Particle capture by air filter media having truncated log-normal fiber diameter distributions and random spacing of fibers

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WFC10  Discover the Future of Filtration & Separation
10th World Filtration Congress April 14–18, 2008 Leipzig, Germany

CONGRESS PROCEEDINGS

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Prof. Richard Wakeman, Great Britain
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Dr. Uwe Delfs, VDI-GVC
Mike Taylor, Filtech Exhibitions
Suzanne Abetz, Filtech Exhibitions
### Monday, 14.04.2008

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
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<tbody>
<tr>
<td>08:00 – 09:00</td>
<td>Registration for Short Courses</td>
</tr>
<tr>
<td>09:00 – 18:00</td>
<td>Short Courses</td>
</tr>
<tr>
<td>16:00 – 18:00</td>
<td>Registration + Poster Installation</td>
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<table>
<thead>
<tr>
<th>Time</th>
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<tr>
<td>08:00 – 10:00</td>
<td>Registration</td>
</tr>
<tr>
<td>10:00 – 11:00</td>
<td>Opening Ceremony</td>
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<tr>
<td>11:00 – 12:00</td>
<td>Plenary Lecture</td>
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<tr>
<td>12:00 – 13:15</td>
<td>Lunch</td>
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<tr>
<td>13:15 – 14:30</td>
<td>Invited Lecture 1, M 1, M 2, M 3, G 1, G 2</td>
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<td>14:30 – 15:00</td>
<td>Coffee Break</td>
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<tr>
<td>15:00 – 16:15</td>
<td>L 1, L 2, L 3, Invited Lecture 2, G 3, G 4</td>
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<td>16:15 – 16:45</td>
<td>Coffee Break</td>
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<tr>
<td>16:45 – 18:00</td>
<td>L 4, L 5, L 6, M 4, M 5, G 5, G 6</td>
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<tr>
<td>18:00</td>
<td>Welcome Reception in the Exhibition Hall</td>
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### Wednesday, 16.04.2008

<table>
<thead>
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<th>Time</th>
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<tbody>
<tr>
<td>08:30 – 09:45</td>
<td>L 7, L 8, L 9, M 6, M 7, G 7, G 8</td>
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<tr>
<td>09:45 – 10:15</td>
<td>Coffee Break</td>
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<tr>
<td>10:15 – 11:30</td>
<td>PL 1, PL 2, L 10, PM 1, PM 2, PG 1, PG 2</td>
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<tr>
<td>11:30 – 12:15</td>
<td>Poster Session, Poster Session</td>
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<tr>
<td>12:15 – 13:15</td>
<td>Lunch</td>
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<tr>
<td>13:15 – 14:30</td>
<td>L 11, L 12, L 13, M 8, M 9, Invited Lecture 3</td>
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<td>14:30 – 15:00</td>
<td>Coffee Break</td>
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<td>15:00 – 16:15</td>
<td>Invited Lecture 4, M 10, M 11, M 12, G 9, G 10</td>
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<td>16:15 – 16:45</td>
<td>Coffee Break</td>
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<tr>
<td>16:45 – 18:00</td>
<td>L 14, L 15, L 16, M 13, M 14, G 11, G 12</td>
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# Session Survey

## Thursday, 17.04.2008

<table>
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<td>L 17</td>
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<td>09:45 – 10:15</td>
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<td>10:15 – 11:30</td>
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<td>11:30 – 12:15</td>
<td>Lunch</td>
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<td>13:15 – 14:30</td>
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<td>Invited Lecture 5</td>
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<tr>
<td>14:30 – 15:00</td>
<td>Coffee Break</td>
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<td>15:00 – 16:15</td>
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<td>Invited Lecture 6</td>
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<td>16:45 – 18:00</td>
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## Friday, 18.04.2008

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<td>09:45 – 10:15</td>
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<td>10:15 – 11:30</td>
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<td>G 22</td>
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<tr>
<td>11:45 – 12:15</td>
<td>Closing Session</td>
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<td>12:30 – 13:15</td>
<td>Lunch</td>
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<tr>
<td>13:30 – 18:00</td>
<td>Post Congress Plant Tours</td>
</tr>
</tbody>
</table>
Tuesday – April 15, 2008

**Opening Ceremony** 10:00-11:00

**Plenary Lecture** 11:00-12:00
Filtration in the Framework of Globalisation and Technical Innovation, Prof. Richard J. Wakeman, Loughborough University, Great Britain (I-19)

**Invited Lecture 1** 13:15-14:30
Solid-Liquid-Separation by Cake Filtration - State of the Art and Future Expectations, Dr. Harald Anlauf, Karlsruhe University, Germany (I-21)

