INTERNATIONAL

FILTRATION NEWS

November/December 2012
Volume 31 No. 6
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Sonobond Offers the Widest Selection of Ultrasonic Bonding Machines for Filtration Assembly

Special Reports:

- Membrane Contactor Technology
- Electropositive Filtration as R/O Pretreatment
- Power Plant Wastewater Reuse
- Selecting Proper Wire Mesh
- Conference Reports from the USA and Europe

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Cover courtesy of Sonobond Ultrasonics

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Your Global Source

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AFS Conference Drills Into Fracking and Produced Water

David Engle of Nexo Solutions, The Woodlands, Texas, discusses processing natural gas at the AFS Fall Conference.

The American Filtration & Separations Society held its 2012 Fall Conference at the Embassy Suites Hotel in Philadelphia, Pa., October 15-18. The event was well attended with a diversified two-track varied program covering a wide range of new innovations and market trends. The focus of the conference was the timely topic of filtration, separations and coalescing in oil and gas recovery, including fracking and produced water, along with biotechnology and associated processes. Many of the fracking, oil/gas and produced water industry experts offered considerable insight from filtration media to filters along with emerging opportunities for suppliers of filtration and separation elements and equipment. The in-depth information into numerous inner-workings and unmet needs was an excellent educational experience for the uninitiated in this rapidly growing market.

COURSES AND CONFERENCE

Monday, October 15th began with a pre-conference Short Course day, with courses covering the subjects: Basics in Air/Gas Filtration, Basics in Liquid Filtration, Microporous Membrane Technology, Filtration & Separations Eight Principal Media and Markets, and Ultrafiltration Membrane Technology. The sessions were well attended as the AFS Short Courses continue to draw increased following. On Monday evening, the past AFS Chairman met once again to further develop and fine-tune the organizations Policy and Procedure Manual.

The main conference began Tuesday, October 16, with a plenary presentation by Antti Hakkinen from Lappeenranta University of Technology who offered a presentation on the subject of Design and Analysis of Filtration Experiments for those responsible for filter media and filter device R&D/product development. Tuesday's tracks consisted of 18 presentations covering Centrifugation, Coalescing, Filtration Media, Nanofibers, Membranes and Liquid Filtration on a variety of topics. Fol-


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Association | News

Between sessions all conference attendees shared informative times with the Tabletop Exhibitors. The following companies were exhibiting at the 2012 AFS Fall Conference: Delta Pure Filtration, Dorstener Wire Tech, Filtrona Porous Technologies, Franklin Adhesives & Polymers, Hitachi Zoren USA, LTD., I.F.T.S. Testing and Research, IBR Laboratories, Keystone Filter Division Met-Pro Corporation, Porometer NV, Quantachrome Instruments, TSI Incorporated and International Filtration News.

lowing the first full day of presentations was an Open Corporate Sponsors meeting where Corporate Sponsors and non-corporate sponsors learned of the progress made over the last two years, adding new benefit activities to drive end-users to AFS Corporate Sponsors and added emphasis in air filtration without diminishing AFS' historic emphasis on liquid filtration. A Networking Reception followed. As a result of the many new corporate benefits, AFS Corporate Sponsorships have increased from 21 in 2009 to 51 in 2012.

Wednesday began with a plenary session lead by Ron Bosch of Champion Technologies who provided detailed insight into the topic of Desalination of Unconventional Produced Water, which is a large and rapidly growing market in oil and gas production. The talk was a lead-in for the day's six sessions of four presentations each on the topics of Water Management, Pretreatment, Shale Gas and Produced Water along with the topics of Nanofibers and Membranes as used in specialty applications, in addition to two sessions on the keys to successful filtration and separations in Biotechnology. For the technologist, marketing or business development person, Wednesday was a very special day providing in-sight and specific detail into both emerging and existing higher-margin filtration business platform opportunities.

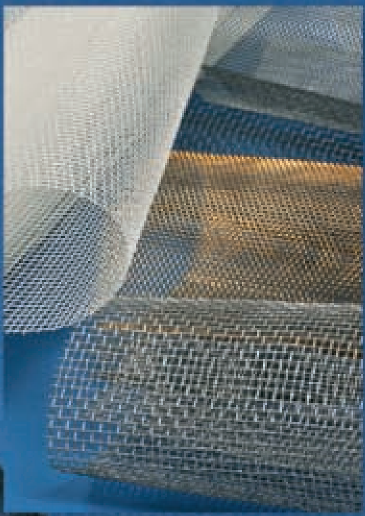
The conference concluded Thursday with a plenary presentation by Karsten Keller from DuPont on the subject of Smart Separations in Biotechnology. Additional sessions continued on the subjects of Biotechnology along with Filtration Media Testing and Procedures for several new and emerging industry filtration media coming to market.

UPCOMING CONFERENCES

The AFS also announced its 2013 slate of conferences. In May, the Society will meet for its Spring Conference in Bloomington, Minn., with a continuation of Advancements and Innovations in Filtration covering a number of topics. The Fall Conference, next October in Cincinnati, Ohio, will concentrate on Innovations in Filtration Media and Market Applications. Both conferences will concentrate on innovations with the AFS emphasizing leading and emerging industry technologies. The stated objective of the AFS is to provide those attending conferences, along with Corporate Sponsors, first-hand and early technology awareness. Watch for further conferences notices and topics for 2014 and 2015 before the end of the year. FN

The American Filtration & Separations Society is the largest Filtration Society in the world and the principal educator of the industry. For those interested in learning more about AFS Corporate Sponsorship, please contact Ed Gregor at 1-704-442-1940.

PHIFER Woven Mesh for Filters



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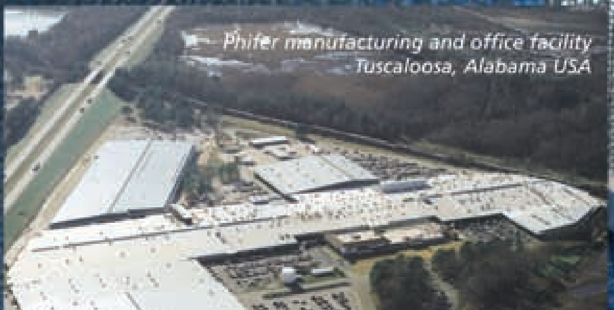

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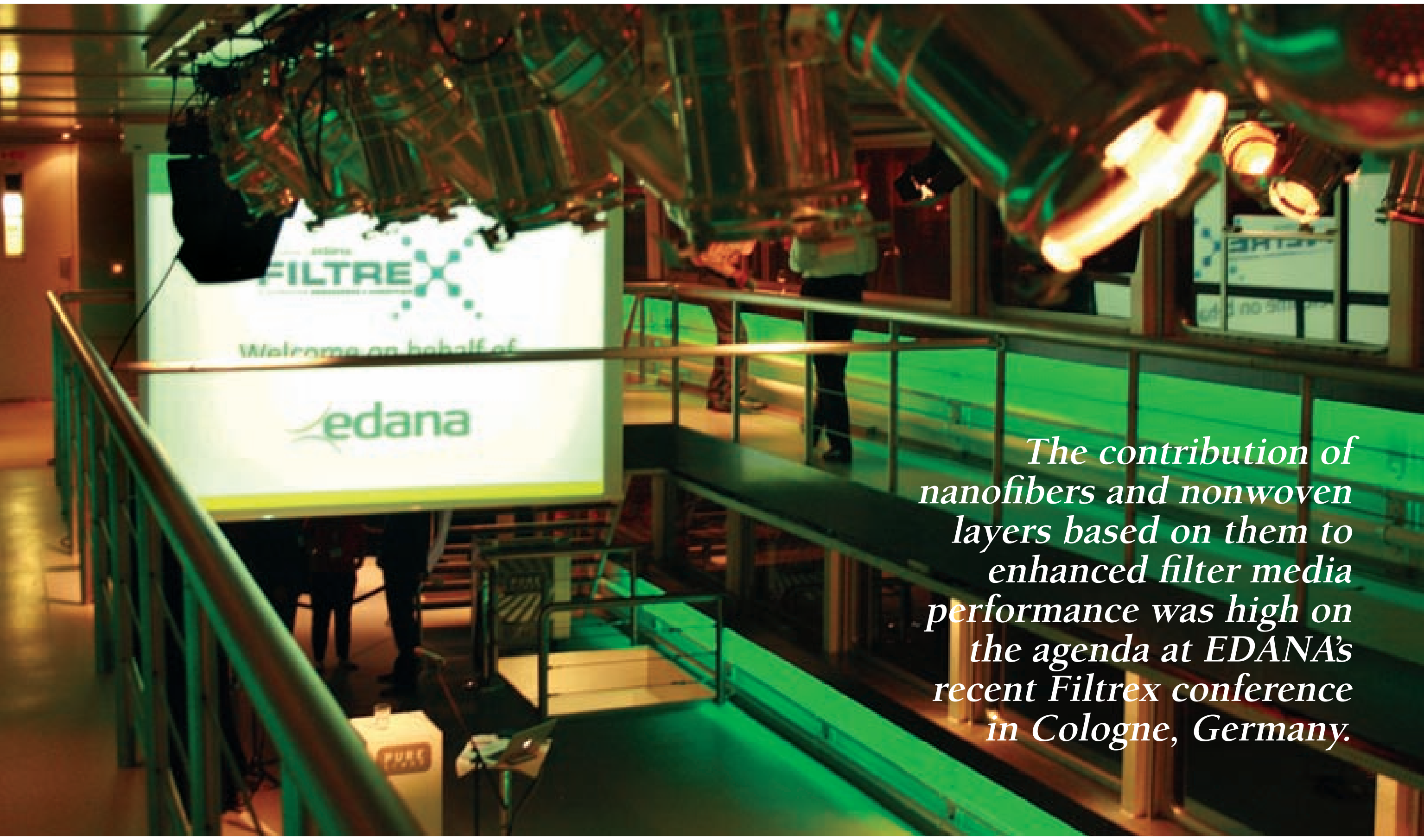
Nanofibers and Nonwoven Layers in Focus at Filtrex

By Adrian Wilson, European Correspondent



Jeanette Huber delivered her keynote address during an evening cruise down the Rhine from Cologne.

The invention of the automatic washing machine should not be underestimated.

This observation – first made by the famous Swedish doctor and academic Hans Rosling – was underlined by Jeanette Huber, Director of Germany's future-gazing Zukunfts Institute, in her keynote address at EDANA's Filtrex 2012 conference held in Cologne, Germany, from September 17-18.

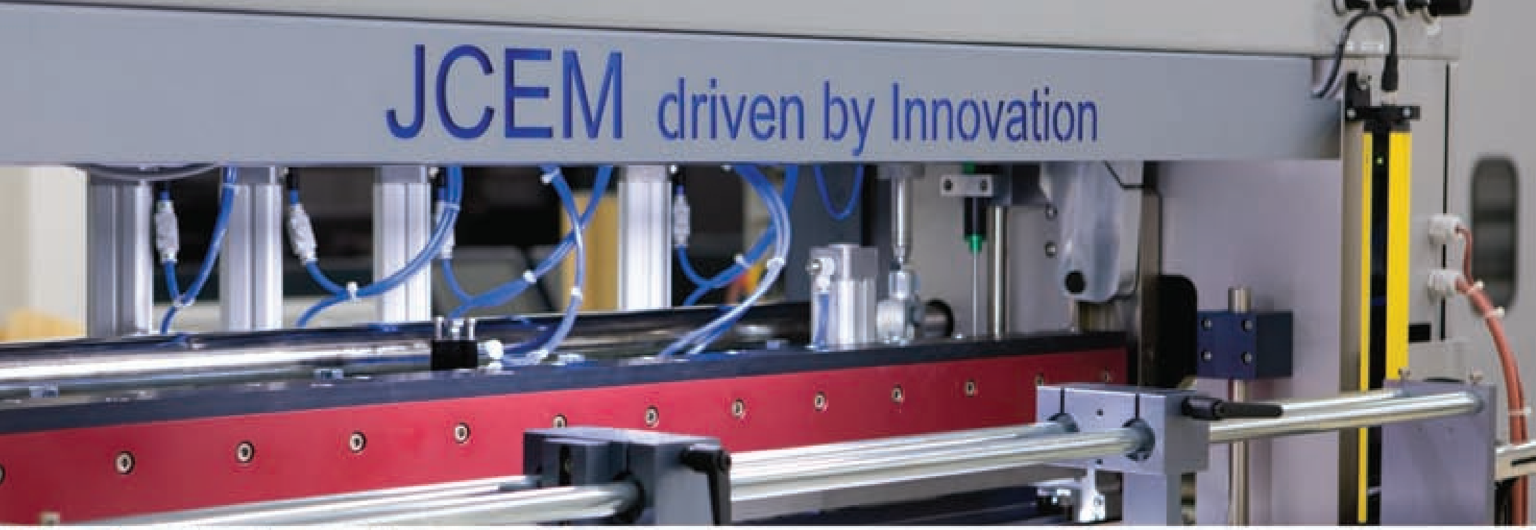
"In freeing up the time of countless generations of women to do better things with their time, the washing machine was a true innovation," she said. "Because true innovation always needs to be about making people happier and making their lives better – allowing for self improvement. Companies are always chasing growth while nations measure success by higher GDP, but above a certain level, GDP does not equate to increased happiness."

