

Effect of slip flow on the pressure drop in fibrous filters

Original

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FILTECH 2009

CONFERENCE PROCEEDINGS

VOLUME II

CONTENT VOLUME I

Scientific Committee	I-2
Session Survey	I-3
Conference Programme	I-4
Session Chairmen	I-17
Survey Lectures	I-19
Papers L-Sessions	I-95
Keyword List (Page Indicator)	I-587

CONTENT VOLUME II

Scientific Committee	II-2
Session Survey	II-3
Conference Programme	II-4
Session Chairmen	II-17
Papers G-Sessions	II-19
Papers M-Sessions	II-477
Keyword List (Page Indicator)	II-773

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October 13 – 15, 2009

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S E S S I O N S U R V E Y

Tuesday, October 13, 2009

8.30 – 9.45

Registration

9.45 – 11.30

Opening Session / Plenary Lecture

11.30 – 12.15

Walk Around – Fair

12.15 – 13.15

Lunch

13.15 – 14.30	S1	L1	M1	G1
	Survey Lecture 1	Sedimentation Analysis in the Gravity Field	Waste Water Treatment	Air Filter I
15.00 – 16.15	S2	L2	M2	G2
	Survey Lecture 2	Sedimentation Analysis in the Centrifugal Field	Produced Water Treatment	Air Filter II
16.45 – 18.00	S3	L3	M3	G3
	Survey Lecture 3	Sedimentation and Flotation for Sorting	Combined Processes	Surface Filtration

Wednesday, October 14, 2009

8.30 – 9.45	L4	L5	M4	G4
	Sedimentation in Centrifuges/Hydrocyclones	Poster Session I	Poster Session I	Poster Session I
9.45 – 11.00	Coffee Break - Fair	Poster Presentation	Poster Presentation	Poster Presentation
11.00 – 12.15	L6	L7	M5	G5
	Filter Media Characterization	Cake Filtration Analysis I	Deposition Control	Industrial Gas Cleaning
12.15 – 13.15	Lunch			
13.15 – 14.30	S4	L8	M6	G6
	Survey Lecture 4	Cake Filtration Analysis II	Membrane Fouling	Filter Test Systems I
15.00 – 16.15	L17	L9	M7	G7
	Depth Filtration Processes	Cake Filtration Processes I	Modelling and Simulation	Filter Test Systems II
16.45 – 18.00	L10	L11	M8	G8
	Depth Filtration Analysis I	Cake Filtration Processes II	Special Membranes	Hot Gas Cleaning

Thursday, October 15, 2009

8.30 – 9.45	L12	L13	M9	G9
	Washing of Particles and Cleaning of Media	Poster Session II	Poster Session II	Poster Session II
9.45 – 11.00	Coffee Break – Fair	Poster Presentation	Poster Presentation	Poster Presentation
11.00 – 12.15	L14	L15	G10	G11
	Separation Enhancement by Magnetic Forces	Depth Filtration Analysis II	Monitoring and Control	Filter Media Clogging
12.15 – 13.15	Lunch			
13.15 – 14.30	S5	L16	G12	G13
	Survey Lecture 5	Separation Enhancement by Physical & Chemical Slurry Treatment	Ab- and Adsorption	Nanofibre Filter Media
15.00 – 16.15	L18	L19	G14	G15
	Backwashing Filtration Processes	Precoat Filtration	Modelling and Simulation I	Special Filter Media
16.45 – 18.00	L20	L21	G16	G17
	Filter Media Development and Application	Selective Separation and Classification	Modelling and Simulation II	Mist and Droplet Separation

Tuesday – October 13, 2009

Opening Ceremony		09:45-10:30	
Plenary Lecture		10:30-11:30	
	Introduction to the characterisation of products prior to formulating a solid-liquid separation problem , Dr. Christophe Peuchot, IFTS - Institute for Filtration and Separation, France		I-19
S1	Survey Lecture	13:15-14:30	
	Advances in Pore Structure Evaluation by Porometry , Dr. Krishna Gupta, Porous Materials, Inc - USA		I-21
L1	Sedimentation Analysis in the Gravity Field	13:15-14:30	
	Evaluation of consolidation-sedimentation properties in batch gravity sedimentation of concentrated suspension , N. Katagiri*, T. Hashimoto, E. Iritani, Nagoya University, Japan		I-95
	Modeling the settling velocity of flocs using fractal geometry , A. Vahedi*, B. Gorczyca, University of Manitoba, Canada		I-103
	Laboratory scale evaluation of inclined settling , T. Sobisch*, D. Lerche, LUM GmbH, Germany		I-112
M1	Waste Water Treatment	13:15-14:30	
	Improved treatment of secondary effluent with ultrafiltration , T. Peters*, Dr.-Ing. Peters consulting for membrane technology and environmental engineering, Germany		II-477
	Processing and characterization of ceramic membranes for efficient removal of lignin from bleaching effluents , M. Ebrahimi*, S. Kerker, A. Wienold, University of Applied Sciences Giessen-Friedberg; H. Neul, A. Ante, Bamag GmbH; M. Hilpert, Sappi Fine Paper Europe; P. Mund, Atech Innovations GmbH, Germany; P. Czermak, Kansas State University, USA		II-485
	Electro-ultrafiltration of liposomal dispersions for the removal of trace micropollutants , H. Saveyn*, M. Hakimhashemi, B. De Bock, P. Saveyn, P. Van der Meeren, Ghent University, Belgium		II-491
G1	Air Filter I	13:15-14:30	
	The effect of pleat count and air velocity on the initial pressure drop and fractional efficiency of HEPA filters , I. S. Al-Attar*, E. S. Tarleton, Loughborough University; R. J. Wakeman*, Consultant Chemical Engineer, UK; A. Husain, Kuwait Institute for Scientific Research KISR, Kuwait		II-19
	Interaction of fluid with porous structure in filtration processes: Modelling and simulation of pleats deflection , H. Andrä, O. Iliev, M. Kabel*, Z. Lakdawala, K. Steiner, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; V. Starikovicius, Vilnius Gediminas Technical University, Lithuania		II-27
	Importance of mechanical filtration in HVAC bags and panel air filter applications , A. Boni*, Hollingsworth & Vose Europe, Germany; J. Manns, D. Healey, S. Cox, Hollingsworth & Vose, USA		II-32
S2	Survey Lecture	15:00-16:15	
	Membrane Pore Characterization Techniques - Status Quo and Future Development , Prof. Kuo-Lun Tung, Chung Yuan Christian University, Taiwan		II-37