**M1 Gas Separation and Pervaporation** 13:15-14:30
Gas separation with supported ionic liquid membranes, A. Seeberger*, C. Kern, A. Jess, University of Bayreuth, Germany (I-40)

**M2 Potable Water** 13:15-14:30
Safe drinking water for everybody?! Membrane technology from small scale to large scale and vice versa, H. Futselaar*, J. Geluk, L. Broens, Norit Process Technology B.V.; J. Jacobs, Norit Membrane Technology B.V., Netherlands (II-55)

**M3 New Fibrous Membranes** 13:15-14:30
Functionalized and doped nanofiber filtration media with ionex and antimicrobial properties, J. Marek*, J. Svobodova, M. Juklickova, Elmarco Ltd.; L. Jelinek, University of Oulu, Finland (I-61)

**G1 Surface Filtration I** 13:15-14:30
Assessment of the cleanable dust filtration behaviour of surface treated needle felts by characterisation parameter determined by image analysis, W. Höflinger*, G. Mauschitz, H. Rud, J. Schuberth, Vienna University, Austria (III-37)

**G2 Electrostatic Precipitation** 13:15-14:30
Charge emission characteristics of a drained DBD electrode apparatus for nano-particle charging and precipitation, M. Wild, J. Meyer*, G. Kasper, Karlsruhe University, Germany (III-52)

**L1 Vacuum and Pressure Cake Filtration Fundamentals I** 15:00 -16:15
Suspension typology and computer aided characterization of the suspension filterability, I. Nicolaou*, FOS Ltd., Cyprus (I-37)

**L2 Sedimentation Fundamentals - Analytical Centrifugation I** 15:00 -16:15
Acquisition of compression-permeability data of soft and hard colloids based on centrifugation experiments, E. Iritani*, N. Katagiri, K. Aoki, M. Shimamoto, Nagoya University, Japan (I-51)

**G3** Continuous treatment and scrubbing of bottom ash from thermal waste treatment to produce improved granulate quality, R. Koralewska*, Martin GmbH; R. Grönnert, R. Hausdorf, Hans Huber AG, Germany; G. Zellinger, Kärntner GmbH; H. Gschaider, Binder+Co AG, Austria (I-76)
Equation for fitting dispersed systems gravity &

Darmstadt University, Germany

H. Nirschl, Karlsruhe University; J. Wagner, G. Hirsch, M. Feist*,
tling behaviour of particle-fiber-mixtures,
Theoretical and experimental approach to the set -
ger results,
Layout of rotary filters on the basis of laboratory
Larox Corp., Finland

pilot and bench scale test equipment,
Study on the scalability of pressure filtration in
University; B. Ekberg, Larox Corp., Finland

Häkkinen*, M. Huhtanen, J. Kallas, Lappeenranta
improving the efficiency of test filtration tasks,
Utilization of statistical design of experiments for

Kissling, M. Piesche, Stuttgart University, Germany

ventilation systems,
Development of oil droplet separators in crankcase
Numerical and experimental investigations on the

Höflinger, Vienna University, Austria

talworking fluid mist collector elements,
Development of a standardised test method on me-
metalworking fluid mist collector elements, P. Wlaschitz*,
W. Höflinger, Vienna University, Austria

(Fil)ration of liquid aerosols with a horizontal fibro-
us filter, A. Charvet*, Y. Gonthier, A. Bernis, E. Gonze,
University of Savoie, France

Numerical and experimental investigations on the
development of oil droplet separators in crankcase
ventilation systems, S. Schütz*, G. Gorbach, A. Zink,
K. Kissling, M. Piesche, Stuttgart University, Germany

Development of a standardised test method on metal-

L4 Vacuum and Pressure Cake
Filtration Fundamentals II
Utilization of statistical design of experiments for
improving the efficiency of test filtration tasks, A. Hakkinen*, M. Huhtanen, J. Kallas, Lappeenranta
University; B. Ekberg, Larox Corp., Finland

Study on the scalability of pressure filtration in
pilot and bench scale test equipment, J. Palmer*,
Larox Corp., Finland

Layout of rotary filters on the basis of laboratory
results, E. Ehrfeld*, R. Bott, T. Langeloh, Bokela GmbH,
Germany

L5 Sedimentation Fundamentals-
Analytical Centrifugation II
Theoretical and experimental approach to the settling behaviour of particle-fiber-mixtures, M. Feist*, H. Nirschl, Karlsruhe University; J. Wagner, G. Hirsch, Darmstadt University, Germany

Equation for fitting dispersed systems gravity &
centrifuge settling data, A. Yelshin*, M. Mota, University of Minho, Portugal; I. Yelshyna, Polotsk University, Belarus

