasing with increasing eccentricity. Static eccentricity most often arises from manufacturing defects, assembly errors such as non-concentric stator bore, soft foot and so on. Static eccentricity most often appears in the vibration domain at 2(f) and will not vary with respect to speed. It can also appear at the stator-bar pass frequency with side bands of 2(f).

By comparison, dynamic eccentricity typically results from problems that arise during operation, such as rotor deflection, damaged bearings, high bearing clearances for sleeve bearings, unbalanced magnetic pull, bowing of the rotor and so on.

Stator faults. Stator-winding faults can be classified in many ways:

- *Turn-to-turn short within the winding of the motor* (results from weak insulation between the turns of the stator coil winding). The motor may continue to operate, depending on the severity of the defect but deteriorate rapidly causing a rise in the winding temperature
- *Short between coils of the same phase* (results from insulation damage in any of the stator phase-winding coils). The motor can continue to operate, depending on the severity of the defect but deteriorate and cause unsymmetrical phase-current distribution in comparison to other phases of the three-phase motor
- *Phase-to-phase short* (from insulation damage between phases; will cause disturbance in the phase sequence). The motor will trip as the protection system disconnects the power supply
- *Phase-to-earth short* (commonly known as an earth fault, this occurs due to grounding of the live power-supply cable). The motor trips as the

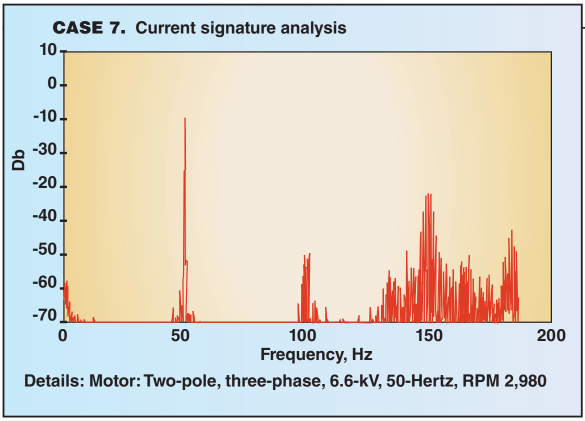


FIGURE 8. In this analysis of the frequency-amplitude distribution of current signal for an electrical motor, the side band at 2 times line frequency and random band at high-frequency indicate nominal unsymmetrical flux distribution and eddy flux flow. The vibration-analysis expert system forecasts the quantum of current imbalance is only 7% and the amplitude of the current signature is relatively low (that is, less severe)

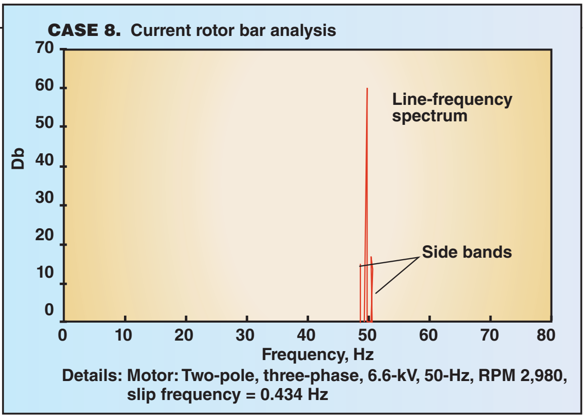


FIGURE 9. This rotor-bar analysis created by a vibration-analysis expert system indicates the presence of high resistance joints in winding. It recommends further trend monitoring for possible degradation progressing in the winding joints. The amplitude at the frequency of the number of rotor poles times slip frequency is marginal, hence it is considered to be a low-severity zone

protection system disconnects the supply

- *Single phasing* (a power-supply fault, resulting in no supply to any of the stator-winding phases). Very low power-rated motors (those below 5 kW) may continue to operate but can experience damage to the winding. The motor will not rotate and will generate a humming noise

Depending upon the nature of the stator faults, harmonics as side bands of 2 times line frequency will appear. These are related to the degree of stator flux unbalance, the number of stator slots, and the supply frequency. Normally due to the structure of the stator winding in the current domain, the side bands will appear as odd-numbered harmonics (1, 3, 5, 7 and so on).

Overall, current-signature analysis is a useful tool to identify vibration sources in the electrical motor system because it identifies these conditions:

- Rotor faults
- Side bands around the line-frequency spectrum, with their magnitude indicating the severity of the fault
- Motor problems (for instance, indicated by an increase in core losses and load current, and a decrease in efficiency and speed)
- Bearing faults, eccentricity faults and stator faults

However, users should keep these points in mind when considering using this technique:

- Knowledge of the bearings is required for detection of bearing faults
- This technique can be applied for rolling-element bearings only
- The magnitude of fault frequencies is relatively small compared to the rest of the current spectrum, but the appearance of any unusual signature in the current spectrum indicates the presence of a fault. The previous signature is needed for comparison to identify the source of the fault
- The current spectra has to be interpreted in two distinct frequency bands (one in the range of *f*1 ± *fr*, and the other in the region of static and dynamic eccentricity frequency components). This also requires previous signature for comparison
- The stator faults generate amplitude peaks at a specific frequency range appearing in the current spectrum
- When there are multiple types of faults, the amplitude of each appears in a complex current signature and varies differently with increasing fault severity. This also requires the previous signature for comparison

Two tables provided online

Interpreting vibration data to pinpoint the source of its origin is challenging. This article provides two comprehensive tables to help readers carry out more detailed analysis.* Table 1 describes key relationships to help the user correlate measurable vibration parameters with common machinery defects. The table describes the vibration amplitude distribution in the holizontal, axial and vertical directions, and the dominant frequency, side-band frequency profile that each exciting source can generate in a rotating machinery system.

Table 2 provides analytical tips for developing and analyzing signature maps (amplitude-versus-frequency graphs), waveform (amplitude-versis-time graphs) and phase-angle shift of vibration measured in three directions for different types of excitation sources. ■

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* Tables 1 and 2 are available at www.che.com along with the full version of this article (search by the article title).


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SAFETY-INSTRUMENTED SYSTEMS:

Control Valves As Final Elements

The scenarios presented here highlight the advantages and disadvantages of using a control valve in an SIS

Afton Coleman
Emerson Process Management

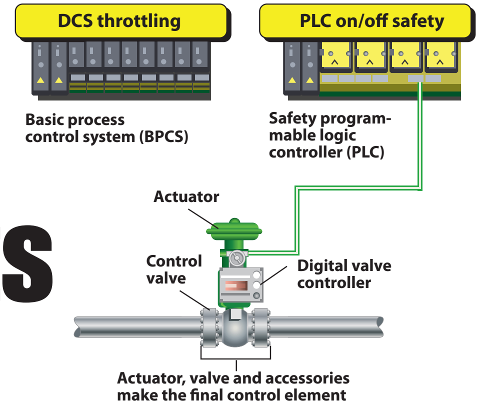

FIGURE 1. This figure shows a control valve being used solely for on-off safety. The digital valve controller is connected only to the safety PLC, which is monitoring the process for dangerous conditions and will command the final control element to act in a safety demand

History is a constant reminder that accidents and catastrophic events can and do occur in process environments. As processes become more complex (for instance, allowing for greater operating temperatures and pressures to be used) and existing basic process control systems (BPCS) and safety systems age, risk reduction becomes more challenging. Regulations from the U.S. Occupational Safety and Health Admin. (OSHA; Washington, D.C.) and the Environmental Protection Agency (EPA) and international regulatory bodies have been put in place to help prevent and mitigate damage and injury.