Wealth, she added, has taken millions out of poverty, but there are, for example, still 900 million people without access to clean water around the world.

It is in directly addressing such problems, she implied, that companies in fields like filtration need to take a leading role in innovation.

NANOFILTRATION

One key area in which there continues to be much development work is in nanofibers and the addition of them in nonwoven layers to filter media. In a second keynote Filtrex address, Kent Hofacre provided details of his work with colleague Aaron Richardson at the Battelle Memorial Institute – the world's largest non-profit R&D organization headquartered in Columbus, Ohio – in



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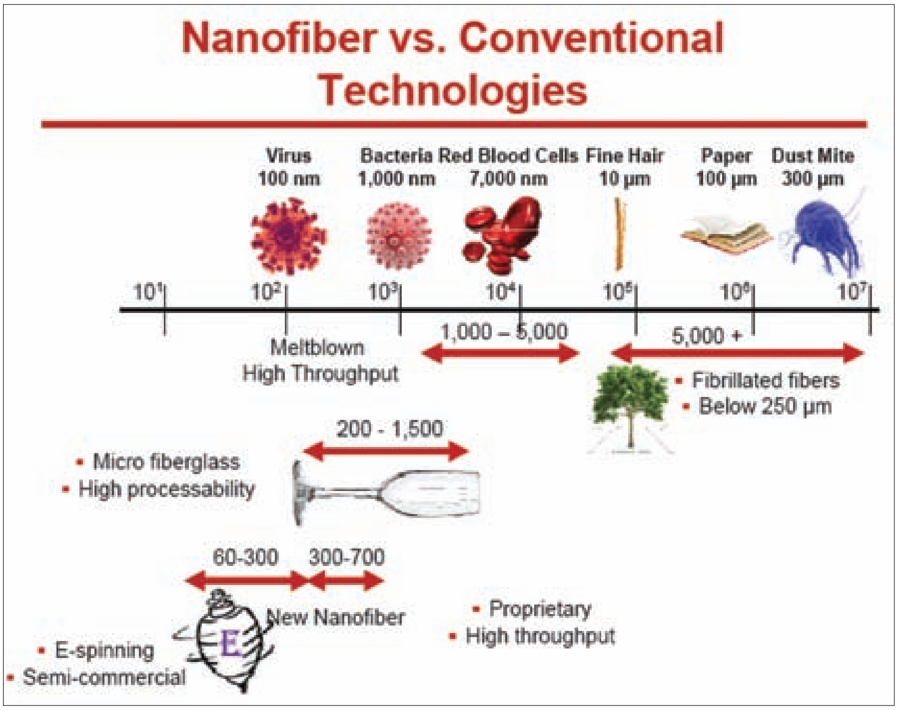


identifying what is known as 'the thermal rebound'.

In terms of filtration efficiency, the effectiveness of nanofibers in filters is expected to improve as their size gets smaller, he explained, and when they go below 100 nm their increased efficiency in capture becomes in part due to Brownian diffusion. But at some point, the particles begin to behave more like vapor and collection efficiency declines – the thermal rebound.

Determining at what size this occurs has already been the subject of a number of research papers, which were cited by Mr. Hofacre. In aerosol filtration, which has been the focus of his work with Richardson, the parameters that influence filter collection efficiency include:

- Fiber diameter
- Electrostatics
- Filter thickness
- Filter solidity
- Aerosol size distribution
- Filtration velocity (surface area)

"In addition to identifying at what particle size this thermal rebound occurs, we have tried to determine the relative contributions of electrostatic and diffusion capture mechanisms, and what level of protection current filtration media used in respirators/HVAC systems provide against nanoparticles," he said.

TECHNOLOGY

In reviewing the available technology for the commercial manufacture of nanofibers falling into three key approaches – electrospinning, electroblowing and centrifugal spinning – Bengt Hagström of the Swedish research institute Swerea IVF said he believed there were key markets yet to be substantially exploited, not only in respect of filtration, but also in medical drapes and gowns, battery separators and potentially even wipes.

Since around 1995, he said, there have been thousands of research projects undertaken on nanofibers.

"This is mainly because it doesn't cost much to set up a lab-sized electrospinning system, since all you need is a syringe device, an electrical voltage system and a collector. As a result every possible combination of polymer and solution has been explored. But the problem, of course, is that production output is very low with such systems, and attempts to scale them up have not always proved successful."

One problem with nozzle or needle-based solutions has been their tendency to clog. Mr. Hagström cited a system that proposed the use of 10,000 such nozzles and was always going to be highly impractical.

"At the end of the day, a polymer together with a solvent becomes basically a glue," he said.

Donaldson, meanwhile, has patents on its rotating nozzle-based processes for the production of its UltraWeb and SpiderWeb product ranges, while Korean company TopTec has a system employing upwards extrusion.

DuPont holds a patent on the electroblowing technique, while another technology cited by Mr. Hagström was the centrifugal system of Germany's Dienes, which is similar to that developed by his own team at Swerea and installed at a cost of around €16,000 at the plant of Swedish filtration company Dinair.

Elmarco's nozzle-free technology was also said to be based on a rotating system. However, fellow speaker Aleš Gardiàn, who just happens to be Elmarco's R&D director, pointed out that this is no longer the case and a stable wire coated with spinning solution, rather than rotating cylinders, is now at the heart of the company's technology.

"As a result, our system is much more robust and convenient," he added.

ACCURATE COSTING

Mr. Gardiàn's message was that in the selection of nanofiber manufacturing technology for a specific application, it is not enough to base a cost comparison on basis weight (in terms of processing time, the machine width and number of electrodes) or on materials cost, since polymers have varying densities and produce different fiber diameters and some polymers are more prone to specific defects than others.

"A true cost comparison needs to be application oriented, since it's the per-

Pictured at the Filtrex exhibition is Executive Director, Dr. Benham Pourdeyhimi, of the Nonwovens Cooperative Research Centre (NCRC) at North Carolina State University, with colleagues Eunkyoung Shim (left) and Genevieve Garland.

formance of the final product that matters, and not the polymer/nanofiber, provided it is suitable in the first place," he said.

"What really matter are product homogeneity, uniformity and repeatable results based on all parameters. Reliability must be verified and proven in industrial production."

Elmarco provides such detailed analyses and Mr. Gardiàn provided scenarios for production with four polymers – PA6, PVDF, PUR, PAN – based on their properties and performance.

"Simplification, such as straight-forward scale-up calculations must be avoided," he said, "as must producing a cost model for other materials based on an existing cost model, even if there seems to be only a small difference."

A customer's variable costs will include:

- Material – polymers, solvents, additives and other chemicals used for operation
- Energy – including electricity and pressurized air
- Labor
- Waste disposal – including not only the disposal of materials not converted into nanofibers, but those employed for cleaning the equipment or chemicals produced in waste treatment

Fixed costs, of course, relate to the investment in the line and its peripherals, as well as the facility costs – including heat, light, water, maintenance, cleaning, lease cost or building depreciation, etc.

"Elmarco has produced millions of square meters of material for different applications and application-oriented values measured on hundreds of samples from production, running at a broad range of production speeds and at optimized conditions," said Mr. Gardiàn.

"As a result, we can provide very reliable estimates based on the full-package set of correlations."

There was further disagreement, however, when he asserted that the quoted Nanospider output of 100 meters per hour was on the low side.

Dr. Benham Pourdeyhimi, executive director of the Nonwovens Cooperative Research Centre (NCRC) at North Carolina State University, which uses the system, said this was actually on the high side.

ELECTRET EFFICIENCY

Dr. Pourdeyhimi's paper detailed work at the NCRC in improving electret filter efficiency by modifying fibrous webs with melt additives, specifically barium titanate (BaTiO3).

A repeatable and practical surface potential decay measurement for fibrous samples has been established and it has been proven that BaTiO3 addition enhanced the initial charge density and charge stability, particularly after charging at Curie point, with the BaTiO3 particles well distributed within PP filaments without the need for compatibilizers.

Thermal charging also produces high charge retention and stability for nucleating agent/PP samples due to dipole polarization, while antioxidants, by contrast, have been shown not to effectively enhance filtration performance.

NANOWEB

Also over from the U.S. at the Filtrex event was Jack Manns, director of marketing at Hollingsworth & Vose, who after outlining a scale of suitability for various materials to accommodate increasingly smaller particles as shown on page 12, introduced his company's Nanoweb.

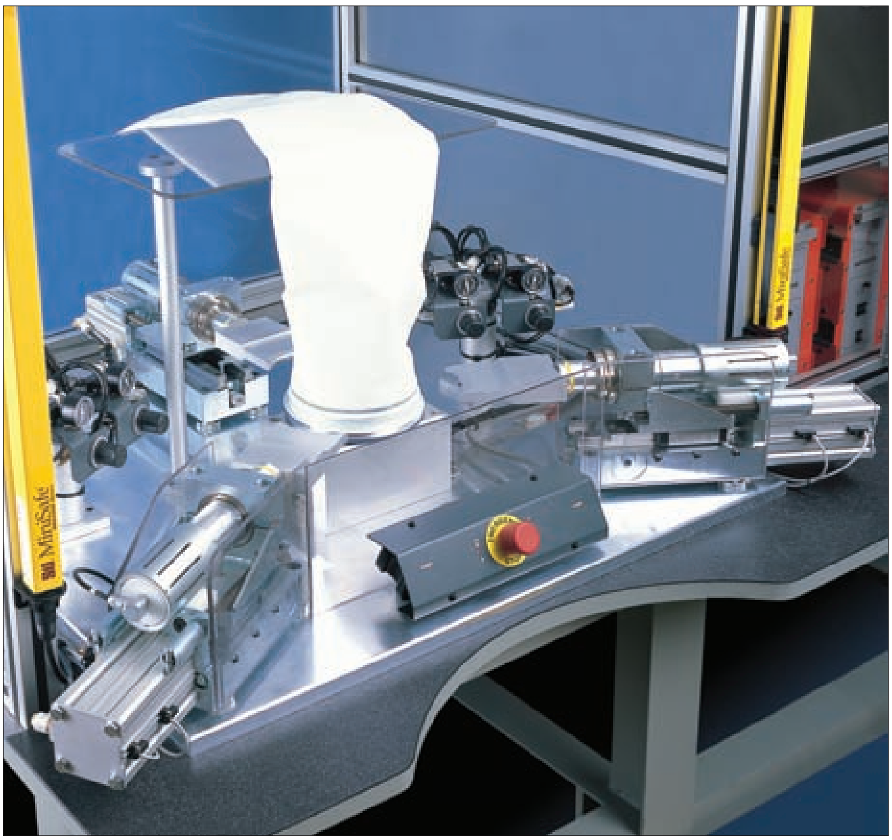
In surface filtration media, Nanoweb was shown to have performance characteristics similar to membranes via the result of comparative tests including fractional efficiency in water, flux, and dirt holding capacity and pore structure.