Measurement of settling velocity enhancement by magnetic flocculation using manometric sedimentation centrifugation, M. Stolarski*, C. Eichholz, H. Nirschl, Karlsruhe University, Germany; B. Fuchs, DuPont, USA

L6 Optimization of Solid-Liquid
Separation Processes II
Life-cycle Cost Analysis for the Selection of the Optimal Equipment for Solid-Liquid Separation, S. Ripperger*, Kaiserslautern University, Germany

Commercial aspects of solid liquid separations in salt
 separation applications, D.E. Keller*, KMPT AG, Germany

Performance increase in solid-liquid separation, D.
Steidl*, BHS-Sonthofen; J. Tichy, Consulting Engineer,
Germany

Seawater intake and pre-filtration with Neodren*,
T. Peters*, Consulting for Membrane Technology, Germany; D. Pinto, E. Pinto, Catalana de Perforaciones S.A., Spain

Application of automatic backflushfilter to improve raw water pre-treatment of reverse osmosis desali-
nation plants, B. Schlichter*, P. Mehlem, R. Wnuk, HYDAC Process Technology GmbH, Germany; M. Parker, HYDAC Technology Corp., USA

Clean edge micro sealing of filtration modules – the cut&weld method, A. Korz*, K. Herzer, A. Hubrich, Textile Fusion Technologies GmbH, Germany

G5 Clogging of Candles and Cartridges
Modelling of the clogging of pleated filter for gas filtration, M. Rebai*, M. Prat, IMFT; M. Meireles, University of Toulouse; P. Schmitz, INSA; R. Baclet, S. Demeulemeester, Mecaplast Group, France

Study of pressure drop and aerosol penetration during clogging of mini-pleated air filters, A. Joubert*, S. Artous, L. Bouilloux, IRSN; S. Calle-Chazelet, D. Thomas, J. Remy, Nancy University, France

Experimental study on flow through concentric porous filter candle, A. Ijaz*, M. Saleem, University of the Punjab, Pakistan

G6 Fine Particle Precipitation
Fine dust precipitation in a Bayer-Reither venturi scrubber, M. Theis*, Bayer Technology Services GmbH; K. Reither, Reither Venturiwäscher GmbH, Germany

Prof. Richard P. Lydon, Clear Edge Group, Great
Britain

Advances relating to Filter Media Developments
Invited Lecture 2
15:00-16:15

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(I-111)
### Wednesday – April 16, 2008

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<th>Session</th>
<th>Title</th>
<th>Time</th>
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<tr>
<td>L7</td>
<td>Vacuum and Pressure Cake Filtration Fundamentals III</td>
<td>08:30-09:45</td>
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<tr>
<td>L8</td>
<td>Technical Centrifugal Filtration Selection and Optimization</td>
<td>08:30-09:45</td>
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<td>L9</td>
<td>Filter Media Cleaning</td>
<td>08:30-09:45</td>
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<tr>
<td>M6</td>
<td>Process/Waste Water Treatment</td>
<td>08:30-09:45</td>
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<td>M7</td>
<td>Reverse Osmosis</td>
<td>08:30-09:45</td>
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<td>G7</td>
<td>Depth Filtration &amp; Particle Deposition</td>
<td>08:30-09:45</td>
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<tr>
<td>G8</td>
<td>Measurement Techniques</td>
<td>08:30-09:45</td>
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<tr>
<td>PL1</td>
<td>Poster Session</td>
<td>10:15-12:15</td>
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</tbody>
</table>

**Filtration of silver nanoparticle agglomerates**, D.Y.H. Pui*, S.-C. Kim, J. Wang, M. Emery, University of Minnesota, USA (III-117)

**Enhancement of the thermophoretic aerosol particles deposition efficiency in a turbulent annular flow configuration**, B. Sagot*, F. Buroni, ESTACA; G. Antonini, University of Compiègne, France (II-122)


**Comparison of calculated and MRI determined 1-dimensional profiles of deposited particle material in depth filter media with ongoing loading**, J. Hoferer*, S. Schollmeier, J. Meyer, G. Kasper, Karlsruhe University, Germany (III-132)

**Evaluation of filter test rigs for fractional efficiency measurements according to filter test standards**, S. Schütz*, M. Schmidt, L. Mölter, Palas GmbH, Germany (III-142)

**Real time tunnel ventilation and filter control systems**, F. Schneider*, Grimm Aerosol Technik GmbH, Germany (III-147)

**Dust measuring technology for the monitoring of particulate emissions**, H. Födisch*, P. Schengler, Dr. Födisch Umweltmesstechnik AG, Germany (III-151)