Notable international standards addressing process safety include IEC 61511 and ISA 84.01. These standards cover the design and management requirements for a safety-instrumented system (SIS) from cradle to grave. An SIS contains one or more safety-instrumented functions (SIF), such as logic solvers, sensors and final control elements that act independently and separately from the basic process control system. These SIFs are selected for a given safety configuration to address site-specific hazards or events.

During system design, all constituents of the SIS must be addressed, especially the final control element, which consists of the valve and actuator, and any instrument and other accessories that can affect the valve's movement. Data have shown that the final control element can be responsible for 50% or more of SIS failures. Any component of the final control element that can affect the safety function must be considered in the safety analysis. This includes the valve and actuator and other components (such as the positioner, solenoids and volume boosters) that can affect the valve's ability to return to its safe state.

Since the final control element is often the weakest link of an SIS, the proper valve and actuator must be selected to improve reliability and availability and to minimize risk. In certain circumstances, the use of a control valve can provide the optimal solution to this problem. There is no specific industry requirement that defines which valve design can be used in an SIS, so control valves do not need to be limited to the realm of the BPCS. With careful consideration, a control valve can also be used as either a final control element or as a redundant element within an SIS. When designing an SIS, the use of a control valve can be considered in three potential configurations, each of which is discussed:

1. Single control valve used only for on-off safety
2. Single control valve used for both safety and control
3. Control valve used as a redundant final control element

Each configuration has its advantages and limitations, and, as with any SIS design, a thorough hazard analysis and complete knowledge of the process and its safety requirements are required to guide the selection of appropriate hardware.

Configuration 1: Control valve used only for on-off safety. In this scenario, shown in Figure 1, a single control valve acts as the safety valve. A digital valve controller (DVC) instructs the valve to travel to its safe state upon signal from the safety logic solver (SLS), depicted as a safety PLC. This device is also capable of performing partial stroke testing and performing valve diagnostics. In fact, some digital valve controllers available can monitor the health of the external solenoid valve. A solenoid valve (not pictured) could be used as a redundant element or in place of the digital valve controller, however using a digital valve controller to perform the safety function has increased in prevalence due to its diagnostic capabilities and ability to log events and testing.

The control valve should be chosen for its suitability in the process media (considering capacity, shutoff, proper material selection and so on), and reliability. Reliability can be determined as a function of proven-in-use data (such as that compiled by the manufacturer, by a third party, or from documented user experience data), or failure-rate values (lambda), which are based on FMEDA studies, and are commonly available in third-party cer-

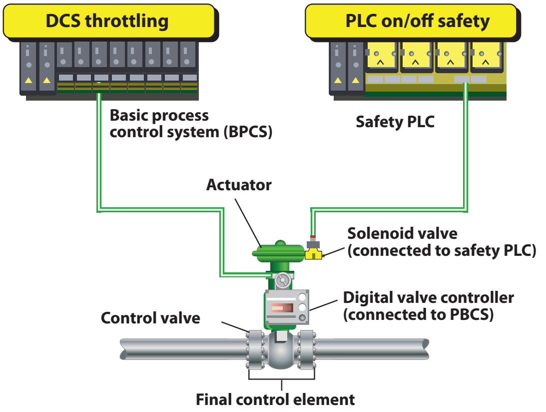

FIGURE 2. In this configuration, a control valve is used in both the BPCS and SIS. The smart digital valve controller is connected to the BPCS (DCS throttling), which allows for typical non-safety use. Meanwhile, the safety PLC is actively monitoring conditions so in the case of a safety demand, it will command the solenoid valve to act and override the BPCS to take the valve to its safe state

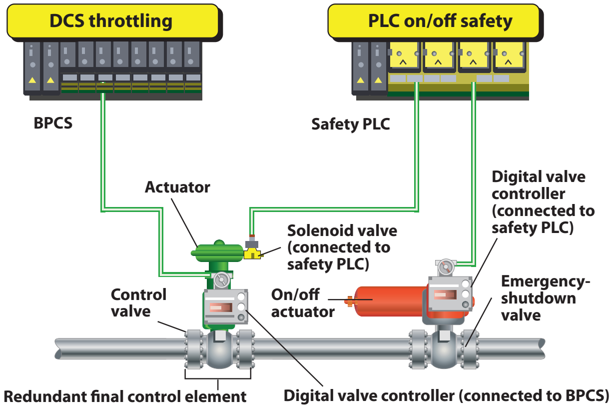

FIGURE 3. The primary emergency shutdown valve is pictured on the right, with the digital valve controller responding to signals from the safety PLC. The redundant final control element is shown on the left, which is pictured as dual use, with the digital valve controller positioning to the BPCS (DCS throttling), and the solenoid valve connected to the safety PLC

tificates or generically available. This failure rate information can be used to calculate the probability of failure upon demand (PFD), which can be correlated to a safety integrity level (SIL). The use of a control valve as a safety valve provides economic efficiencies, too, by increasing the number of common parts that are maintained in inventory, assuming that the SIS final control element is the same product as the one used in the BPCS.

Configuration 2: Single control valve shared for safety and control. This particular application of a final control element should be considered with great care. IEC 61511 sets strict guidelines and advises that the user should, whenever possible, keep the SIS independent and separate from the BPCS. Figure 2 shows the final control element with digital valve controller that is designed as part of a BPCS throttling control. The valve also has a solenoid that the safety logic solver commands to perform its safety function upon demand.

The advantage of this configuration is that the final control element is essentially self-testing. As the valve is expected to throttle to perform its BPCS function, the end user can be confident that the valve is able to move when commanded. Another advantage is the resulting cost savings that come from having only one valve perform both BPCS and SIS functions, as well as the benefit from having common parts with other BPCS valves in the facility.

However, the limitation associated with applying a control valve in this fashion is that the valve working for the BPCS cannot cause the safety event that the valve is expected to address in the SIS. In other words, the final control element cannot be the cause of the problem it is expected to mitigate — rather, it can only be used for a safety function that is completely independent of its purpose as a control valve with the BPCS. For this reason, this type of application is technically a less-viable option, and should only be utilized with a complete and thoroughly considered up-front analysis (including process suitability, HAZOP and safety-lifecycle analysis) that ensures that this potential conflict between BPCS and SIS will not exist.

Configuration 3: Control valve used as a redundant element. A control valve can also be used as a redundant element to an emergency shutdown valve. Figure 3 shows the control valve connected in a similar way to what described in Configuration 2. The digital valve controller provides throttling control, and the solenoid valve waits for a signal from the safety logic solver to perform the final control element's safety function.

Figure 3 also shows a second valve in series. Both valves will perform the safety function upon a safety demand, however, in the case that one experiences an issue and cannot perform the safety function, having a redundant valve improves the likelihood that the process will be shutdown safely. Two final control elements in a redundant configuration can also be solely used to perform the SIF and not be dual use (this is not pictured).

The scenario shown in Figure 3 will be a fail-closed valve. For a fail-open configuration, the redundant elements should be in parallel, both valves would be designed to be normally closed, and both final control elements would be connected to the safety logic solver ready to respond to a safety demand.