The key difference is that its cost is significantly lower for suitable applications than either membranes or alternative nanofiber technologies.

"A lot of membranes are used as pre-filters for other membranes and this is where we see beneficial substitution with our new product," Mr. Manns said.

Optimization is now underway at Hollingsworth & Vose to develop a 0.1-0.2 µm nanofibrous media with the efficiency, resistance and dirt loading performance similar to even higher-performing membranes.

Sonobond's Ultrasonic Bonding Equipment Provides Fast, Dependable and Cost-Effective Filtration Assembly Without Thread or Glue



Sonobond's award-winning RingMaster Filter Bag Machine delivers fast, reliable assembly of heavy-duty industrial liquid and chemical filter bags. Those attending Filtration 2012 in Philadelphia will be able to view a video of this machine in action at the Sonobond exhibit in Booth #702.

Sonobond Ultrasonics is the leading provider of ultrasonic bonding machinery for assembling filters and filtration products. This equipment is used for a wide variety of applications in the automotive, airline, food, paper, pharmaceutical, air & water filtration, liquid absorption, agricultural, petroleum, and environmental fields.

ADVANTAGES OF ULTRASONIC

Ultrasonic bonding is a reliable, well-established, and environmentally friendly process that utilizes ultrasonic vibrations to fuse synthetics and nonwoven materials. This bonding method does away with the need for needles, thread, adhesives, or other consumables, while also eliminating related concerns about stitch holes, glue gaps, and broken threads.

Sonobond's ultrasonic bonding process is completed in only seconds, takes up a minimal amount of material at the seam, and provides a much stronger and dependable bond than is produced with stitching, glue, or hot air methods. Sonobond bonders have the added advantage of being four times faster than sewing machines and ten times faster than adhesive machines. The equipment is also easy to operate and requires minimal training. Sonobond's ultrasonic technology is so reliable that it is used to assemble the disposable medical apparel that helps protect personnel from hazardous fluids.

MACHINES FOR EVERY APPLICATION

Sonobond's extensive and versatile line of ultrasonic bonding equipment enables manufacturers to choose the machine or machines best suited for their specific requirements. Here is a brief overview of the bonders most often selected for filtration assembly:

The Sonobond SeamMaster™ Series features ultrasonic machines that seal, sew, and trim material in one quick, continuous rotary process. This equipment can be set up as a stand-alone unit or incorporated into production lines.

Although similar in appearance and operation to a traditional sewing machine, the Sonobond SeamMaster uses no needles or thread. Fraying and unraveling of bonded edges and seams are virtually eliminated. Customers can select from over 500 standard pattern wheels—plus custom designs—for slitting, sealing, seaming, embossing, and tacking.

MULTIPLE USES

Sonobond's SeamMaster High Profile Bonder features a high clearance between the wheel and horn. This makes it ideal for hand-guided applications with tight tolerances and for working around curves. An important feature of this machine is the availability of a special fixture for bonding pleated filters.

Sonobond's SeamMaster High Profile Ultrasonic Bonder is an easy-to-operate machine and is available with a special fixture for bonding pleated filters. It is used to assemble jet fuel filters, commercial air filters, oil-absorbent booms, and much more.

Sonobond's ultrasonic equipment is used to assemble filters and filtration products for a wide variety of industries. Ultrasonic bonding is much faster than sewing or adhesive methods.

Numerous manufacturers use this versatile machine for filtration assembly purposes. For example, American Air Filter International utilizes this equipment to assemble various types of commercial air filters, such as those used for HVAC, dust collection, nuclear, and bio-chemical applications. Enfilter Limited bonds the longitudinal seams of its liquid and gas filter cartridges. EvoOrganic puts together environmentally friendly filtration fabrics for agricultural, landscape, and garden products. Kuss Filtration uses the High Profile bonder in assembling its fuel filters. Supply Pro assembles oil-absorbent pads, booms, and pillows with the machine, and Velcon Filters utilizes this ultrasonic equipment to create filtration components for commercial and military jet fuel handling.

BOX-STYLE FILTERS, FILTER BAG ENDS

Sonobond's SureWeld™ 20 Ultrasonic PlungeBonder™ is a powerful, dependable, multi-use machine that is ideal for sealing large, multi-layer and difficult-to-bond materials in just one hit. It is often used for sealing box-style filters and filter bag ends. This machine—as well as its welding horns and nests or fixtures—can be customized for specific applications. For example, a special two-head version is used by American Air Filter to assemble cube filters. Other manufacturers utilize this equipment for such applications as assembling automotive air filters and HEPA-rated filters used in bag-less vacuum cleaners.

FILTER BAG ASSEMBLY

Sonobond's award-winning RingMaster™ Filter Bag Machine is specially designed for the high-quality, high-volume assembly of heavy-duty filter bags used for a variety of chemical and industrial liquid applications. This innovative ultrasonic bonder joins the plastic collar to felted filter media to create a dependable 360° bond. The entire process is completed in two steps, takes less than ten seconds, and produces up to 250 bags per hour. Custom tooling is available to accommodate a variety of bag sizes and ring diameters. A video showing this machine in action can be seen on the company website: www.SonobondUltrasonics.com.

The Filter Collar Bonder™ is designed for lower-production assembly of bag filters. The unit creates a reliable 360° weld between the bag and the plastic ring in as little as 45 seconds. Between 50 and 80 bags per hour can be assembled in this way.

FREE VIABILITY TEST

Because Sonobond has such an extensive number of ultrasonic bonding machines, the company offers a no-cost, no-obligation Ultrasonic Bonding Viability Test to help determine the equipment best suited for any specific application. Filtration assemblers are encouraged to provide materials so that sample bonds can be made. Once it is decided to install a Sonobond machine, this work is completed as quickly as possible, with minimal disruption to the customer's production process. Sonobond also provides prompt, dependable technical support before, during, and after installation.

For more information contact:
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Email: MAlleman@SonobondUltrasonics.com
Tel: 1-800-323-1269
Website: www.SonobondUltrasonics.com

Liqui-Cel Membrane Contactor Technology Being Evaluated for Dissolved Gas Removal from Water in Many Hydrocarbon Processes

By Gareth Taylor, Membrana - Charlotte, a Division of Celgard, LLC

8 x 80 Liqui-Cel Membrane Contactor System

The oil and gas industry has utilized various deaeration technologies for many years to remove dissolved gases, particularly oxygen, from injection water. Minimizing the environmental impact, improving operating efficiency, avoiding process issues and protecting system components are just a few of the reasons deoxygenation is necessary in many hydrocarbon recovery and water processes.

Common methods of deoxygenation include installing a vacuum tower and/or chemical injection (for example, dosing water with sodium bisulfite). However, vacuum towers are bulky and use an enormous footprint. They cannot be easily expanded to meet future demand, and, in many cases, are not operated at optimal efficiency because planned flow capacity may change after tower construction begins or even after installation. Additionally, vacuum towers can also have long lead times so ordering must be done well in advance.

Removing dissolved gases with chemicals requires storing large volumes of chemicals and handling by employees. Environmental regulations are becoming more stringent, which increases chemical disposal costs.

However, with the introduction of Liqui-Cel® 8 x 40 and 8 x 80 High Pressure Membrane Contactors there has been an increase in discussion and activity about utilizing membrane contactor technology to remove dissolved oxygen from water in many hydrocarbon related applications because they use a much smaller footprint and weigh far less than deaeration towers. Liqui-Cel Contactors maintain positive pressure after degassing, eliminating the need for booster pumps or reducing booster pump capacity requirements and they do not require chemicals to operate. The devices are ASME code-rate to 300 psi to handle high inlet pressures.

Liqui-Cel® 8 x 80 Membrane Contactor vs. Traditional Deaeration

	250,000 BWPD		115,000 BWPD	
	Liqui-Cel® 8 x 80	Vacuum Tower	Liqui-Cel® 8 x 80	Vacuum Tower
Height (ft)	11-20	60-75	11-20	57-72
Footprint (sqf.)	310	530	172	255
Dry Weight (lbs.)	13,800	62,000	6,900	32,000
Operating Weight (lbs.)	21,840	125,000	10,920	61,000
Flooded Weight (lbs.)	21,840	310,000	10,920	145, 000
Average O2 Outlet	< 10ppb	< 10ppb	< 10ppb	< 10ppb

Footprint dimensions and weights are estimates only and will vary according to project requirements.

Lower concentrations of dissolved gases can be achieved with less weight and a smaller footprint.

LIQUI-CEL TECHNOLOGY

Liqui-Cel Membrane Contactors use a microporous hollow fiber membrane to remove gases from or add gases to liquids. Gas flows on one side of the membrane and liquid flows on the other side at a higher pressure relative to the gas stream. Because the membrane is hydrophobic it prevents intrusion of liquid into the pores and acts as an inert support that allows direct contact between a gas and a liquid phase without dispersion.

Applying a vacuum and/or an inert sweep gas to the gas phase lowers the partial pressure of the target gas. This creates the driving force for dissolved gas in the liquid to transfer through the hollow fiber membrane pores. The transferred gas is then carried away by the vacuum pump or sweep gas.

INJECTION SEAWATER DEOXYGENATION

Oil can initially be retrieved from a reservoir using only the natural lift mechanisms, such as gravity, natural water displacement, gas expansion and others. However, over time these natural mechanisms will no longer provide sufficient pressure to force oil to the surface. Other methods must then be employed to maintain pressure in the reservoir to keep up the production rate. One such method that is commonly used is water injection.

Water injection entails sending large volumes of water into a well to keep pressure elevated enough to lift oil to the surface. Injection water can come from several sources including seawater, river water, produced water and even aquifer water.

After pre-filtration, injection water is deoxygenated to reduce the impact of corrosion and help prevent the growth of bacteria that can produce toxic hydrogen sulfide. Bacterial growth can also lead to serious production problems and impede extraction by blocking the pores in the rock.

Historically, to remove dissolved O2 from injection seawater on offshore platforms, bulky deaeration towers and oxygen scavenging agents were used.

14 x 40 Liqui-Cel Membrane Contactor in CSG Pilot Degassing System

Currently, Liqui-Cel Membrane Contactor technology is being evaluated in various hydrocarbon extraction applications to displace these older technologies because of the reduced weight and footprint used by the contactors. Liqui-Cel Membrane Contactors also maintain positive pressure after degassing, which may eliminate the need for booster pumps. They are modular and can be easily expanded to meet capacity demands even after initial installation.

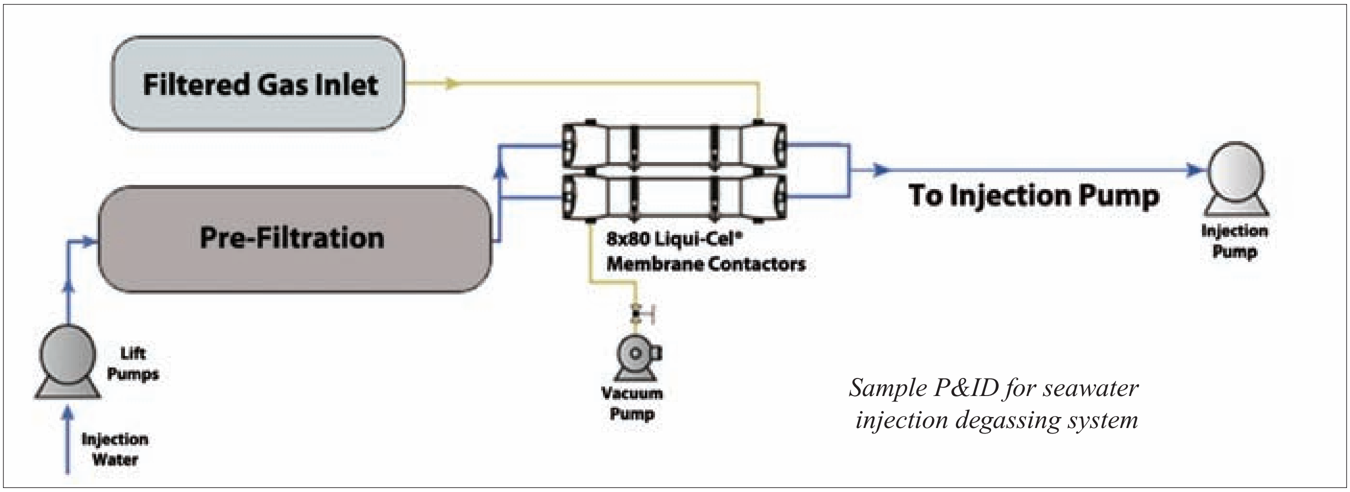
Case Study 1: Liqui-Cel Membrane Contactor Deoxygenating Injection Seawater

Currently, a Liqui-Cel Membrane Contactor system is being used in a pilot trial at a major oil and gas producer in the United States. The membrane contactors have been shown to remove dissolved oxygen from filtered seawater for injection purposes. The system skid is intended to be placed on an offshore platform in the next pilot phase.