**Deep Bed Filtration for Water and Wastewater**

**Water depuration by means of fibrous filter medium**, A. Budyka*, A. Shepelev, V. Rykunov, K. Lukina, Karpov Institute of Physical Chemistry, Russia (I-553)

**Field experiences with membrane filtration for reuse of biological wastewater effluents**, T. Baum*, S. Theiss, H. Eipper, Pall GmbH, Germany (II-115)

**Impacts of the influent toxicity on the efficiency of tertiary filtration of wastewater from petroleum industry**, S. Heng*, N. Lesage, Q. Su, Total Petrochemicals, France (II-120)
Centrifugal Sedimentation and Filtration
CFD multiphase flow simulation of a solid bowl centrifuge with radial compartments, X. Romani Fernández*, H. Nirschl, Karlsruhe University, Germany (I-572)


Hydrocyclones
Multiphase flow simulation of a hydrocyclone, R.-M. Wu*, C.-Y. Hsu, Tamkang University, Taiwan (I-582)

Particle Measurement - Contamination Control Granulometry and morphology by microscopy and image analysis, O. Huín*, Microvision Instruments SAS, France (I-586)

Microbes verification on oxygen consumption rate measurement of biofilm in drinking water, L.-F. Chen*, W.-L. Lai, Shu-Te University, Taiwan (I-591)

Separation Enhancement by Magnetic Forces
Using Magnetic Filtration for Removal of Heavy Metals from Water by Nanomagnetic Extractants, S. M. AlFadul*, King Abdulaziz City for Science Technology, Saudi Arabia; A. W. Apblett, Oklahoma State University, USA (I-596)

Separation of pharmaceutical products with reverse micelles, S.H. Mohd-Setapar, R.I. Wakeman, E.S. Tarleton, Loughborough University, Great Britain (I-601)

PL2 – Poster Session 10:15-12:15
Separation Enhancement by Electric Forces Electrofiltration of PHB, G. Gözke*, I. Perner-Nochta, C. Posten, Karlsruhe University, Germany (I-606)

Separation Enhancement by Chemical Additives Charge effects determine the filtration resistance in cake filtration and crossflow filtration experiments, H. Saveyn*, D. Curvers, P. Van der Meer, Ghent University, Belgium (I-611)

Laboratory Vacuum and Pressure Cake Filtration Miniaturisation of filtration processes - A necessity for the pharmaceutical industry, A. Schreiner*, R. Schneeberger, Novartis Pharma; S. Jerman, ETH Zurich, Switzerland (I-615)

Are standards in designing industrial filters for solid liquid filtration wisely and necessary?, J. Tichy*, H.-P. Schmid, BHS-Sonthofen GmbH; S. Ripperger, Kaiserslautern University, Germany (I-616)

Filtration Properties in Organic Solvents, S. Neubauer*, U.A. Peuker, Clausthal University, Germany (I-620)

Technical Vacuum and Pressure Cake Filtration Study on parameters affecting belt filtration of a metal precipitate suspension, S. Hirvisaari*, A. Häkkinen, J. Kallas, Lappeenranta University; B. Ekberg, Larox Corp.; A. Rautanen, Tamfelt Corp.; S. Storbacka, OMG, Finland (I-625)

Development of an automated online quotation tool, O. Sieking, E. Enenavaara, S. Henttu, Larox Corp., Finland; H. Brezina*, Larox GmbH, Germany (I-630)

Technical Vacuum and Pressure Cake Filtration – Media and Components Easy installation and improved performance with a new filter press cloth design for applications in e.g. waste water, B. Maurer*, R. Gaiser, H. Dür, Sefar AG, Switzerland (I-633)

Press Filtration Fundamentals
Mass transfer from porous particles during the pressing of biological materials, M. Petryk, Ternopil University, Ukraine; E. Vorobiev*, University of Compiègne, France (I-636)

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Influence of extractant molar volume on the alkali metal membrane extraction in closed system, Z. Albaraka*, D. Trebouet, M. Burgard, Strasbourg University, France; J.M. Loureiro, University of Porto, Portugal (II-281)

M18 Membrane Characterisation
15:00 - 16:15

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Characterization of the 3D pore morphology and connectivity of polymeric membranes by nano-transmission X-ray microscope, T.-T. Wu*, K.-L. Tung, C.-C. Chien, C.-Y. Lin, Chung Yuan University, Y.-F. Song, G.-C. Yin, Y.-M. Chen, National Synchrotron Radiation Research Center, Taiwan (II-291)

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Simulation of Particle Separation Processes Prof. Ulve Janoske, University of Cooperative Education Mosbach, Germany (III-29)