The advantage of using a control valve as a redundant safety element is that redundancy, when implemented correctly, improves diagnostic coverage and can improve the SIL rating. The primary drawback of this type of design is the cost of purchasing and maintaining multiple final control elements, as well as increased risk of spurious trips. ■

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Consider Wet Agglomeration To Improve Powder Flow

One way to avoid the flow problems associated with fine particles is to enlarge them

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Jenike & Johanson

Chris Kozicki,
Feeco International

FIGURE 1. Fine potash powder is one example of an application that can benefit from particle enlargement

Agglomeration is the process of converting fine powder particles into larger particles by the introduction of external forces. Agglomeration is often desirable because the process yields a product that has a higher bulk density, contains less dust, and has improved flowability. Figure 1 shows samples of fine potash powder and powder that has been agglomerated.

Fine powders often exhibit flow problems in a hopper, bin or silo, such as flow stoppages, erratic flow, flooding and limited discharge rates. Flow stoppages occur when attractive forces between particles, such as Van der Waals forces, valence forces and hydrogen bridges, cause a cohesive arch to develop at the vessel outlet. In some cases, powder may only flow in a narrow channel when a feeder or gate is operated. If the material has enough cohesive strength to become stable as the flow channel empties, flow stoppages will occur when powder along the walls remains stagnant. Erratic flow results when ratholes collapse, causing the powder to arch as it impacts the outlet. (For an illustration of arching and ratholing, see the online version of this article at www.che.com.)

If a stable rathole forms in a hopper, bin, or silo and fresh powder is added, it may become entrained in the air and become aerated. Because most feeders are designed to handle solids and not fluids, flooding may result when the fluidized material reaches the outlet. Flooding can also occur when ratholes collapse into an emptying flow channel. A fine powder sometimes cannot be discharged at the desired rate due to its low permeability, which leads to an adverse pressure gradient at the outlet of the vessel and gas flowing counter to the solids.

Particle size and flow patterns

The manner in which a powder flows in a hopper, bin, or silo has a great effect on the likelihood of these solids flow problems occurring. There are two primary flow patterns that can occur in a bin or silo: mass flow and funnel flow. (See the online version of this article for an illustration of these flow patterns.) In funnel flow, an active flow channel forms above the outlet, with stagnant material remaining at the periphery. Funnel flow occurs when the walls of the converging section of a vessel are not sufficiently steep or low enough in friction for the powder to flow along them.

Mass flow occurs when all the powder inside a vessel is in motion whenever any is withdrawn, and takes place when the walls of the hopper section are steep enough and low enough in friction for the powder to flow along them. As long as the outlet is large enough to prevent arching, all the powder flows when material is discharged, keeping the contents of the bin fully live.

Funnel flow can cause erratic flow, exacerbate segregation and reduce the live capacity of a vessel. Funnel flow can also induce high loads (depending on vessel size) on the structure and downstream equipment due to collapsing ratholes and eccentric flow channels. In addition, if the narrow flow channel empties out, a stable rathole may form. With fine powders, controlling flowrate is often challenging. Since a funnel flow channel is often unstable, its size can change dramatically or it may collapse, creating flowrates that range from no flow at all to complete flooding. In addition, the bulk density at the outlet will vary significantly over time.

Eliminating flow problems can often be accomplished by ensuring that a mass flow pattern exists in the vessel. Stable ratholes cannot form and because the material is more likely to de-aerate, flooding is less likely. In addition, the bulk density of the discharged powder is less variable.

Mass flow hoppers, bins and silos designed to handle fine powders frequently require steep walls and large outlets due to the material's high cohesive strength, high wall friction and low permeability. Often particle size enlargement allows mass flow vessels to be built with smaller outlets (allowing less expensive feeders to be used), walls that are less steep (which is advantageous if there are height restrictions) and less expensive wall materials.

Designing for mass flow

The flow pattern inside a hopper, bin or silo — funnel flow or mass flow — can be predicted by measuring the friction

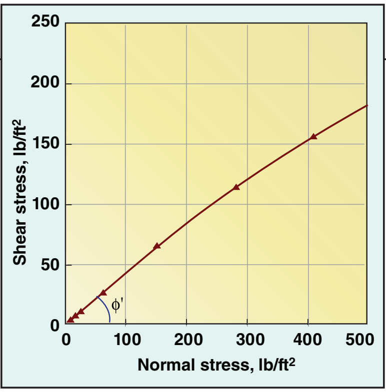

FIGURE 2. The wall yield locus, plotted here for a sample of fine potash powder, is a function of a material's wall friction properties

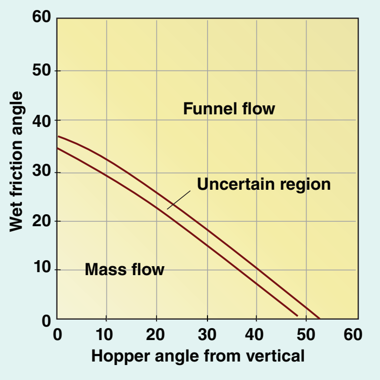

FIGURE 3. In design charts, such as this one for conical hoppers, any combination of wall friction angle (ϕ') and allowable hopper angle (θC) that lie within the mass flow region of the chart will provide mass flow

COMMONLY USED BINDERS

Inorganic binders

Alkali silicates
Gypsum
Alum
Lime
Bentonite and other clays
Lime hydrate
Caustic soda
Magnesia/magnesium oxide
Colloidal alumina and silica
Magnesium chloride
Cement
Plaster of Paris
Dolomite
Sodium borate
Fuller's Earth

Organic binders

Asphalt
Maltose
Asphalt emulsions
Molasses
Cellulose
Paraffin
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Coal tar
PVA (polyvinyl alcohol)
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Gelatine
Starches
Lignosulfonates (lignin)
Sucrose

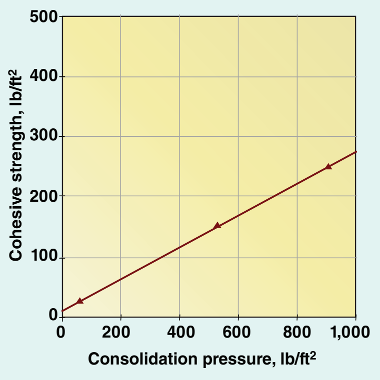


FIGURE 4. The relationship between cohesive strength and pressure is called the flow function, and is shown here for fine potash powder

between the powder and the hopper wall material. Wall friction is measured by a method described in ASTM D-6128 [1]. Various normal loads are applied to a sample of powder, which is forced to slide along a coupon of wall material. The resulting shear force is measured as a function of the applied normal force, and a wall yield locus is constructed by plotting shear force against normal force. The angle of wall friction at a particular pressure (ϕ') is the angle that is formed when a line is drawn from the origin to a point on the wall yield locus. A wall yield locus for a sample of fine potash powder on 304, No.-2B finish stainless steel is given in Figure 2.

Design charts originally developed by Jenike [2] provide allowable hopper angles for mass flow, given values of the wall friction angle. An example chart for conical hoppers is shown in Figure 3. Values of the allowable hopper angle (θC; measured from vertical) are on the horizontal axis, and values of the wall friction angle (ϕ') are on the vertical axis. Any combinations of ϕ' and θC that lie within the mass flow region of the chart will provide mass flow.

Designing right to the limit of the mass flow region is not recommended for conical bins. If the combination of wall friction angle and hopper angle lies too close to the funnel-flow line, a switch to funnel flow can occur. Hence, a 4–5 deg margin of safety is employed with respect to the mass flow boundary. For the potash powder whose wall friction properties are described by Figure 2, a conical hopper with walls sloped 12 deg from vertical is recommended to ensure mass flow.