CORROSION CONTROL

Steam flooding, cyclic steam injection and steam-assisted gravity drainage are all methods that are being used more widely to extract heavy oil. Steam injection is the main thermally enhanced oil recovery (TEOR) method of stimulation used in tertiary recovery applications.

In this process, boilers are used to



Sample P&ID for seawater injection degassing system

provide the constant flood of steam required for injection; however, dissolved gases in the feedwater must be removed to help control corrosion within the boiler and piping. Liqui-Cel Membrane Contactors remove dissolved gases with no or minimal chemical usage. Boiler feedwater degassing is a common application for these membrane contactors.

Case Study 2: Liqui-Cel Membrane Contactors Used for Degassing Boiler Feedwater

Liqui-Cel Membrane Contactor degassing systems are in operation on multiple derricks in Venezuela to remove oxygen from boiler feedwater. These installations are being used to help prevent corrosion and pitting within the boiler to protect capital investment.

DEGASSING PRODUCED WATER

During oil and gas extraction, formation water is brought to the surface along with the gas or oil. The water that comes to the surface is known as produced water and can contain a mixture of oil, gas, inorganic salts, organic compounds, bacteria, injected chemicals, dissolved gases and solid particles. The concentrations of each component can vary widely depending on the well location. Water quality can range from meeting federal or state drinking water standards to low quality levels with Total Dissolved Solids (TDS) up to 180,000ppm.

Produced water may be contaminated with chemicals added during water injection or with naturally occurring heavy metal components. Iron compounds and sulfur deposits may also form when the water is exposed to oxygen in the air. Therefore, water treatment must take place before produced water can be disposed of in accordance with environmental regulations.

There are several methods available to dispose of the produced water. According to the Produced Water Society, 65% of the produced water generated in the United States is injected back into the producing formation, 30% into deep saline formations and 5% is discharged to surface waters. Produced water that is re-injected goes through several water treatment process steps for purification, which often includes deoxygenation.

Case Study 3: Liqui-Cel Contactors Degas Produced Water in Coal Seam Gas (CSG) Extraction

Produced water treatment systems using Liqui-Cel Membrane Contactors for this application are currently being evaluated in Australia. The company extracting the gas faced environmental considerations when evaluating how to dispose of the produced water that was to be re-injected into underground aquifers.

To meet the water quality standards for re-injection, a water treatment system was built that would include filtration, RO, UV and Liqui-Cel Membrane Contactors, which are used to deoxygenate the produced water before re-injection. Dissolved O2 concentration levels at the water treatment system outlet should be lower than the dissolved oxygen concentration levels of the formation water.

Liqui-Cel Membrane Contactors are expected to achieve low oxygen concentration levels in water for re-injection while minimizing chemical usage.

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Website: www.Liqui-Cel.com

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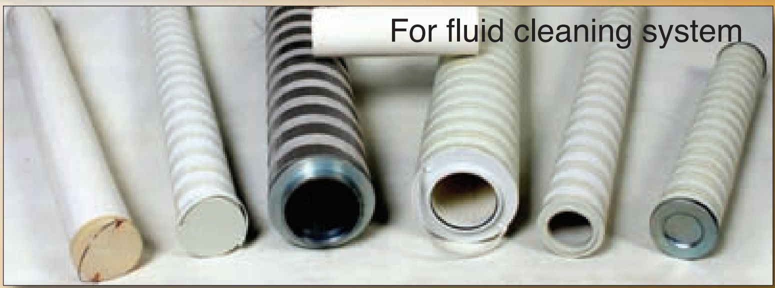

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Electropositive Filtration as a Pretreatment for Reverse Osmosis

By Gregg Poppe and Katariina Majamaa, Dow Water & Process Solutions

The importance of monitoring the performance of a reverse osmosis system to look for signs of fouling, and then diligently cleaning the membranes in an effective manner to keep them healthy is vital. This practice lowers operating costs (chemicals, labor, and energy) and prolongs the membrane life [more details available in "Lower Membrane Operating Costs by Keeping Membranes Clean," International Filtration News, November/December 2009].

It is also very important to design the overall water treatment system in such a way that the concentration of foulants is minimized along each step. Such attempts may not completely eliminate fouling, but can certainly enable the system to run more productively and extend the period between cleanings. For example, it is best to remove suspended solids upstream of the reverse osmosis system, allowing the RO membrane to do what it does best—remove dissolved solids [more details available in "The Basics of Ultrafiltration and Reverse Osmosis," International Filtration News, November/December 2010 and "New Option for Ultrafiltration Pretreatment," International Filtration News, November/December 2011].

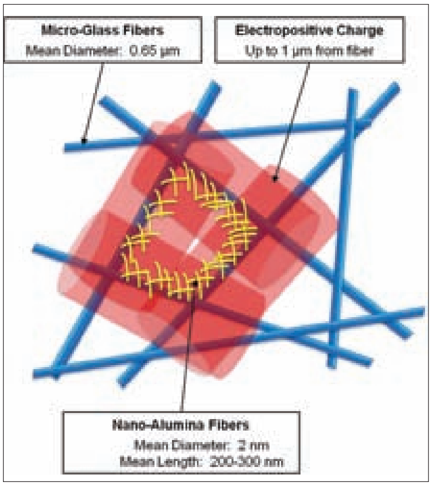
In addition to suspended solids, organic fouling and biological fouling are two other common issues for RO systems, particularly those treating wastewater for reuse. Electropositive filter media is showing some promise as an effective pretreatment option to remove substances such as microorganisms that pass through conventional pleated filters or naturally occurring organic matter that can pass through ultrafiltration before they enter an RO system.

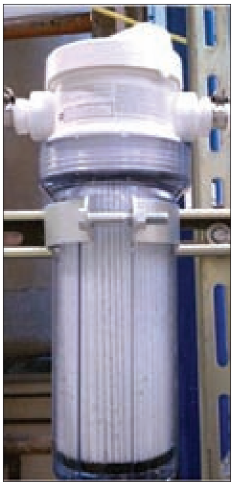
HOW AND WHY

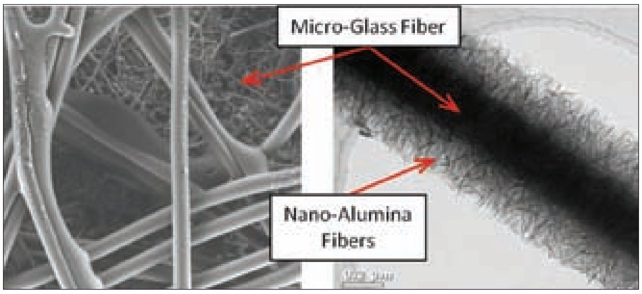
Electropositive filtration is based upon electro-adhesion, as illustrated in Figure 1. The blue lines represent the micro-glass scaffold structure. The smaller yellow lines represent nano-alumina fibers. Studies have shown the field of positive charge (red areas) can be detected up to 1 µm away from the fiber structure, allowing for near full coverage of the pore. Note that there may be areas of overlapping charge fields that may contribute to higher magnitudes of attraction.

Most solutes—organic material, microbial macromolecules, bacteria, viruses, and nano-particulates—carry a net negative charge in a normal pH range near 7. These negatively charged particles that enter the interior of the pore of the filtration media will be attracted to one of the areas of positive charge, removing it from the process stream.

Research on the removal efficiency of electropositive filtration as a pretreatment for reverse osmosis is being led by Jonathan Brant, Ph.D., at the University of Wyoming. The electropositive filter used in the testing was provided by Ahlstrom Filtration. The filter media was packaged into a pleated arrangement to







Left: Figure 1. Depiction of electropositive filtration media.
Center: Figure 2. Pleated cartridge containing the Ahlstrom electropositive filter.
Right: Figure 3. Magnified view of electropositive filtration media.
(All illustrations courtesy of University of Wyoming)

increase the surface area to volume ratio (Figure 2). A magnified view of the Ahlstrom filtration media is revealed in Figure 3. The average pore size of the electropositive filter is about 2 µm.

REMOVAL OF ORGANICS MATERIAL

Humic substances are the major organic constituents found in nature, for example in soil, streams, and ocean water. Humic acid, produced by biodegradation of dead organic matter, is a principle component of this class of material. Humic acid and other humic substances in water will cause organic fouling in RO membranes. Removal of these substances prior to reverse osmosis is, therefore, desirable to maintain a steady rate of water production and to reduce the frequency of RO membrane cleaning.

To quickly screen the effectiveness of the electropositive filter to remove humic acid from feed water, a tap water feed solution containing 584 mg/L NaCl plus 15 mg/L humic acid was prepared. The color of the feed water containing humic acid was noticeably dark and the turbidity was 10.7 NTU. After filtering the solution through the electropositive filter, the turbidity dropped to only 0.16 NTU and the color was removed (Figure 4).

To evaluate the impact of using the Ahlstrom electropositive filter as pretreatment to RO, a side-by-side test system was used. In the first system—the experimental control—feed water was treated by ultrafiltration with a nominal pore size of 0.03 µm. The UF filtrate was temporarily passed through a storage tank and then pressurized and fed to a pressure vessel containing RO membranes. In the second system of this parallel arrangement—the "test" system—the only difference was the insertion of the pleated electropositive filter media (Figure 2) between the UF filtrate storage tank and the RO unit.

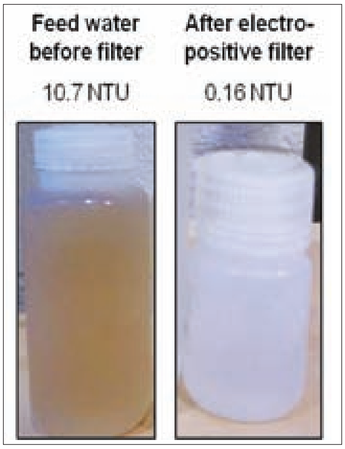
The feed water was the same for both the control loop and for the loop with the electropositive filter. For the first 72 hours, only tap water (~584 mg/L NaCl) was used. Starting at 72 hours, the tap water was enriched with 5 mg/L humic acid.

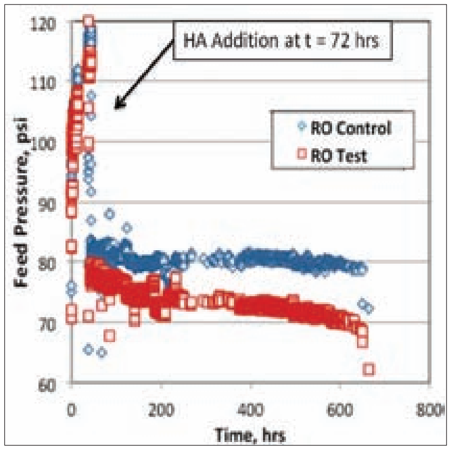
Figure 5 shows the results of this side-by-side testing for about 4 weeks of operation. Data from the experimental control is represented by blue diamonds, and data from the line including the electropositive filter is represented by red squares.