L29 Adsorption-Absorption in Deep Bed Filtration for Water&Wastewater 16:45 - 18:00

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Deep bed filtration optimization: Study of physical fouling and chemical saturation of permeable reactive barriers at pilot scale, P. Ginisty*, IFTS; A. Esnault-Filet, Soletanche Bachy, France (I-454)

Use of wood fiber filter for advanced treatment of municipal wastewater, M.-Y. Oh*, M.-Y. Kim, Y.-K. Kim, Kangwon University, Korea (I-459)

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Advances in laboratory performance evaluation of hydraulic filter elements - Application to the study of aircraft hydraulic filter elements, P. Madhavan, L. Bensch, Pall Corporation; X. Tao*, Southwest Research Institute, USA (I-469)

Measurement of water separation efficiency of diesel fuel filters, C. Peuchot*, N. Petiton, IFTS, France (I-474)

L31 Separation Enhancement by Chemical Additives III 16:45 - 18:00

Industrial wastewater treatment utilizing zeta potential measurements, S. Emeish*, Al-Balqa' Applied University, Jordan (I-479)

Artificial neural networks for on-line control of coagulation in drinking water treatment, H.-J. Malzer*, A. Nahrstedt, S. Panglisch, IWW Water Center; S. Strugholtz, University of Duisburg-Essen; J. Gebhardt, aquatune – Dr. Gebhardt & Co. GmbH; W. Zach, Stadtwerke Düren, Germany (I-484)

Classification of manganese-doped zinc sulfide nanoparticles by size, Y. Mori*, Y. Arao, H. Ishizuka, Doshisha University, Japan (I-489)

M19 Membrane Modules Modelling (CFD)
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CFD studies for flow and concentration profiles in feed channels of spiral-wound membrane modules, M. Shakaib*, S.M.F. Hasani, M. Mahmoud, NED University Karachi, Pakistan (II-305)

Modelling the two phase flow in a pilot submerged Membrane bioreactor, E. Nguyen Cong Duc*, B. Lesjean, Berlin Center of Competence for Water; C. Levrecq, Anjou Recherche, France (II-310)

M20 Submerged Membranes 16:45 - 18:00

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Membrane separation processes assisted by in situ streaming potentials measurement in low pressure MF/UF immersed membranes, M. Pontiè*, Angers University, France (II-320)

Treatment of wastewater using microfiltration submerged membranes, S. Bou-Hamad*, A. Al-Safar, A. Al-Saraiifi, Kuwait Institute for Scientific Research, Kuwait (II-325)
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G17 Filter Media Fabrication  16:45-18:00
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Nanofibres by centrifuge spinning to improve filter media, M. Dauner*, A. Ullrich, ITV Denkendorf; F. Reiter, Reiter Oberflächentechnik GmbH, Germany (III-278)

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M23 Membrane Bio Reactor I  08:30-09:45

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Numerical investigations of diesel particulate filter systems with 2D and 3D simulation models, T. Deuschle*, M. Piesche, Stuttgart University, Germany (III-323)

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Framework for selecting thin-cake candle filter technology for removing solid contaminant fines from recirculating acid gas scrubbing fluid streams, B.A. Perlmutter*, G.E. Schlager, BHS-Filtration Inc., USA (I-499)

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Microsieves – Low filter area, high performance, A. Damm*, Bayer Technology Services GmbH, Germany; B. Broacades, Fluxion B.V., Belgium (II-350)

Micro filtration with silicon nitride micro sieves and high frequency back pulsing, C.N. Koh*, T. Wintgens, T. Melin, Aachen University, Germany; F. Pronk, B. Broacades, Fluxion B.V., Belgium (II-354)

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The Effects of diesel fuel additives on water separation performance, S. Hutzler*, G.B. Bessee, Southwest Research Institute, USA (I-529)

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Removal of arsenic from wastewaters by batch airlift electrocoagulation, H.K. Hansen*, P. Nunez, C. Jil, Technical University Federico Sta. Maria, Chile

Nanofiltration operation as a sustainable water defluoridation operation dedicated to large scale pilot plants for the future, M. Pontié*, H. Dach, Angers University, J. Leparc, Veolia Water, France; A. Lhassani, University of Fes, Morocco

Properties of downward and upward ultrafiltration of nanoparticle suspensions, Y. Mukai*, S. Shida, E. Iritani, Nagoya University, Japan

Experimental study on the desalination of polymer-flooding oil-extraction wastewater with UF-EDR combined system, S.-L. Yu*, J. Xu, X. Zuo, D. Wang, J. Liu, H. Lu, Harbin Institute of Technology, P.R. China