L2	Sedimentation Analysis in the Centrifugal Field	15:00 -16:15
	Sedimentation and consolidation behaviour of flocculated suspensions characterized by different methods measuring transmission , T. Sobisch*, A. Zierau, D. Lerche, LUM GmbH; A. Bjeoumikov, IFG GmbH; M. Holke, IAP e.V., Germany	
	The use of analytical centrifugation for the assessment of particulate matter compressibility , P. Van der Meeren*, D. Curvers, H. Saveyn, Ghent University, Belgium; P. J. Scales, University of Melbourne, Australia	
	Characterization of sedimentation and consolidation behaviour of kaolin suspensions in presence of dispersant , C. Le Coeur*, O. Larue, E. Vorobiev, University of Compiègne, France; T. Detloff, T. Sobisch, A. Zierau, D. Lerche, LUM GmbH, Germany	
M2	Produced Water Treatment	15:00 -16:15
	Application of inorganic membrane technology in the efficient treatment of oilfield produced water , M. Ebrahimi*, D. Willershausen, L. Engel, University of Applied Sciences Giessen-Friedberg; P. Mund, P. Bolduan, Atech Innovations GmbH, Germany; P. Czermak, Kansas State University, USA	
	Treatment of hypersaline oilfield produced water in a membrane sequencing batch reactor , A. Fakhru'l-Razi*, A. R. Pendashteh, D. R. A. Biak, C. A. Luqman, Z. A. Zurina, University Putra Malaysia, Malaysia; S. S. Madaeni, Razi University, Iran; W. M. Zahid, King Saud University, Saudi Arabia	
	Peroxidase-peroxide system catalyzed the removal of phenol and total hardness from produced water , K. F. Mossallam*, F. M. Sultanova, N. A. Salimova, Azerbaijan State Oil Academy, Azerbaijan	
G2	Air Filter II	15:00 -16:15
	Experimental investigation on the particle distribution and rearrangement in filter media , T. Häusle*, A. Hammen, H. Sauter, Mahle Filtersysteme GmbH, Germany	
	Fungal colonization of fibrous air filter media: Influence on filter's permeability and fungal particules release , J. C. Bonnevie-Perrier, L. Le-Coq*, Y. Andrés, Ecole des Mines de Nantes, France	
	The Eurovent certification program of air filters , I. Bodenstaff*, AAF International, Netherlands	
S3	Survey Lecture	16:45 -18:00
	Towards predicting filtration and separation - Progress and challenges , I-48 Dr. Andreas Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM - Germany	
L3	Sedimentation and Flotation for Sorting	16:45 -18:00
	Use of colloidal gas aphrons for separation of water based printing inks and impurities from paper stock suspensions , D. Voß*, S. Schabel, University of Darmstadt, Germany	
	Separation of fibre fines and inorganic fines in recovered paper suspensions , I-145 G. Hirsch; S. Schabel, D. Voß*, University of Darmstadt; M. Feist; H. Nirschl, Karlsruhe University, Germany	
	Tracer studies of the flow structure in a DAF pilot plant , L. Jönsson*, I-153 University of Lund; M. Lundh, Kretsloppskontoret, Sweden	

M3 Combined Processes 16:45 -18:00

Regeneration of stainless steel pickling solutions by a multi-stage process consisting of retardation, electro dialysis and membrane electrolysis, H. J. Rapp*, Osmo Membrane Systems; F. Rögener, M. Sartor, T. Reichardt, BFI, Germany II-521

Total regeneration of mixed pickling acid from stainless steel production - Combination of nanofiltration and thermal processes, F. Rögener*, T. Reichardt, BFI; J. Schmidt, F. Knaup, Steuler Anlagenbau, Germany II-529