Flow stoppages will be prevented if the stresses imparted on an obstruction to flow (such as a cohesive arch or stable rathole) are greater than the cohesive strength that the material gains due to its consolidation in a hopper, bin or silo. The cohesive strength of a bulk solid can be determined using the method described in ASTM D-6128 [1] where a direct shear tester is used to measure the shear strength of a material under varying consolidation pressures. The relationship between strength and pressure is called the flow function. The flow function for a sample of fine potash powder is shown in Figure 4.

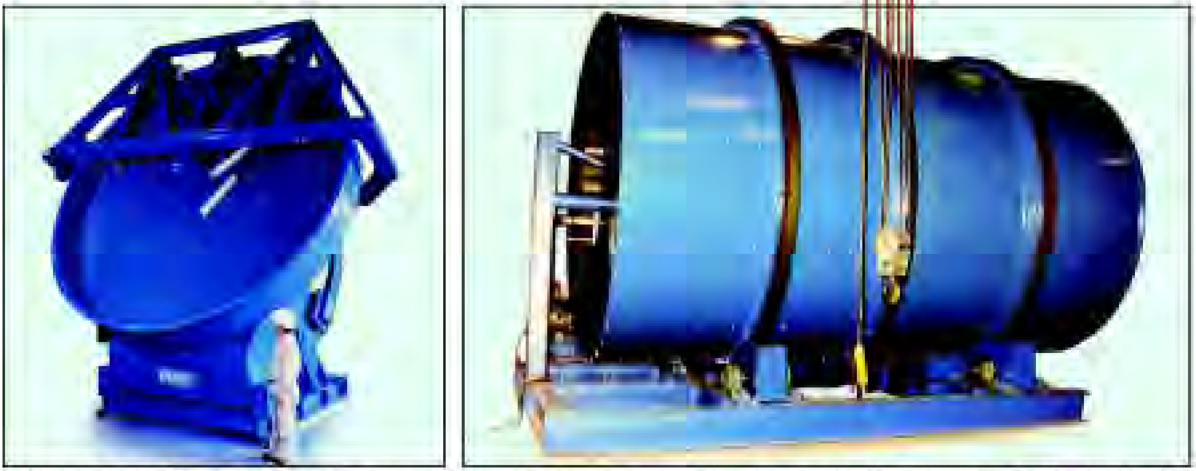
The stresses imparted on an arch of powder that forms at the vessel outlet are proportional to the material's bulk density. Once a material's flow function has been determined and its bulk density has been measured, the minimum outlet diameter that will prevent a cohesive arch from developing can be calculated using an analysis developed by Jenike [2]. For the powder whose flow function is given in Figure 4, the analysis shows that a conical mass-flow hopper requires a 6-in. dia. outlet to prevent arching. Note that this outlet diameter will prevent arching but does not ensure that the desired discharge rates can be achieved. Fine powder flowrates are limited because of high permeability, as discussed in Johanson [3].

Wet agglomeration processes

Wet agglomeration processes combine powder, liquid (usually water) and, if necessary, a binder, imparting shear to form agglomerates. Also known as tumble-growth agglomeration, wet agglomeration processes (Figures 5 and 6) include rotating drums, disc or pan agglomerators, pin and ribbon mixers, and fluidized beds.

In general, particle size enlargement by wet agglomeration occurs in three stages. The first is a mixing stage where powder, liquid and binder are combined. Next, moist particles are joined together to form so-called green agglomerates. Drying or curing takes place in a final stage. The wet agglomerates are formed by first forming nuclei that then grow into larger aggregates by layering or coalescence. In some cases, nucleation and aggregate growth take place in two separate pieces of equipment that are operated in series.

Nucleation gives rise to seed par-



FIGURES 5 and 6. Wet agglomeration processes combine powder, liquid (usually water) and, if necessary, a binder, imparting shear to form agglomerates. Here, disc (left) and drum (right) agglomerators are shown

ticles, which are formed when several individual particles adhere to each other. The nucleation stage can be time-consuming because the seed agglomerates are weakly bonded and readily disintegrate back into individual particles. Eventually, larger aggregates are formed when small agglomerates coalesce or individual particles adhere to larger agglomerates. Once larger agglomerates are created, growth becomes accelerated as the increased mass and higher kinetic energy of agglomerates cause them to pick up individual particles more rapidly and incorporate them onto their surfaces. The relative rates of size enlargement (nucleation, coalescence and layering) and size reduction (attrition and consolidation) establish the final particle size along with the material's tendency to wick moisture from its core to outer layers.

The optimal amount of liquid added to a powder — the amount that gives the resultant agglomerates their greatest integrity and resistance to breakage — is typically 40–90% of its liquid saturation. The liquid saturation is the fraction of total void space that can be filled with the liquid. When water (or another liquid) is added to a dry bulk solid, liquid bridges will begin to form at contact points between particles. This is known as the pendular stage of saturation. All free moisture is attracted to the interfaces between the solid particles by capillary effects, and surface tension draws the particles together. As saturation levels are increased, the funicular stage is eventually reached where all internal solid surfaces become surrounded by liquid. At this point, the mixture becomes more fluid-like, tensional forces disappear, and the agglomerates become weaker. When the powder becomes fully saturated, it reaches its capillary state, and at higher moisture levels, the system begins to behave as a slurry. Saturation states of powder are illustrated in Figure 7.

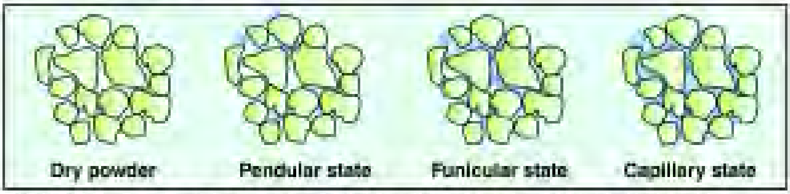
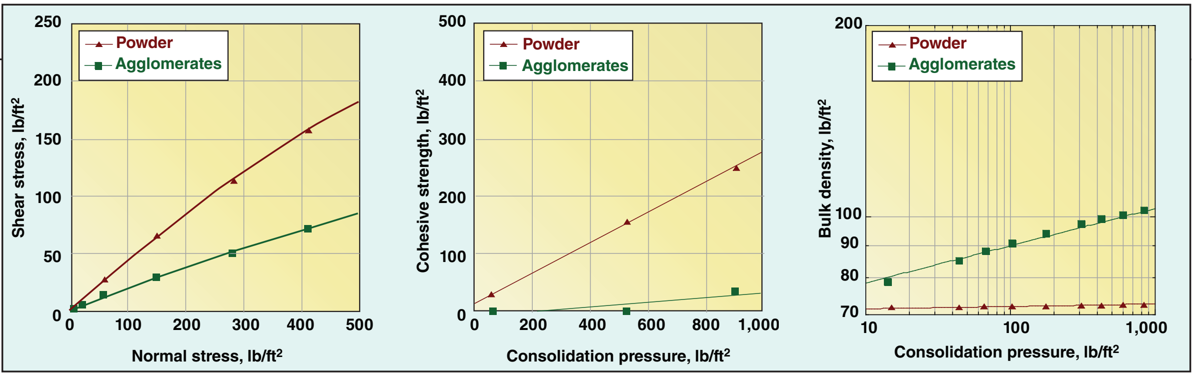


FIGURE 7. The liquid saturation is the fraction of total void space that can be filled with the liquid. The four saturation states of powder are shown here

An under-saturated bulk solid can be converted to a saturated state by compaction (dry agglomeration) alone, without further addition of moisture [4]. Likewise, pendular and funicular states of the same powder can be reached at different moisture contents. Hence, the optimal amount of liquid that must be added to a powder to resist breakage often depends on the device, scale and properties of the material undergoing agglomeration.