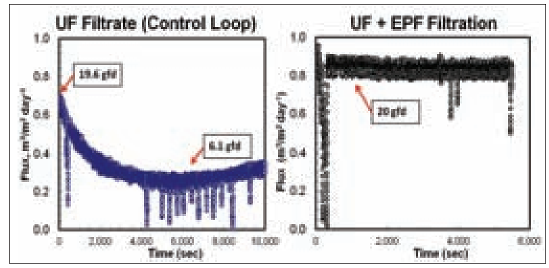
Higher feed pressures were used in the first couple of days of the experiment and then both systems were dialed in to maintain a constant flux of 8.5 gallons/ft^2/day (gfd). The feed pressure of the two independent systems was allowed to vary to achieve this constant flux. Therefore, indications of fouling should then be evident by the requirement of higher feed pressure to maintain the flux set point.

The plot of feed pressure illustrates that the pressure increased rapidly on the RO control (which did not contain the electropositive filter) and it was then consistently higher throughout, indicating that it was suffering from organic fouling to a higher degree than the test system, which did include the electropositive filter.

An accelerated test was also conducted by collecting samples of the RO feed water from each system and then filtering it through an RO membrane in a dead-end filtration test. In this test, the RO membrane operates in dead-end filtration mode (rather than cross-flow as is the case in a spiral wound RO element) and the flux through the membrane is monitored while holding pressure constant. As foulants accumulate on the membrane, the flux is expected to drop. The results of this short-duration fouling study can be seen in Figure 6. In the control loop where the RO feed was simply UF filtrate, the flux dropped over the course of the filtration. More work could be done to understand the mechanism, but the flux decline was presumably due to organic fouling caused by the humic acid, which could not be removed by the upstream UF unit. However, in the experimental loop where the RO feed was treated by both UF and the electropositive filter, the flux was







Left: Figure 4. Visual evidence of humic acid removal by Ahlstrom electropositive filter.
Center: Figure 5. Feed pressure required to maintain constant RO flux.
Right: Figure 6. Flux loss in short-duration fouling test of RO feed waters.

very constant, presumably because the electropositive filter effectively removed the humic acid foulant from the RO feedwater.

FUTURE APPLICATIONS

Although much more work is needed to study the performance, replacement rate and economics of this type of filter, the work summarized here shows potential for electropositive filter media such as the Ahlstrom material in removing a significant fraction of foulants before they ever reach the RO membranes. Since so many non-salt constituents (naturally-occurring organic matter, bacteria, etc.) have a net negative charge in the pH range of typical water sources, these foulants could conceivably be removed by this type of filter as a complimentary technology to UF pretreatment in larger industrial-sized systems.

Gregg Poppe and Katariina Majamaa are global application development specialists at Dow Water & Process Solutions, focusing on the industrial water and power generation markets.

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Selecting the Proper Woven Wire Mesh

By Peter Jones and Greg Rhoden, Phifer Inc.

Wire is woven in various mesh configurations to meet customer specifications or industry standards (left) from fine wire that is drawn down from rod and prepared for weaving (right).

Woven wire mesh is an integral component in the design and production of many types of filters. While some filters use wire mesh as the primary filtering medium, numerous pleated filters are constructed from media that will not conform to a pleated configuration or are subjected to pressure that the media will not tolerate. For this reason, wire mesh is commonly used to provide strength, support and separation for the filter media. High-speed pleating and related filter manufacturing equipment are driving the demand for higher quality and consistency in meshes supplied to the industry.

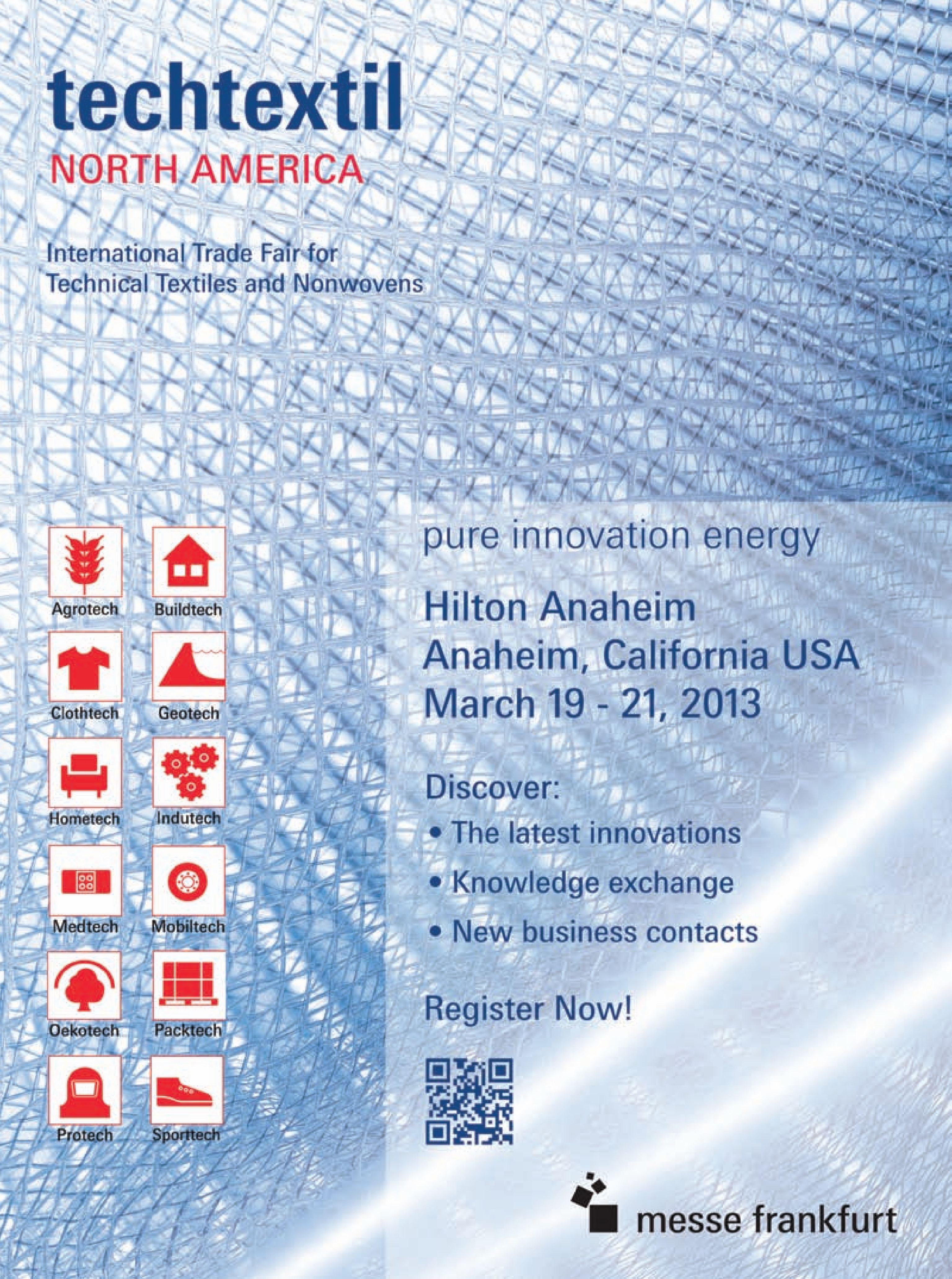
Today, steel, aluminum and stainless steel are the most common metal mesh materials used in filter manufacturing. The raw materials and processes that a top-tier mesh supplier uses are critical factors in determining quality and reliability.

RAW MATERIALS

There are two primary raw materials used in the production of wire mesh for filters: the metal and a coating. Coatings are applied to the wire mesh after it is woven to provide additional protection and stability to the woven mesh. Epoxy-based coatings are widely used with wire mesh for filtration, as well as acrylic-based and polyester-based coatings.

PROCESSES

Small-diameter wire (fine wire) for weaving is drawn down to weaving size from larger diameter redraw rod or intermediate wire. Mesh suppliers with in-house wire drawing and preparation capabilities are better able to control mesh quality versus those who purchase finished wire for weaving due to their control of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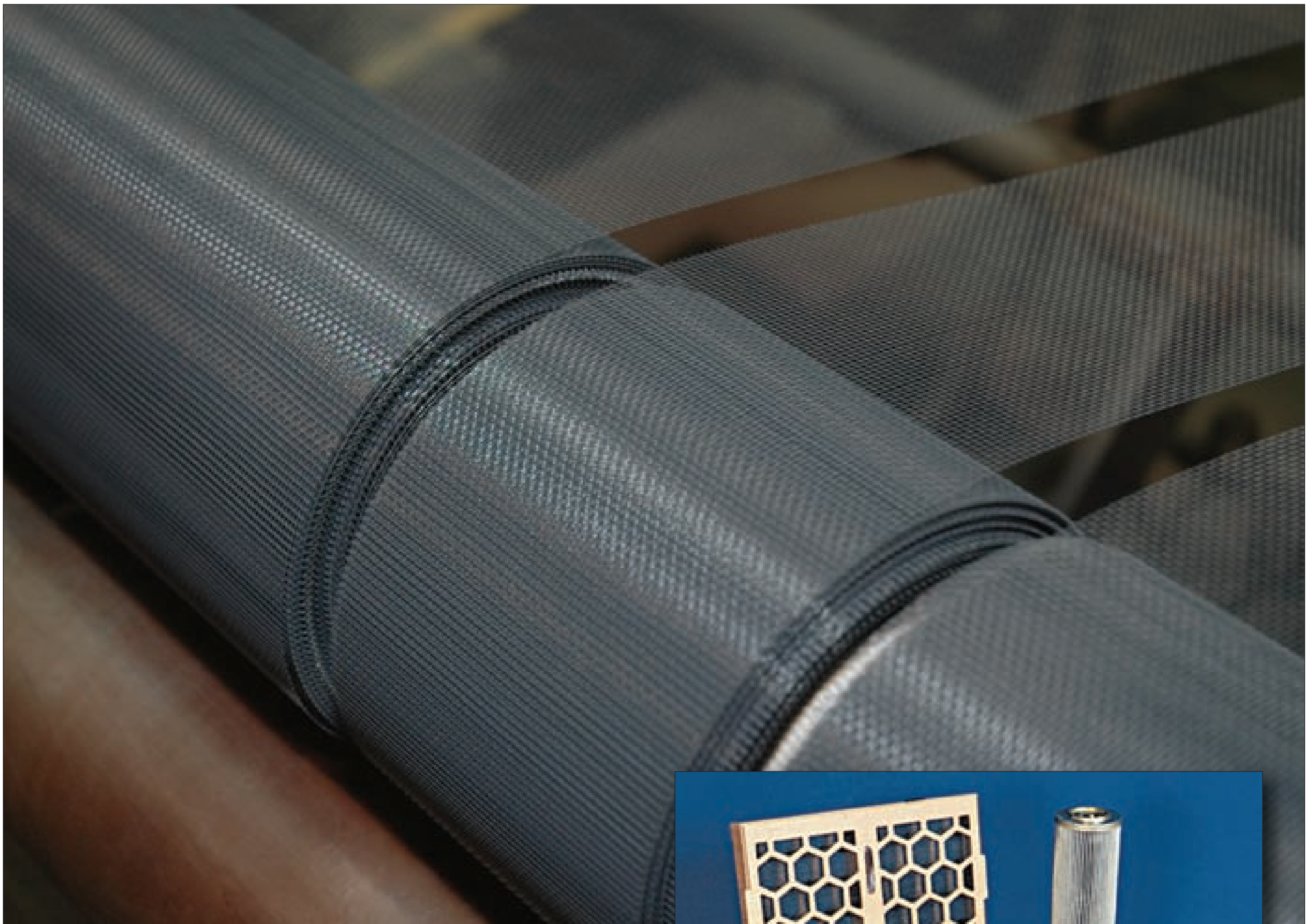

Wire mesh can be slit to custom widths (top) and is used in multiple types of filters including air, oil, fuel, and hydraulic fluid filters (right).

the wire diameter, roundness, tensile strength and other characteristics that impact the quality of the woven mesh. Other advantages include better process control, the ability to react quickly to special orders and faster delivery of the finished product.