Influence of membrane polymer on adsorptive fouling in microfiltration of wine, O. Schuster*, W. Ansorge, B. von Harten, Membrana GmbH; M. Ulbricht, University Duisburg-Essen, Germany

Application of binary packing for polysaccharides separation by hydrodynamic chromatography, A. Yelshin*, M. Mota, J.A. Teixeira, A. Yelshin, University of Minho; R. Diash, University of Bragança, Portugal

Improved virus retention assurance using novel high productivity parvovirus retentive filters, G. Tkacik*, M. Krishnan, Millipore Corp., USA; G. Kern, Millipore SAS, France


Mechanism of enhanced biological nitrogen and phosphorus removal in ICAS-MBR System, Y. Wang, S.-L. Yu*, F. Zhao, D. Wang, Harbin Institute of Technology, P.R. China

Effect of cyclophosphamide and its main metabolites on the performance of a membrane bioreactor, C. Albasi*, L.F. Delgado, V. Faucet-Marquis, A. Leszkowicz, University of Toulouse; M. Audran, Lapeyronie Hospital, M. Castegnaro, CDS, France

HYCOKNIT® - High efficient cleanable filter media for process gas filtration, E. Schmalz*, STFI e.V.; W.P. Frenzel, ILK GmbH, Germany

Low pressure plasma coatings allows to produce in an economical, environmental friendly way, M. Pauwels*, Europlasma N.V., Belgium

High efficient cleanable depth filter media for process gas filtration and an inno-vative all-purpose compact filter apparatus, E. Schmalz*, STFI e.V., Germany

Flow phenomena in mechanical separation technology, C. Seyfert*, N. Sautter, S. Schütz, M. Piesche, Stuttgart University, Germany

CFD numerical flow simulation of particulate-laden and bulk solid flows - A state of the art, M. Lotfey*, ANSYS Fluent Deutschland GmbH, Germany

The design of electrostatic precipitators by use of physical models, P. Tronville*, Torino University; G. Bacchigla, R. Sala, IRS s.r.l.; I. Gallimberti, Padova University; F. Zatti, Area Impianti s.p.a., Italy

Announcement of the Host of the next WFC.

Effect filter performance under various contaminants, X. Tao*, Southwest Research Institute; P. Madhavan, L. Bensch, Pall Corporation, USA

The Programme lists countries and regions and is subject to amendments. Errors and omissions excepted.
PARTICLE CAPTURE BY AIR FILTER MEDIA HAVING TRUNCATED LOG-NORMAL FIBER DIAMETER DISTRIBUTIONS AND RANDOM SPACING OF FIBERS

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Richard D. Rivers, EQS Inc., 1262 Bassett Avenue, Louisville, KY 40204, USA
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ABSTRACT

Studies by present authors have detailed procedures for 2-D simulations of flows through air filter media having fibers with truncated log-normal distributions, these fibers being located at random positions. Flow simulation is the essential first step to enable calculation of the particle capture efficiency of a fibrous filter medium. In the present study both aerodynamic and diffusive effects on particle capture were investigated. Comparisons are given between efficiency measurements on media samples and values calculated by CFD simulations of the same media for spherical particles from approximately 0.4 µm to 10 µm diameter. Results show that pressure drop calculated with the slip boundary condition is closer to measured values, and also that Brownian motion is important for efficiency calculation for particles of diameter less than 1 µm.

KEYWORDS

Fibrous air filter media, Particle fractional efficiency, CFD simulation, Aerodynamic forces, Diffusion, Random fiber distribution

1. Introduction

To optimize the design of the filter media for any desired efficiency on any aerosol of known characteristics, it is necessary to develop methods to calculate the particle-capture efficiency of the media studied. For the prediction of filter performance, knowledge of the aerosol dynamic interaction with the flow between the fibers of the filter material is crucial. Computational fluid dynamics (CFD) allows achieving very detailed information about the complex flow pattern within the medium, and then calculating the paths of particles carried by this flow. For the studies reported here, the authors have simulated the actual 3D structures of the filter media by two dimensional (2D) patterns of circles having truncated log-normal diameter distributions, with centers located at random positions in the simulating CFD domain.

The separation of airborne particle by fibrous filters is due to the combination of several collection mechanisms (1) (2). Particles smaller than 1 µm are strongly affected by Brownian diffusion, large particles very little. The reverse is true of aerodynamic drag. In this study, both effects are included in the CFD simulation of particle capture. Particle bounce and re-entrainment are considered negligible; once a particle touches a fiber surface we assume that it is captured. This is a good approximation for a liquid aerosol which wets the fiber surfaces and spreads into a
thin layer on them (2). The test aerosol used for efficiency measurements was generated from liquid DEHS, di(2-ethylhexyl) sebacate, which has these properties. We also limit ourselves to the case of essentially clean filter media, whence the air flow will not be influenced by the deposited particles.