Often, binders are added prior to or during agglomeration to increase the strength of the agglomerates. Binders are generally liquid solutions, suspensions of fine solids, or dry powders. Commonly used inorganic and organic binders, are listed in the box (opposite page) [5, 6]. Highly viscous binders, such as colloidal silica, are effective since both the adhesive forces at the binder-solid interface and the cohesive forces within the viscous binder act to strengthen the aggregates. Solid bridges form when dissolved matter in liquid bridges precipitate during cooling or drying. Similarly, colloidal particles form solid bridges when they become concentrated in diminishing liquid bridges and become consolidated due to the liquid's surface tension.

Even if a binder has no solid components, drying may still increase the strength of the agglomerates by drawing the particles closer together, because capillary forces associated with the interstitial liquid increase as the liquid content is reduced. Once in close proximity, the magnitude of Van der Waals and other molecular forces between adjacent individual particles increases. This leads to further densification and greater integrity of the agglomerated product. In some



FIGURES 8. Agglomeration reduces the cohesive strength (left) of potash, reduces its wall friction (center) on 304, No.-2B finish stainless steel and also increases its bulk density (right)

instances, a material to be agglomerated has natural binding properties that are simply activated by the addition of moisture.

As a general rule, flowability improves with increasing particle size. Cohesive strength usually increases with decreasing particle size due to greater specific surface-area and a greater number of contacts between particles. There are many exceptions to the rule; for instance, sub-micron particles are often added to powders as parting agents to increase the distance between individual particles and reduce the magnitude of interparticle forces. Fortunately, shear cell testing is straightforward, and cohesive-strength and wall-friction tests can be quickly conducted to confirm the potential benefits of particle size enlargement on a material's flowability.

As an example of improved flowability that can result from agglomeration, potash was agglomerated on a continuous basis by adding fine powder, water and a dry organic binder to a pin mixer, followed by a disc agglomerator, and finally a direct fired rotary dryer. The resulting pellets were then screened to separate the desired pellets (Figure 1) from the undersize and oversize fractions. The green agglomerates contained 8–14% moisture and 1.5–3.5% binder.

The cohesive strength, wall friction and bulk densities of the fine potash powder and agglomerates of potash are compared in Figure 8. Note that agglomeration reduces the cohesive strength of potash, reduces its wall friction on 314, No.-2B finish stainless steel, and increases its bulk density. Powders with lower strength, less friction, and higher bulk density flow more readily.

While a 6-in. dia. outlet is recommended to prevent the fine powder from arching in a conical hopper, the shear cell tests and subsequent analysis reveal that cohesive arching will not occur in a hopper, bin, or silo that handles the agglomerated product. Instead, the outlet size of a vessel that handles the agglomerates should be selected by consideration of particle interlocking or desired discharge rates. In addition, the agglomerated material requires significantly less-steep walls to allow mass flow. If a conical hopper, bin, or silo with a 6-in. dia. outlet is fabricated or lined with 304, No.-2B finish stainless steel, walls sloped 25-deg from vertical are recommended to ensure mass flow (versus 12-deg if the material is handled in a fine powder form).

Final remarks

Flowability of fine powders is often improved by agglomeration. Agglomeration results in powder with a higher bulk density and often reduces its cohesive strength and wall friction.

A key to producing quality agglomerates in a wet process is to ensure that the proper ratio of powder, moisture and binder is used. If insufficient liquid is added, layering is difficult, and excess dust in the product is produced. If liquid content is too high it will yield agglomerates with poor integrity, as the bonds between individual particles will be weak.

In a continuous wet-agglomeration process, the hopper that feeds the equipment should also be designed for mass flow to ensure its reliable operation since the performance of most agglomeration systems is strongly influenced by feedrate of the powder and any binder used. In mass flow, the bulk density of the powder is independent of the level of powder inside the hopper, flowrates are steady (assuming that the outlet is large enough to prevent flowrate limitations that result from counterflow of air), and ratholes cannot form. The proper ratio of powder, moisture and binder is easier to maintain if systems designed for mass flow are used, which allow agglomerates with the greatest integrity to be produced. ■

Edited by Rebekkah Marshall

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Effective Plant Safety Management

Three critical junctures and seven critical steps for plant safety are outlined

Nasim Hassan
HSN Associates of Delaware

Although plant safety should be a top priority every day, there are certain times when extra vigilance is needed to make sure that safety practices are being maintained. This article outlines three periods deemed to be "critical" for plant safety and specific items to pay attention to in these periods.

Three critical periods

The following three phases in a production plant's life are potentially critical in regards to safety practices:

Transition. The first period deemed to be critical is the transition phase when a company acquires a production plant, petroleum refinery or any other manufacturing facility. During this period many experienced people leave the company while new management is learning the details of plant operations.

Restructuring. The second period is a phase of restructuring, when due to slow economic conditions the demand for a product has slowed down. The company needs to save operating and maintenance costs. During this period some sections or the whole plant may be shut down.

Routine. A third period that comes to mind is when the plant operation becomes routine and inexperienced people are allowed to take over and run the facility. The experienced staff relaxes and becomes less vigilant in reviewing plant safety on a regular basis.

Seven essential elements

During the periods mentioned above, it is particularly important for managers to include the following elements in their management of plant safety.

1. Review of technology. Whenever a plant is acquired, a thorough review of the acquired technologies must be made. Typically, companies feel confident in acquiring facilities when they are operating similar plants or manufacturing similar products. For example, a petroleum refining company taking over another refinery has good knowledge of refinery operations. However there are several different process technologies available for the same operations or reactions. For example, there are many different alkylation processes in operation to produce motor and aviation fuels.

Similarly in petrochemical production, such as for vinyl chloride, there are many routes for the same reactions and intermediate products. Some technologies employ fixed beds for oxychlorination while others use fluidized bed reactors. A review of process technologies will reveal the differences in the technology and operating procedures. Once the differences have been identified, then all plant operators must be trained in all new technologies.

2. Plant operating procedures. Experience shows that the same plant can be started in a number of ways. All companies develop operating procedures to start up and shut down a plant. New procedures are certainly needed when the unit operations are different in plants where a different technology is employed. I have seen a wide variety of processes for ethylene, polyesters, vinyl chloride and polyvinyl chloride (PVC). There are similar examples of various processes in petroleum refining. The operating procedures also differ depending on the complexity of the plant. Operating procedures should be updated on a regular basis.

3. Review of safety interlock and shutdown systems and procedures. The safety interlocks and shutdown systems are developed after comprehensive hazards and operability studies. Many are introduced after actual plant experience. These interlock systems must be reviewed and upgraded if required.

All major companies control and operate their plants based on their in-house development. A thorough review will certainly improve the existing systems due to the combination of expertise from merged or acquired companies. I have seen many times that safety interlocks are bypassed because new plant operators did not understand the rationale behind the safety interlocks.