Finished wire is woven to customer's specifications or to industry standards. High-quality input wire is paramount to the weaving process to help control consistency in the mesh and provide a reliable product for processing by the filter manufacturer. For example, distortion in the mesh can cause consistency issues when paying the wire mesh off into a pleating line.

After weaving, the mesh can be further processed in a number of different ways depending on the end customer's needs. The mesh could be shipped directly after weaving with no cleaning or coating (referred to as "natural" or "mill finished"). It might be cleaned of drawing and weaving lubricants and shipped as cleaned only, or it can be cleaned and coated according to customer requirements. Prior to the coating process, it is sometimes necessary for the mesh to be heat treated, or annealed. The annealing process is critical for the wire mesh to be pleated. Aluminum, a softer metal, often does not require annealing, while steel and stainless steel mesh almost always require softening through the annealing process to be pleated efficiently. Strict quality control of the annealing process ensures that the wire mesh will remain consistent and reliable in the filter manufacturer's pleating operation.

Many filter manufacturers require custom slitting of wire mesh. Precision slitting capability is paramount for a wire mesh supplier to meet the exacting width tolerances required in many filters. Another important and valuable factor for filter manufacturers is the capability of supplying rolls of wire mesh in maximum lengths. Longer input rolls require less frequent roll changes and increase pleater input.

PRODUCT SELECTION

Filter manufacturers have a number of options when choosing a wire mesh to add support and strength to their filters. Physical properties, chemical properties and cost are factors to consider in selecting the most suitable wire mesh for filtration applications.

Aluminum has a relatively high strength-to-weight ratio, can be pleated easily with or without annealing and is generally lower in cost per foot than most other metals. It is also not as susceptible to rust and oxidation as ferrous metals and can be used with or without a coating depending on the application.

Low carbon steel provides high strength to withstand the cyclic pressure differentials present in many fluid filtration systems, is easy to pleat when properly annealed and is a low cost option in comparison to other metals offering similar physical properties. In most cases, it should be coated to prevent rusting.

Stainless steel mesh, though a higher cost option, offers still greater strength, high heat resistance, is more resistant to corrosion, and can be used with or without a coating. It is generally more suitable for applications with highly-acidic or caustic solutions at elevated temperatures.

Wire mesh has long been a component of many types of filters. The predominant use of wire mesh in filters is as a support mechanism for various types of filter media. With advances in filter media efficiency and development of high-speed filter manufacturing technology, choosing the right mesh product and the right supplier are critical to a filter manufacturer's success. FN

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Power Plant Wastewater Reuse - A Case History

By Peter S. Cartwright, PE

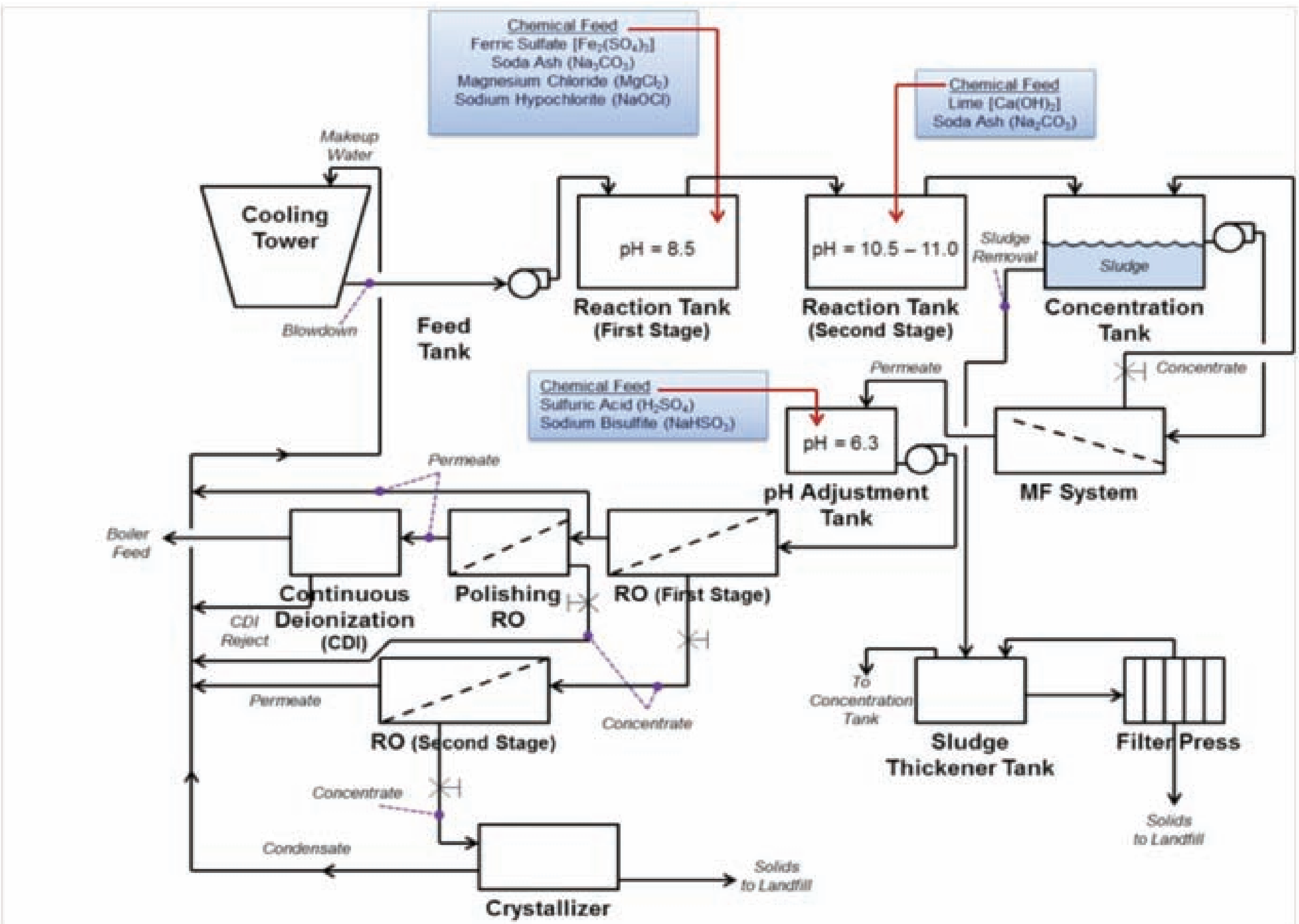

Figure 1. Schematic of Zero Liquid Discharge Process

The High Desert Power Project, LLC, is a large California power generator using chemical addition and membrane technologies to treat and reuse cooling tower blowdown in a ZLD (Zero Liquid Discharge) process.

PROCESS DESCRIPTION

Clarified California Aqueduct Water feeds the cooling tower. Cooling tower blowdown is pumped to a first stage reaction tank. Ferric sulfate, soda ash, magnesium chloride and sodium hypochlorite (bleach) are added; the pH in this tank is approximately 8.5, which initiates precipitation of calcium carbonate and silica.

Effluent from the first stage reaction tank overflows into a second stage reaction tank, which receives lime and soda ash, raising the pH to 10.5-11.0, to further precipitate calcium carbonate and silica.

This tank overflows into a concentration tank, which also receives the concentrate ("reject") stream from a microfiltration (MF) system. The concentration tank collects precipitated and chemically saturated solids, and the resulting sludge is fed to a sludge thickener tank.

The suspended solids slurry in the

concentration tank is directed to an MF system for a virtually complete removal of these solids. The MF permeate (that portion of the feed stream that passes through the membrane), flows into the pH adjustment tank where it receives sodium bisulfite to neutralize chlorine (from the bleach addition) in the tank, and hydrochloric acid to lower the pH to 6.3.

As the result of receiving the MF concentrate, the total solids concentration in the concentration tank increases to about 5%, at which time the solids are pumped to the sludge thickener tank that feeds a filter press. The dewatered solids are hauled to a landfill and the liquid portion is directed back to the concentration tank.

From the pH adjustment tank, the treated MF permeate is processed with reverse osmosis (RO) technology, and the first stage permeate stream is either returned as makeup to the cooling tower or fed to a polishing RO. Permeate from the polishing RO is directed to a continuous deionization system to produce boiler feedwater, and the concentrate stream becomes part of the cooling tower makeup water.

The concentrate stream from the first stage RO is fed to a second stage RO, with the permeate from this system directed back to the cooling tower as makeup water, and the concentrate stream fed to a crystallizer. The solids from this unit are delivered to a landfill, and the crystallizer condensate returned to the cooling tower as makeup.

FILTRATION REQUIREMENTS

As water evaporates, as in a cooling tower, the level of contaminants in the blowdown water increases significantly.

The technologies required to remove dissolved solids (reverse osmosis, continuous deionization, and others), are deleteriously affected by suspended solids and slightly soluble salts that precipitate upon concentration.

Conventional lime softening is the traditional water softening process for high volume flows, and involves adding lime (Ca(OH)2) and soda ash (Na2CO3). As the pH is increased from the lime addition, calcium carbonate, magnesium hydroxide and magnesium carbonate precipitate. Magnesium hy-