2. Flow and CFD Considerations

In this study, we first explored the capabilities of a commercial CFD code solving the Navier-Stokes (N-S) equations for the gas flow and we made some trials using an open-source CFD code, OpenFOAM (3). Other approaches are possible, and may be necessary for inclusive solutions to this problem. These include the use of the Lattice-Boltzmann simulation (4) and the Direct Simulation Monte Carlo (5) methods.

In order to calculate the efficiency it is necessary to describe the air flow pattern through the medium. A critical element in this solution is the selection of boundary conditions at the impermeable surfaces within the computational domain – here, randomly placed circles. When the objects in the path of a gas flow are large relative to the gas mean free path, there are many simultaneous or nearly simultaneous collisions between gas molecules and surface, and the individual collisions are not apparent. Since there are so many collisions with each direction of impact equally probable, the gas at the body surface behaves as if the molecules there had zero tangential velocity, i.e. it is standing still. This is the condition of “continuum flow”, and a force tangential to the surface, viscous drag, is generated. The condition is also called the “no slip” boundary condition.

For quite small bodies in the flowing gas, far fewer collisions between gas molecules and the surface of the body occur in a given time interval. The gas at the surface no longer behaves as if it were standing still; the tangential velocity at the surface is non-zero, and various degrees of “slip” are said to occur - the flow regime “slip flow”. The criterion determining the shift from one regime to another for a body in a flow is the Knudsen number (Kn), which is λ/D, [mean free path of air] divided by [object characteristic dimension]. In our case, the characteristic dimension is fiber diameter. Continuum flow is fully established at Knf = 0.001, and the N-S equations with no-slip boundary equations apply. For 0.001<Kn<0.1, the N-S equations with “full slip” boundary conditions apply. For Knf >10, “molecular flow” conditions apply, and the N-S equations no longer describe the behavior at all. The range 0.1<Knf<10 is a transition between slip and molecular flow, also requiring a set of flow equations different from N-S. The effect of Brownian diffusion and the influence of slip at the boundary for our model are discussed below.

We consider the flow through the CFD domain to be incompressible, steady state, 2D and viscous at very low Reynolds number. In the filter medium, fibers lay approximately in planes perpendicular to the flow (6), hence in 2D are represented by circles. The finite volume method is implemented to calculate the flow field (i.e. the computational domain is subdivided into many small control volumes). The governing differential equations are converted into their algebraic equivalents and numerically integrated over these control volumes. Through this process the flow field is solved. The trajectory of a discrete phase particle (or droplet) in this flow field is predicted by
integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for the x direction in Cartesian coordinates) as

$$\frac{\rho_p \pi d_p^3}{6} \frac{du_p}{dt} = F_D(u - u_p) + F_b,$$

where $d_p$ is the particle diameter and $\rho_p$ the particle density. $F_D(u - u_p)$ is the aerodynamic drag force on the particle and $F_b$ represents the amplitude of the Brownian force component. $u$ and $u_p$ are the x-component of the local gas and particle velocity respectively. Similar equations are written for the y-components. In these equations for particle dynamics, gravitational force and electrostatic forces are all considered to be negligible.

An example of the computational domain to be solved is shown in Figure 1.

Figure 1 – Layout of simulated fibers generated randomly in computational domain

The gas flows from left to right in the direction of increasing $x$. Gas velocity is set uniform and parallel to the $x$ axis at $x = -X_1$ (i.e. $v_x = V_0$ and $v_y = 0$). At $x = L_2$, the gradient of the pressure is set equal to zero. Boundaries at $y = 0$ and $y = W$ are assigned symmetry conditions. Although there is no plane of symmetry in the actual fibrous structure, the lateral flow is probably negligible inside the media. On the symmetry boundary particles are not allowed to escape and are reflected. Slip conditions at the circular boundaries applied in separate runs were either “no slip” (null tangential velocity at the wall) or “full slip” (no shear stress close to the wall). Theory suggests that these slip conditions should have been applied on the circle boundaries according to their diameters and hence $Kn$. The results of particle capture simulation (see below) suggest that $Kn$ dependency should be implemented; it might not affect pressure drop results significantly, because the number of large diameter circles is small. The open source CFD code OpenFOAM will allow such modifications to boundary conditions in future studies.