4. Review of corrosion control systems. Control of corrosion in plant equipment is intricately linked with

PLANT SAFETY RECOMMENDATIONS

While plant safety should always be given top priority, safety audits are particularly recommended during the transition phases of mergers and acquisitions. Safety audits also become important when experienced engineering staff is reduced due to restructuring or retirement. In fact, experienced engineers should conduct training programs for plant operators and engineers before they retire. This small investment will help reduce potential operating problems and industrial accidents. ❑

plant safety. There are many kinds of corrosion protection systems employed in chemical and petrochemical industries. These systems are developed after years of plant experience. This is an area that is often ignored when chemical plants or petroleum refineries are sold to new owners.

I have seen plants with near-perfect safety records lose that record within months of acquisition by new owners. Looking deeply into the reasons, I found that plant engineers and operators did not understand the function of various corrosion protection systems. In a vinyl chloride plant, for example, the overhead condenser for an ethylene dichloride distillation column was protected by the circulation of dilute caustic solution. After a new owner took over the facility, the circulation of caustic was stopped because the inexperienced engineers did not understand its role in preventing corrosion in the condenser and overhead piping.

5. Training of plant engineers and operators. This area also gets sidelined, particularly in old facilities. Experienced engineers take it for granted that young engineers will learn with hands-on experience. They can certainly learn the plant operation, but may not understand why the system was designed in a certain way.

There should be an ongoing training program for new engineers and even experienced engineers if new technology is introduced in a plant. The review of various reactions and side reactions, optimum operating conditions, limits and safety precautions should be essential for every person. In older facilities, there is a wealth of information available but only experienced people know how to access it. Training materials should be easily accessible to all new operators.

6. Review of past incidents and investigative reports. My experience shows that the same problems occur over and over again in the same facility. People are alert for a few years after an accident. Then safety reports get filed away and forgotten. A new company taking over old facilities is busy with big ticket items. Plant safety records and reports are reviewed at a much later stage.

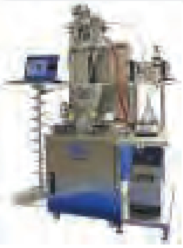
I recommend a thorough review of a plant's past safety history, followed by a plant safety audit that looks at the particular areas where past accidents have occurred.

7. Implementation of EPA (U.S. Environmental Protection Agency) and OSHA (U.S. Occupational Safety and Health Admin.) Standards. This should be a priority in any plant, and needs to be given top priority during the plant shutdown period. I have seen vent scrubber systems shut down because a plant is not routinely sending any hazardous vapors to the vent scrubber. However, there may be some storage tanks or vessels containing hazardous materials. These materials are vented to the scrubbers in overpressure conditions. If the vent scrubbers are shut down, then severe environmental and health related incidents can occur. ■

Edited by Dorothy Lozowski

Author

Nasim Hassan is a consultant (HSN Associates of Delaware; 7 Signal Hill Drive, Hockessin, DE, 19707; Phone: 302-239-9272; Email: nhassa@yahoo.com; Website: www.hsnrcs.com) in chemical technology licensing, plant safety, process analysis, process simulation and process design. He has over 35 years experience in the design and operation of chemical and petrochemical plants. Hassan has worked for BE&K Engineering (a KBR subsidiary), ICI Americas and Stauffer Chemical Co. as senior staff engineer and project manager. He has designed and started up a number of chemical and petrochemical plants for licensees in Africa, Asia, Europe and the U.S. Hassan has an M.S.Ch.E. from the Institute of Chemical Engineering, Punjab University, Pakistan and is a member of AIChE.



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This newly introduced, horizontal rotary extension (photo) provides the ability to install a rotary through the side of a bin wall (such as those in concrete silos) up to 12-in. thick. This optional assembly includes an extended drive shaft with a protective shaft guard that keeps the shaft centered and a "no packing" seal at the end of the shaft. Standard lengths of 6, 8, 10 and 12 in. are available. When fitted with the manufacturer's collapsible paddles, the rotary can be easily installed through an existing 1.25- or 1.5-in. opening. The horizontally extended rotary design also features a unique protective bearing at the end of the shaft extension that forms a seal between the rotary shaft and the shaft guard. This bearing prevents bin material from getting packed up into the extension and causing the rotary to give a false "full" signal when the paddle stops turning. — *BinMaster, Lincoln, Neb.*

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This radar sensor offers advantages for water applications

The new radar sensor Vegapuls WL 61 was conceived especially for use in water supply and distribution systems and is an alternative to ultrasonic systems. The tightly encapsulated cable and robust housing make the high protection rating of IP 66/68 (1 bar) possible. Thanks to the different mounting options, the sensor can be easily integrated into existing infrastructure. The measurement data can be transmitted either directly to an existing control system or to a signal conditioning instrument that provides suitable relays for pump control. — *VEGA Grieshaber KG, Schiltach, Germany*

www.vega.com

A digital level controller provides easy access to information

In addition to displacement sensor technology for measuring liquid level or the level of interface between two liquids, the Fieldvue DLC3020f (photo) uses the digital Foundation Fieldbus communication protocol to deliver diagnostics, alerts, and other information. The capability to select and define process fluids allows on-the-fly fluid changes for batch or continuous applications without calibration. The DLC3020f is designed to directly replace pneumatic, analog or HART transmitters and controllers. — *Emerson Process Management, St. Louis, Mo.*

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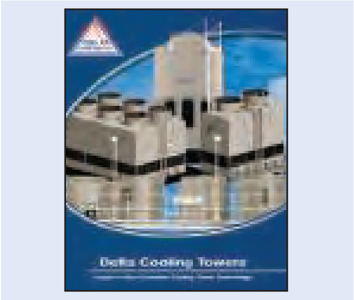

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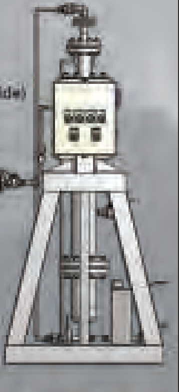

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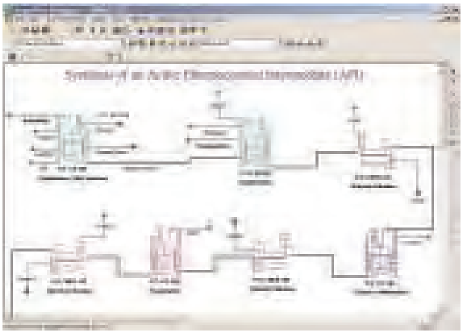


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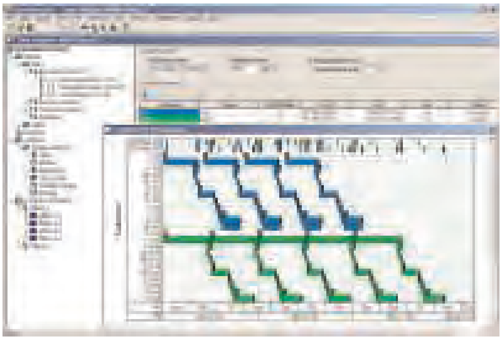