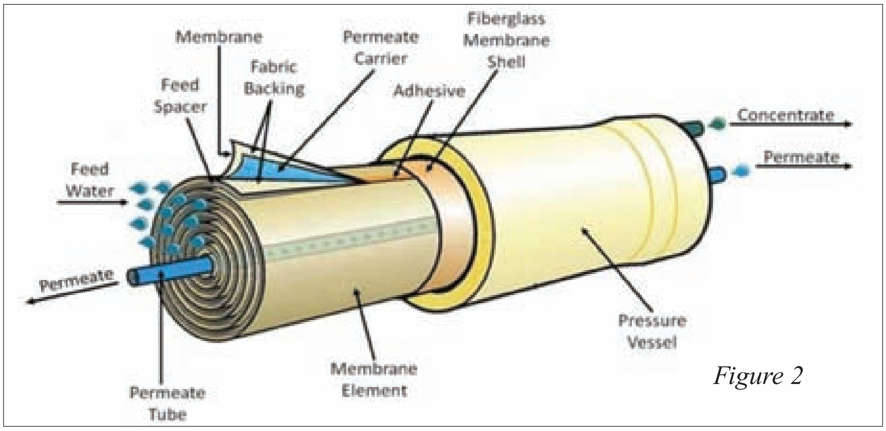

Figure 2

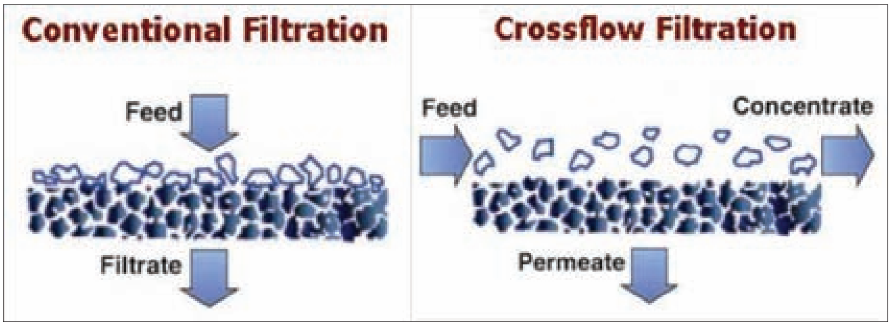

Figure 3

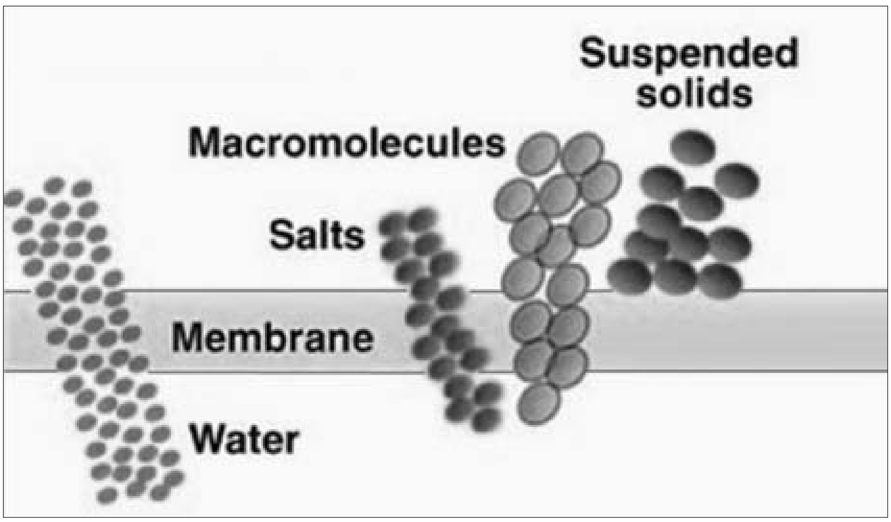

Figure 4

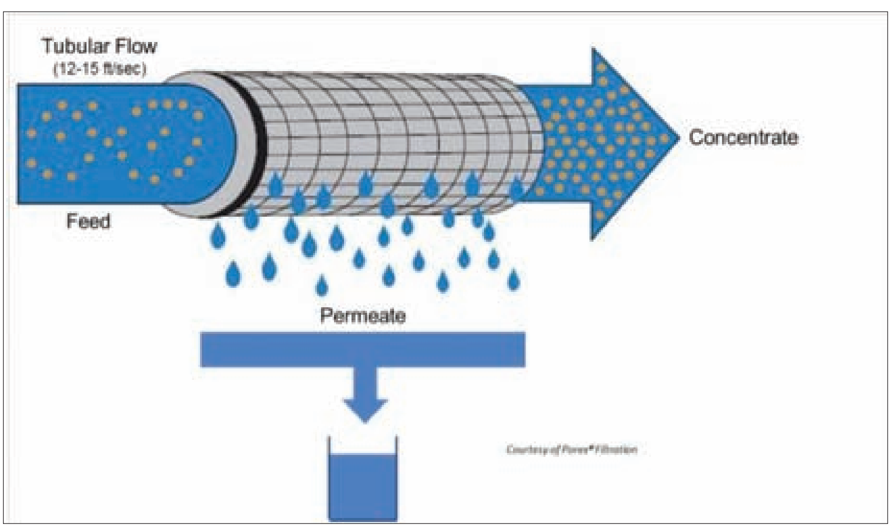

Figure 5

droxide also removes silica via absorption as it precipitates.

Virtually all reverse osmosis membrane elements sold today are of the spiral wound configuration, as illustrated in Figure 2.

INSIDE A PRESSURE VESSEL

Although the least expensive of all the membrane element configurations, spiral wound reverse osmosis membrane elements are the most susceptible to fouling by suspended solids. In many cases, the normal multimedia filtration process, often utilized in lime softening, does not provide adequate suspended solids removal to minimize membrane fouling. This is where the superior filtration capabilities of MF technology can be exploited.

MICROFILTRATION

Microfiltration is a crossflow, pressure-driven membrane separation technology designed to remove submicron (and larger) suspended solids from water supplies. It differs from conventional ("dead-end") filtration in that in this process, the entire water supply passes through the filter medium, whereas in the crossflow process, a portion passes through the membrane, becoming "permeate," while the remainder exits the system as "concentrate," carrying away almost all of the suspended solids.

Figure 3 compares these two processes.

The mechanism of microfiltration is depicted in Figure 4.

The MF membranes used in this application are Porex® TMF tubular membranes, depicted in Figure 5.

Specifically, the tubes are 1" I.D., with a polyethylene substrate supporting a PVDF (polyvinylidene fluoride) layer with 0.10µ pores. The membrane modules are illustrated in Figure 6.

Each membrane module consists of ten 72" long tubes enclosed inside a PVC housing.

The feed flow is down the center of the tube (lumen feed) with the permeate passing through the tubular wall and collected from the area around the outside of the tubes inside the housing. A total of 216 Porex® modules are in this MF system.

SYSTEM DESIGN

Porex® TMF System

The modules are divided into six skids, each containing three trains of 12 modules linked in series. The feed stream enters one end of the first module with the concentrate exiting the other end as feed for the next

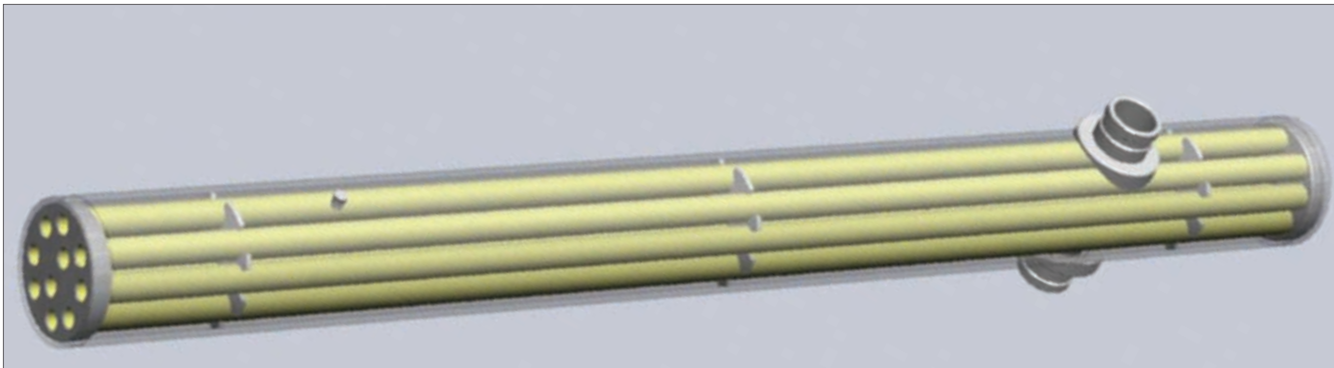

Figure 6

module. This flow continues through the 12 modules, and returns to the concentration tank. Meanwhile, the permeate from each module is collected in parallel and fed to a header where it is directed to the pH adjustment tank for further treatment by

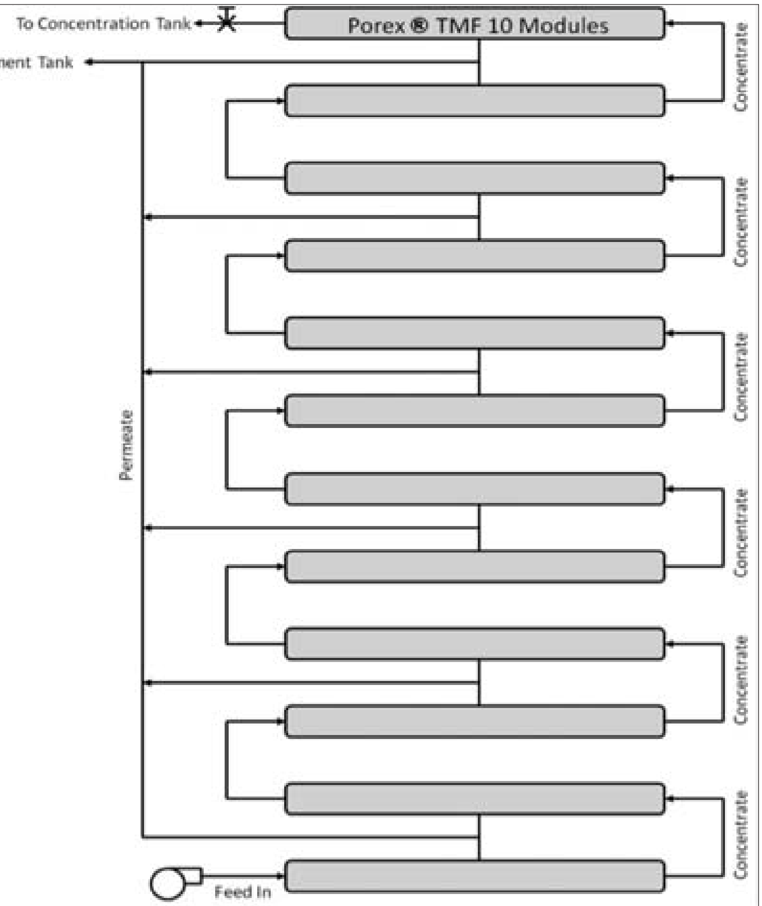

Figure 7

Parameter	MF Feedwater	MF Permeate
pH	8.0	10.7
Total Hardness	2122 mg/L	127 mg/L
Total Alkalinity	58 mg/L	197 mg/L
Turbidity	4.63	0.03 NTU
Silica	99 mg/L	6 mg/L

Figure 8

Figure 9

	Membrane Systems Flows and Recoveries		
	First Stage RO	Polishing RO	Second Stage RO
Feed Rate (gpm)	350	110	150
Permeate Rate (gpm)	255	82	100
System Recovery (%)	73%	75%	67%

reverse osmosis.

A train of 12 modules is illustrated in Figure 7. The table in Figure 8 summarizes the performance of this MF system.

REVERSE OSMOSIS (RO)

The first stage RO removes dissolved solids with a portion of its permeate supplying the cooling tower with makeup water, and the remaining permeate flow directed to a polishing RO for additional dissolved solids removal and then further purified in a continuous deionization unit to produce high quality boiler feedwater.

The concentrate streams from the first stage and polishing RO units are combined and fed to a second stage RO with its permeate utilized as cooling tower makeup water, and its concentrate treated in a crystallizer to produce solids for landfilling and the condensate used for cooling water makeup.

As the MF process so effectively removes suspended solids, the RO concentrate streams could actually be returned to the front end of the system for further treatment.

Figure 9 lists the feed and permeate rates for the RO systems; along with the resulting recovery calculations (permeate rate divided by feed rate) for each.

CONCLUSIONS

Each component in this system contributes to the overall success of this unique design. The chemical additions to the reaction tanks result in hardness and silica precipitation. The MF system continuously removes clarified water from the solids. This treated water is further polished with RO technology to remove salts to either generate cooling tower makeup water or to feed continuous deionization technology to produce boiler feedwater.

The effectiveness of MF technology is underscored by the fact that the RO units can recover a very high percentage of the treated water for complete reuse. In addition, the RO membranes need cleaning no more frequently than every six months.

The sludge resulting from hardness and silica precipitation is dewatered in a filter press and landfilled. The liquid stream from the filter press is redirected to the MF system.

The concentrated salts from the reverse osmosis units are rendered insoluble in a crystallizer with these solids landfilled. The crystallizer condensate is also used as cooling tower makeup. FN

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Idle Stand-By Filters Cost More Money

By James Joseph, Joseph Marketing

Many coolant filtration systems which use bag or cartridge filters are set up with two vessels in parallel; one is on stream while the other is on stand-by. The concept is to have one of the vessels always ready to go on line quickly to keep the operation running while the spent filter element is being changed.

Figure 1 is a photo of two bag filters sandwiched in the midst of tanks and equipment with valves to switch over when a signal indicates the need.

This is a well-established strategy, but for many installations, an idle stand-by filter is costing more money sitting there than if it were on the line working along side the other filter. Here's why.

While on stream the on-line filter is handling the full flow of the coolant-cleaning loop. The other is just waiting. Since element life and costs could be an issue particularly when the frequency of changing is a burden, another option to reduce the burden, can be taken without any major cost for renovation. If it is physically possible and conceptually acceptable, a good step is to put both vessels on line to run in parallel, with each handling ½ the flow the single vessel did. The axiom is that if the flow through the filter area is reduced to half the flow previously sent through the filter, the element will last at least 4 times longer.

That is hard to see by many not close to filtration concepts, since the natural thought is that with half the flow the element will last just twice as long. However, it doesn't work that way with fluids flowing through a barrier of media and a cake of contaminants. The phenomenon follows the physics of hydraulic flow through an orifice.

A hydraulic engineer uses the equation in Figure 2 to calculate the pressure differential across an orifice with a given flow rate.

If a media and its cake in Figure 3 are looked upon as an equivalent to an orifice, the same equation aids in understanding the statement: ½ the flow means 4 times the life of the media.