### Table 1 – Input data for air flow simulation and particle capture (F6 medium)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max diameter of fiber (µm)</td>
<td>15.76</td>
</tr>
<tr>
<td>Min diameter of fiber (µm)</td>
<td>1.15</td>
</tr>
<tr>
<td>Media domain length (µm)</td>
<td>430</td>
</tr>
<tr>
<td>Total domain length (µm)</td>
<td>670</td>
</tr>
<tr>
<td>Media thickness (µm)</td>
<td>75</td>
</tr>
<tr>
<td>Solid fraction (%)</td>
<td>7.60</td>
</tr>
<tr>
<td>Average air temperature (K)</td>
<td>293</td>
</tr>
<tr>
<td>Inlet air velocity(m/s)</td>
<td>0.0617</td>
</tr>
<tr>
<td>Particle release rate (kg/s)</td>
<td>0.001</td>
</tr>
<tr>
<td>Particle density (kg/m³)</td>
<td>912</td>
</tr>
</tbody>
</table>

If the mesh used is dense enough the discretization scheme of the first order gives results very similar to the second order discretization scheme. Because of the limit of the BlockMesh mesh generator in OpenFOAM for meshing our geometry, Blender, Calculix and Gmsh mesh generators were tried and compared. Blender requires the
user to create rectangular cells first, link the vertices of rectangles, and then set the subsurface level to create circles, which control the mesh size. This is very labor-consuming. The generated rectangular mesh is then extruded into 3D in Calculix, where surfaces are selected to facilitate OpenFOAM boundary setting.

![Comparison of the mesh around fibers - Blender (a),(b); Gmsh (c),(d)](image)

Figure 2 - Comparison of the mesh around fibers - Blender (a),(b); Gmsh (c),(d)

In our model, there are regions where inter-fiber distance is small compared with dimensions of the domain. Therefore, the mesh in the gap needs to be small, while the mesh in other spaces is larger. As is shown in Figure 2 (a) and (b), rectangular meshes generated by Blender are smooth. But since criteria are difficult to set for linking rectangular cells in the open areas to the circular fiber boundaries, some mesh cells may extend into some circle boundaries.

Gmsh is an automatic 3D mesh generator for unstructured mesh and its mesh resolution is controlled by setting a characteristic length. A finer mesh could be generated in critical areas without generating too many cells elsewhere in the domain (Figure 3). For this reason, Gmsh was chosen as our preprocessor-mesh generator.

![The whole domain model mesh using Gmsh](image)

Figure 3 - The whole domain model mesh using Gmsh

3. Results and Discussions – Simulation of pressure drops
As one would expect, the predicted pressure drop with “full slip” boundary conditions implemented was lower than when “no slip” conditions were implemented (Figure 4).

![Simulated pressure drop as a function of air velocity](image)

Figure 4- Simulated pressure drop as a function of air velocity

Experimental values of air flow resistance for the three media (F6, F8 and H13) are reported in (6). For the F6 medium, the measured pressure drop at 0.0617 m/s was 11 Pa. The simulation with full slip at 0.0617 m/s gives approximately 18.5 Pa. This
difference could be due to several things: too many fine fibers in the simulated
diameter distribution; blockage of too much of the domain by a single large circle;
inapplicability of the N-S equations to flow in geometries of the present scale; and the
difficulty of accurate measurement of such small pressure drops.

Simulation of particle-capture efficiency
When a particle touches an impermeable boundary (i.e. a circle representing a fiber) it
is considered captured, hence eliminated from the computational process.
Fractional efficiency simulation results for 0.4 µm and 2.0 µm particle sizes are
reported in Table 2.

Table 2 - Effect of slip boundary and Brownian motion on efficiency
for different particle diameters (F6 medium)

<table>
<thead>
<tr>
<th>Condition combination:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Slip</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Brownian motion</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Simulated efficiency (%)</td>
<td>0.4 µm</td>
<td>2</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.0 µm</td>
<td>6</td>
<td>51</td>
<td>16</td>
</tr>
<tr>
<td>Measured efficiency (%)</td>
<td>0.4 µm</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 µm</td>
<td></td>
<td></td>
<td>54</td>
</tr>
</tbody>
</table>

For 2 µm diameter particles the experimental result is close to the simulated ones for
combinations 2 and 4. The simulated efficiency is, as expected, very sensitive to
Brownian diffusion. The poor agreement between measurement and simulation
suggests that the simulation algorithm overestimates the effect of Brownian motion.

4. Conclusions
Simulation using the truncated log-normal fibrous model and the OpenFOAM CFD
code with Gmsh as mesh generator gives good agreement with measured capture
efficiency for 2 µm diameter particles. The simulation confirms the importance of
Brownian motion for sub-micrometer particles. Further modification is needed to bring
simulated and measured efficiencies together for the sub-micrometer diameter range.

5. Acknowledgements
This paper is supported by China Scholarship Council (No. 2007U20027).

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