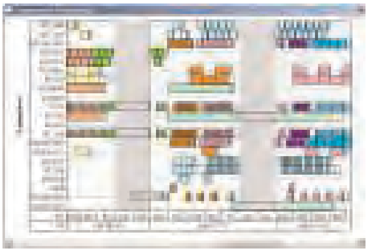

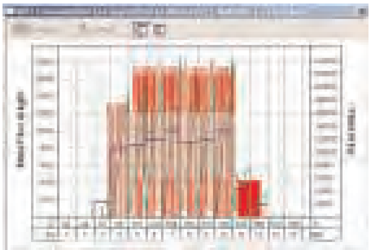

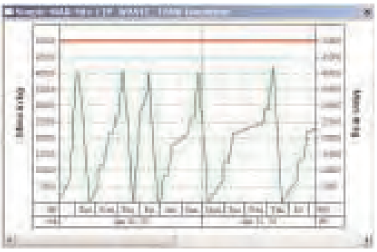

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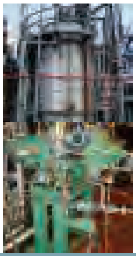

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08 Organic Chemicals
09 Agricultural Chemicals
10 Petroleum Refining, Coal Products
11 Rubber & Misc. Plastics
12 Stone, Clay, Glass, Ceramics
13 Metallurgical & Metal Products
14 Engineering, Design & Construction Firms
15 Engineering/Environmental 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
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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

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BUSINESS NEWS

PLANT WATCH

Dow to increase ethane cracking capabilities

December 3, 2010 — The Dow Chemical Co. (Midland, Mich.; www.dow.com) plans to increase ethane cracking capabilities on the U.S. Gulf Coast and improve its ethane cracking capabilities by 20–30% over the next two to three years. In addition, Dow announced it is reviewing joint venture (JV) options for building a natural gas liquids (NGL) fractionator to secure this supply of ethane.

BASF builds production facility for battery materials

November 16, 2010 — BASF SE (Ludwigshafen, Germany; www.basf.com) has commenced construction of a more than $50-million production facility for innovative cathode materials for lithium-ion batteries used to power hybrid and full-electric vehicles. The facility, in Elyria, Ohio, is being built with the help of a $24.6-million grant from the U.S. Dept. of Energy (DOE; Washington, D.C.; www.energy.gov) under the American Recovery and Reinvestment Act.

Petrobras selects UOP technology for two refineries

November 11, 2010 — UOP LLC (Des Planes, Ill.; www.uop.com), a Honeywell company, has announced that Petroleo Brasileiro S.A. (Petrobras) has selected UOP to provide all of the process technologies for two new, maximum diesel refineries. UOP hydrocracking and hydrotreating technologies will be used to produce high-quality diesel fuel from Brazilian national crude oils. Petrobras plans to construct a two-train, 600,000-bbl/d facility in Maranhão, Brazil, to be known as Premium I, and a single-train, 300,000-bbl/d facility in Ceará, Brazil, to be known as Premium II. Basic engineering for the refineries is currently under way. Commissioning of the first train at the Premium I facility is planned in 2014 and the Premium II facility in 2017.

JGC lands water-treatment project in Saudi-Kuwait neutral zone

November 11, 2010 — JGC Gulf International, JGC Corp.'s (Yokohama, Japan; www.jgc.co.jp) subsidiary in Saudi Arabia, has been awarded the Water Treatment Facilities – Phase 3 (onshore) project by Khafji Joint Operations (KJO), a JV between Aramco Gulf Operations and Kuwait Gulf Oil Co. JCG Gulf will perform engineering, procurement, construction (EPC) and pre-commissioning work for new water-treatment facilities for treating 170,000 bbl/d of produced water, new water injection facilities and utilities associated with KJO's crude processing facilities. The project is scheduled for completion in 2013.

Teijin to enter high-performance polyethylene market

November 10, 2010 — Teijin Ltd. (Tokyo; www.teijin.co.jp) will enter the high-performance polyethylene (HP-PE) market by establishing its first production facility in Emmen, the Netherlands, aiming to start commercial production in the second half of 2011. Teijin plans to grow its HP-PE business quickly through innovation and market cultivation, targeting a global market share of 15 to 20% by 2015.

SNC-Lavalin-led JV wins contract on Cobre Panama copper-mine project

November 8, 2010 — Joint Venture Panama (JVP), a JV led (70%) by SNC-Lavalin (Montreal, Canada; www.snclavalin.com), along with partners GyM S.A. (a member of Graña y Montero Group) (15%) and Techint International Construction Corp. (15%), has been awarded a contract by Minera Panama SA (MPSA), a 100%-owned subsidiary of Inmet Mining Corp. of Canada, to provide the engineering, procurement and construction management (EPCM) services for the development of the Cobre Panama copper mine project. The estimated capital cost of the project is over $4 billion. The process throughput at the Cobre Panama copper mine will initially be a nominal 150,000 ton/d, increasing to a nominal 225,000 ton/d from year ten. The mine life is expected to be 30 years.

Celanese to construct industrial-use ethanol plants in U.S. and China

November 8, 2010 — Following necessary approvals, Celanese Corp. (Dallas, Tex.; www.celanese.com) intends to construct one, and possibly two, industrial ethanol complexes in China. Initial production capacity of each complex is expected to be around 400,000 ton/yr, and production could begin within 30 months after project approvals. The China units would utilize coal as the primary raw material. Celanese also intends to build an approximately 40,000-ton/yr industrial-ethanol unit at its Clear Lake, Tex., facility. Following approvals, construction of the unit is anticipated to begin in mid-2011 and to be completed by the end of 2012. The Clear Lake facility would utilize natural gas as its primary raw material.

MERGERS AND ACQUISITIONS

BASF signs letter of intent with Ineos to form a joint venture called Styrolution

November 30, 2010 — BASF SE and Ineos Industries Holdings Ltd. (Lyndhurst, U.K.; www.ineos.com) have announced their intention to combine their global business activities in styrene monomers (SM), polystyrene (PS), acrylonitrile butadiene styrene (ABS), styrene-butadiene block copolymers (SBC) and other styrene-based copolymers as well as copolymer blends into a new JV called Styrolution. BASF and Ineos will continue to operate as strictly independent companies until the completion of the deal which, subject to the approval by the appropriate antitrust authorities, is anticipated in 2011.

...and plans to acquire CRI/Criterion's global styrene catalysts business

November 29, 2010 — BASF SE has signed an agreement to acquire the styrene catalysts business of CRI/Criterion (Houston; www.cricatalyst.com), a wholly owned subsidiary of Shell. Financial details of the transaction were not disclosed. Closing of the acquisition was expected to occur by year-end 2010, subject to all requisite regulatory approvals.

Evonik and SKC form a JV for H_2O_2 production

November 12, 2010 — SKC (Seoul, Korea) has acquired a 45% share in Evonik Degussa Peroxide Korea Co. (Ulsan), a subsidiary of Evonik Degussa GmbH (Essen, Germany; www.evonik.com). Evonik Degussa Peroxide Korea is the largest manufacturer of hydrogen peroxide in Korea.