For example, if we assume that the cake shown in Figure 3 (with its different paths for fluid) is equivalent to an orifice with a diameter of .33 inches and the flow is 10 GPM, we can calculate with the equation and obtain the following results:

- At 10 GPM, the pressure differential of 23 psi
- At 5 GPM, the pressure differential is 5.9 psi

This means at 5 GPM the pressure climbs at the lower rate. With ¼ of the pressure obtained with the higher flow rate, the media will last 4 times longer. Granted, calculations are only a guide since in real life there are many other factors, which can affect media life. Valid points, which exist, include the variable cake thickness, the influence of foreign material and change in the slope of the pressure curve climbing rapidly near the end. However, these are also found in the single vessel flows so the ratio for media life does not change much.

Therefore, if there are two vessels and there are ways around not having a quick stand-by, consideration should be given to putting both on line. If the concern about not shutting down to change elements is a strong economic argument, then the system should be left as is. But, if the operations have a procedure where routine shutdowns are part of the daily schedule or the machine function can tolerate a brief interruption without a major cost, than the rewards of both vessels on line are worth it. Here are some advantages:

REDUCTION OF REPLACEMENT ELEMENTS

Assume a bag or cartridge filter system with one vessel on line (while the other is on stand-by) has to change the element every shift. By putting the second filter on line, the elements last four shifts. So the net result is that every four shifts the operation uses two elements with both ves-

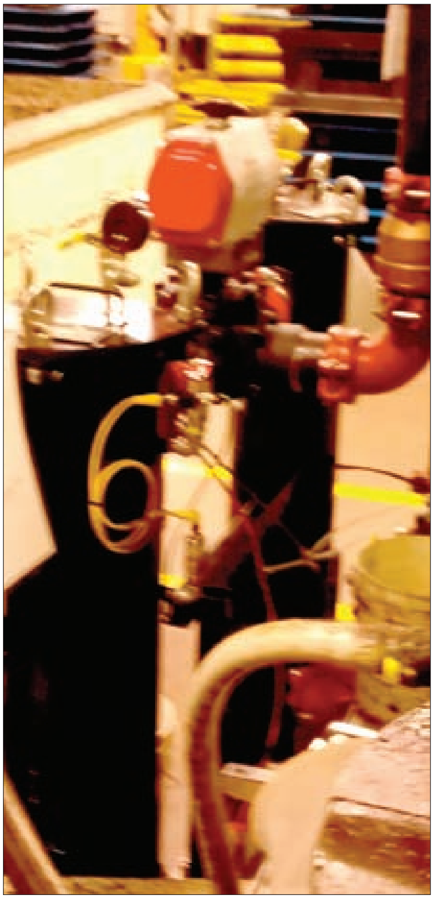

Figure 1.

sels instead of 4 elements with one vessel. The replacement cost is cut in half.

CLEANER COOLANT

In addition there are other advantages. The two vessels with ½ the flow will yield cleaner fluid and allow the use of even tighter fabric for higher clarity of the coolant. This could be a major advantage if the level of clarity with one vessel is not high enough to meet the needs of the operation. This offers even a wider scope of rewards such as longer coolant life, better tool life, lower scrap and cleaner machines. Plus, there is less fluid dumping and disposal.

MINIMIZE GROWTH OF BACTERIA

There is another advantage, which is probably only evident to the person who has to change the elements and not to anyone else unless they are told. An idle vessel waiting on stand-by with a clean element but with a residue of dirty coolant still in the chamber allows for the growth of bacteria. The warm dark chamber sitting idle with no circulation is a good incubator.

$$\triangle P = [\, Q \div (D \div 0.23)^2 \,]^2$$

P = Pressure Differential
Q = GPM
D = Orifice diameter in inches

Figure 2. Hydraulic equation

With this situation, as soon as the standby-by vessel is put on line two things happen:

- The system is inoculated with bacteria. Usually controlling bacteria needs a good (and expensive) biocide.
- The bacteria usually generate a gel-like substance while sitting in the chamber and the filter element is immediately coated with this foreign material, as it is put on stream. The coating effectively shortens the life of the new element and changing can be even more frequent.

The only way to prevent this is to ask the operator to thoroughly clean the chamber before inserting the clean element. This is not going to happen because of the time and resources needed on the line to accomplish this.

SUMMARY

The rewards of placing both vessels on line can be measured by:

- Reduction in element usage
- Cleaner coolant and all the advantages that go with it
- Lower potential problems with bacteria
- Reduced volumes of solid waste disposal with spent elements

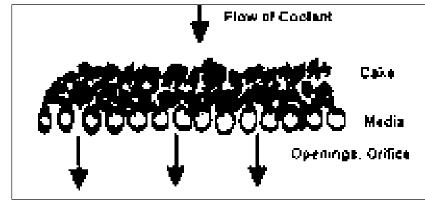

Figure 3. Cake and Media Openings-Orifice

This concept has been proven many times over the years with many different types of filters.

This scenario is not limited to water base fluids. Oils can have the same advantage except the idle bacteria problem is not as great.

The real task is to get over the mind set that an idle stand-by filter is needed. Once accepted, the cost to implement is low and the rewards can be significant. FN

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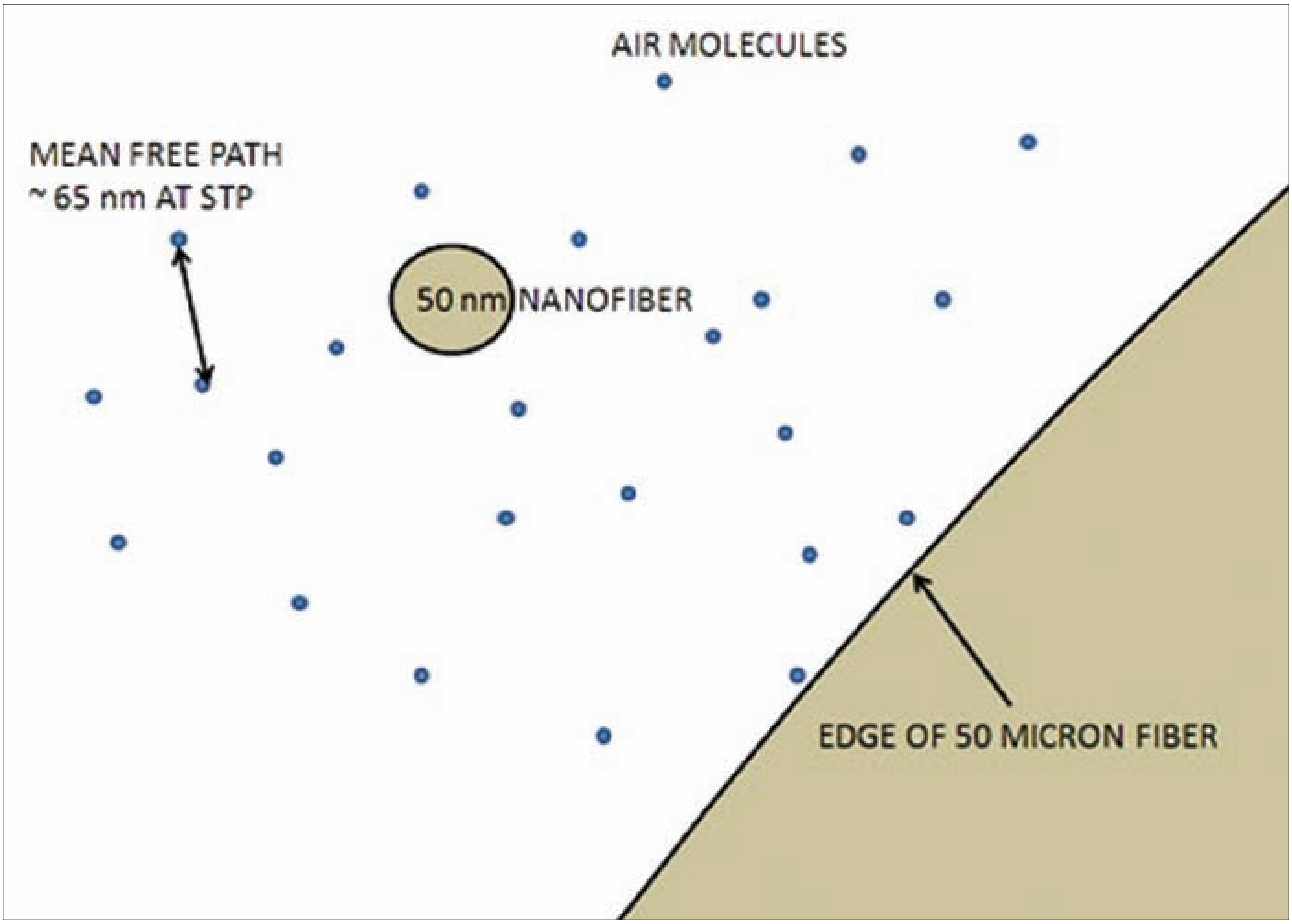
"Slip-Flow" and How It Affects Filter Performance

By Dr. George Chase, The University of Akron



A 50 nm nanofiber and the edge of a 50-micron fiber

Recent scientific interest in nanofibers has many people exploring their use in filter media. One of the advantages of nanofibers for gas phase depth filtration is the slip-flow phenomena. The purpose of this article is to describe what is meant by the slip-flow phenomena and how it applies to filtration.

Suppose you have a hypothetical camera that can take an instant snapshot of the distribution of molecules in air. What you might see is something like that shown in Figure 1, where the molecules are more or less randomly distributed in the photograph. Also in the photograph are a 50 nm nanofiber and the edge of a 50-micron fiber.

Figure 1. Hypothetical photograph snapshot of air molecules near a 50 nm nanofiber and a 50-micron diameter fiber.

As the air flows past the 50-micron fiber, the molecules collide with the fiber and stick to the surface long enough for the air molecules to acquire the velocity of the micro fiber plus a random motion associated with their thermal energy. If the microfiber is stationary, then the air molecules at the surface of the fiber have only the random motion due to temperature.

The motion of a continuum is the average velocity of all of the molecules in a small volume element with the average velocity assigned to the centroid of the volume element. Near the surface of the microfiber, because the air molecule velocities are random, by definition the sum of the velocity vectors of the molecules must be zero.

In contrast, the nanofiber is so small that when the air passes it, only a fraction of the air molecules actually contact the nanofiber. As a result, only these fractions of the molecules have their velocities modified to the random motion due to their thermal energy. The remaining air molecules that do not collide with the nanofiber surface retain their bulk flow motion (plus the random motion due to temperature). In this case, the continuum velocity near the nanofiber surface is not zero. The movement of the molecules past the nanofiber without colliding with the nanofiber is referred to as "slip flow."

This slip flow phenomena affects filtration in two important ways. First, because fewer molecules exchange momentum with the fiber, there is less air drag on the fiber. This means that for flow through a filter medium of nanofibers and a medium of microfibers of equal fiber lengths, the pressure drop through the nanofiber medium will be less.

However, a comparison of media of equal masses of nano and microfibers may result in greater pressure drop for the nanofiber medium. In practice, the nanofibers are not applied alone. The nanofibers may be applied by augmenting microfiber media by mixing the nanofibers with microfibers or by adding a layer of nanofibers to the surface of the microfiber medium. On a surface area basis, when nanofibers are mixed with the microfibers, the surface area increases faster than the pressure drop increases and so for media of equal fiber surface areas the media augmented with the nanofibers will generally have less pressure drop. Media with a surface layer of nanofibers may have a higher pressure drop if the nanofiber layer acts like a membrane with small holes that restrict the gas flow.

The second way that slip-flow is important is it improves the single fiber capture efficiency of small particles on the nanofibers. Because of the slip-flow phenomena, the gas flow streamlines pass much closer to the surface of the nanofiber than the microfiber. This means that direct interception of small particles in the gas stream improves because more of these particles pass close enough to collide with the nanofiber than with the microfiber.

More information on slip-flow and its effect on filter performance may be obtained in writings such as RC Brown, Air Filtration, Pergamon Press, Oxford, 1993.

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