BASF restructures paper-chemicals business

November 11, 2010 — BASF SE`s Paper Chemicals Div. (www.paper-chemicals.basf.com) will reorganize its global business structures. The business in optical brighteners for paper is to be exited in Europe, and it is planned to close the corresponding production operations at the site in Grenzach, Germany. In addition, BASF intends to relocate paper dye production from Grenzach to Ankleshwar, India. In the course of the relocation, the paper dye product range is to be reduced. The planned restructuring is expected to be implemented in the period from 2011 to 2013. ■

Dorothy Lozowski

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

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Economic Indicators

2010 🟦 **2009** 🟧 **2008** 🟩

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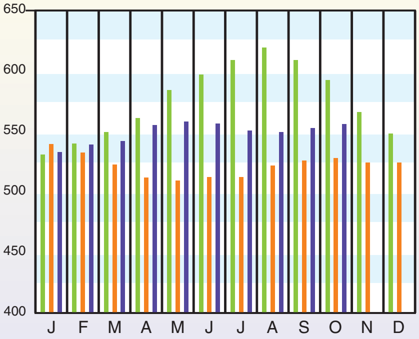
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Oct.'10 Prelim.	Sept.'10 Final	Oct.'09 Final
***CE* Index**	556.2	552.5	527.9
Equipment	667.5	662.3	623.6
Heat exchangers & tanks	617.8	611.8	567.0
Process machinery	627.0	625.1	605.5
Pipe, valves & fittings	840.2	834.1	768.9
Process instruments	426.0	422.0	409.8
Pumps & compressors	902.5	902.9	896.3
Electrical equipment	484.7	482.5	464.2
Structural supports & misc	689.6	680.9	636.5
Construction labor	330.6	328.9	331.7
Buildings	503.2	502.4	495.4
Engineering & supervision	336.6	337.3	344.6

Annual Index:

2002 = 395.6
2003 = 402.0
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9

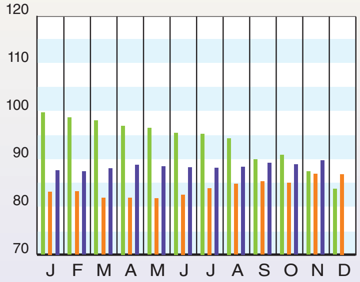
Starting with the April 2007 Final numbers, several of the data series for labor and compressors have been converted to accommodate series IDs that were discontinued by the U.S. Bureau of Labor Statistics



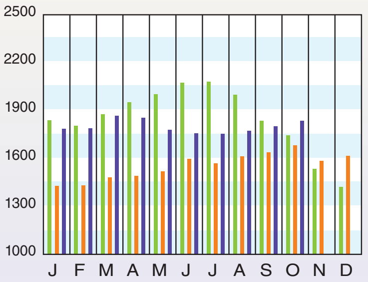
CURRENT BUSINESS INDICATORS

	LATEST			PREVIOUS						YEAR AGO		
CPI output index (2007 = 100)	Nov.'10	=	89.8	Oct.'10	=	88.9	Sept.'10	=	89.2	Nov.'09	=	86.9
CPI value of output, $ billions	Oct.'10	=	1,837.3	Sept.'10	=	1,802.8	Aug.'10	=	1,773.0	Oct.'09	=	1,681.7
CPI operating rate, %	Nov.'10	=	72.6	Oct.'10	=	71.8	Sept.'10	=	72.1	Nov.'09	=	69.5
Producer prices, industrial chemicals (1982 = 100)	Nov.'10	=	276.0	Oct.'10	=	267.6	Sept.'10	=	264.1	Nov.'09	=	247.0
Industrial Production in Manufacturing (2007=100)	Nov.'10	=	91.5	Oct.'10	=	91.2	Sept.'10	=	90.9	Nov.'09	=	86.8
Hourly earnings index, chemical & allied products (1992 = 100)	Nov.'10	=	154.7	Oct.'10	=	157.3	Sept.'10	=	159.2	Nov.'09	=	150.4
Productivity index, chemicals & allied products (1992 = 100)	Nov.'10	=	124.0	Oct.'10	=	122.2	Sept.'10	=	122.9	Nov.'09	=	119.6

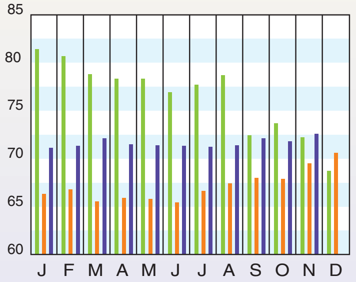
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



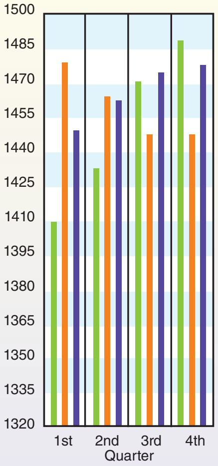
Current Business Indicators provided by Global Insight, Inc., Lexington, Mass.

MARSHALL & SWIFT EQUIPMENT COST INDEX

(1926 = 100)	4th Q 2010	3rd Q 2010	2nd Q 2010	1st Q 2010	4th Q 2009
M & S INDEX	1,476.7	1,473.3	1,461.3	1,448.3	1,446.5
Process industries, average	1,537.0	1,534.4	1,522.1	1,510.3	1,511.9
Cement	1,532.5	1,530.0	1,519.2	1,508.1	1,508.2
Chemicals	1,507.3	1,505.2	1,493.5	1,481.8	1,483.1
Clay products	1,521.4	1,518.3	1,505.6	1,496.0	1,494.3
Glass	1,432.7	1,428.5	1,416.4	1,403.0	1,400.1
Paint	1,545.8	1,542.1	1,527.6	1,515.1	1,514.1
Paper	1,447.6	1,444.5	1,430.1	1,416.4	1,415.8
Petroleum products	1,640.4	1,637.0	1,625.9	1,615.6	1,617.6
Rubber	1,581.5	1,579.3	1,564.2	1,551.0	1,560.5
Related industries					
Electrical power	1,434.9	1,419.2	1,414.0	1,389.6	1,377.3
Mining, milling	1,579.4	1,576.7	1,569.1	1,552.1	1,548.1
Refrigeration	1,809.3	1,804.8	1,786.9	1,772.2	1,769.5
Steam power	1,506.4	1,502.3	1,488.0	1,475.0	1,470.8

Annual Index:

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



CURRENT TRENDS

Capital equipment prices (as reflected in the *CE* Plant Cost Index) increased from September to October. Meanwhile, Global Insight's CPI output index, CPI value of output and CPI operating rate all increased in November.

According to the American Chemistry Council's (Arlington, Va.; www.americanchemistry.com) most-recent weekly economic report at *CE* press time, economic data being released "suggests that the soft patch is over," and points specifically to "strong gains in inorganic bulk petrochemicals and organic intermediates, and plastic resins."

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

Patent applications for polymer nanocomposites have increased by 375% in the last seven years.

Process Economics Program Report:
Polymer Nanocomposites

Polymer nanocomposites have garnered a great deal of interest from academia and industry in nanoscience and nanotechnology. In this new report, SRI Consulting's Process Economics Program (PEP) reviews the current state of polymer nanocomposites and focuses on nanoparticles and polymer nanocomposites that are already commercialized or have a commercial potential.

Continual progress has been made with commercialization in automotive, biological implants, sports equipment, packaging, and aircraft components. However, wide spread commercialization has moved at a slower pace than expected. Several critical technological challenges still need to be overcome, including reducing cost and significantly improving manufacturing technology. The field of polymer nanocomposites is still very much in the development phase. This report is a technology survey covering technology trends, the current state of literature covering manufacturing polymer nanocomposites, material properties and challenges. The status and potential applications, current markets and producers for polymer nanocomposites are reviewed. The report covers polymer nanocomposites containing clay-based and carbon-based nanoparticles, along with an overview of polymer nanocomposites containing other types of nanoparticles including metal oxide, polymeric, and cellulose nanoparticles.

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