Industry state of the art in membrane filtration of fruit juice and wine for product clarification, E. Zimmer*, D. Jermann, Bucher Processstech AG, Switzerland II-534

G3 Surface Filtration 16:45 -18:00

Dust emission characteristics of pulse jet bag filters, H.-S. Park*, K. S. Lim, KIER - Korea Institute of Energy Research, Korea II-55

Testing and analysis on performance of PSA filter media used for bag filter, Z. Liang*, H. Shen, Donghua University, P.R. China II-61

Removal of fine particulate matter from exhaust gases by metallic micro-sieves, E. Stahl*, J. Robert, G. Deerberg, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, Germany II-67

Wednesday – October 14, 2009

L4 Sedimentation in Centrifuges/Hydrocyclones 08:30 -09:45

Flow patterns and sediment build-up in tubular bowl centrifuges, L. E. Spelter*, H. Nirschl, Karlsruhe University, Germany I-161

CFD simulation of flow and sedimentation in centrifugal field, X. Romání Fernández*, H. Nirschl, Karlsruhe University, Germany I-169

Separation efficiency determining parameters in high gradient magnetic centrifugation, K. Wagner*, M. Stolarski, C. Eichholz, H. Nirschl, University Karlsruhe, Germany I-177

L5 Poster Session I 08:30 -09:45

· **Cake Filtration** ·

Green liquor sludge separation, a comparison between gasifier and recovery boiler produced liquors, T. Mattsson*, T. Richards, Chalmers University of Technology, Sweden I-185

Pilot scale research on oily sludge compression treatment, X. Hu*, S. Chengzhi, Y. Shufan, D. Jun, C. Chaozhong, Northeastern University; L. Chonghua, et al., PetroChina Liaohe Petrochemical Company, P.R. China I-193

· **Separation Enhancement by Physical and Chemical Slurry Treatment** · I-201
Fundamentals of stability of sulfur in iron chelate, K. Forsat*, K. Mohammadbeigy, Research Institute of Petroleum Industry (RIPI), Iran

Dairy effluent treatment plant with UASB reactor, E. Henríquez Díaz, O. Pérez Báez, A. Naranjo Ojeda, d. I. C. Ling Ling*, University of Las Palmas de Gran Canaria, Spain I-208

The comparability and optimization of different process of sludge dewatering, I-213
Y. B. Li*, J. Jin, Liaoning Provincial Environmental Protection Bureau, P.R. China

M4 **Poster Session I**

08:30 -09:45

Effect of polymer swelling on the nanofiltration performance of poly(vinyl alcohol), II-542
O. Farid, J. P. Robinson*, University of Nottingham, UK

β -Cyclodextrin-Modified polysulfone membranes for the removal of endocrine disrupting chemicals (EDCs), II-550
S. Choi*, S.-Y. Kwak, Seoul National University - Korea

Preparation and characterization of aluminum oxide cermet microfiltration membrane using atmospheric plasma spraying, II-552
C.-C. Hsiung*, T.-C. Ling, K.-S. Chang, K.-L. Tung, T.-T. Wu, Y.-L. Li, C.-H. Kang, W.-Y. Chen, D. Nanda, Chung Yuan University, Taiwan

Preparation and characterization of novel hydrophilic low pressure nanofiltration membranes for water softening, II-560
M. Jahanshahi, A. Rahimpour*, N. Mortazavian, Babol University of Technology, Iran

Nanoporous polyethersulfone membranes prepared with synthesized poly(sulfoxide-amide) as additive in the casting solution for milk filtration, II-567
A. Rahimpour*, Babol University of Technology; S. S. Madaeni, Razi University; A. Shockravi, S. Gorbani, Teacher Training University, Iran

Supported lipid membrane systems for commercial aquaporin water filtration applications, II-575
J. S. Groth, M. Perry, T. Vissing, Aquaporin A/S; J. S. Hansen, J. Vogel, S. Ibragimova, C. H. Nielsen, O. Geschke, J. Ern us, Technical University of Denmark; C. R. Hansen, Copenhagen University, Denmark

Drying of transformer oil with different filter techniques, II-579
C. Glasner*, J. Robert, G. Deerberg, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, Germany

Immobilization of fungal laccase on membrane and its use for decolorization of dye, II-587
N. Katagiri*, Y. Ogi, E. Iritani, Nagoya University, Japan

Membrane bioreactor with submerged ceramic flat membranes for the production of organic acids, II-594
T. Hahn*, Z. Kovacs, I. Hannemann, K. Grau, University of Applied Sciences Giessen-Friedberg; H. J. Schmidt, Membrane Engineering GmbH; M. Kraume, Technical University Berlin, Germany; P. Czermak, Kansas State University, USA

Long term experiences using microfiltration membranes for separation of bacterial biomass in recirculating aquaculture system, II-600
A. Gerbeth*, B. Gemende, N. Pausch, M. Schwind, University of Applied Sciences Zwickau; A. von Bresinsky, Fischwirtschaftsbetrieb Andreas von Bresinsky; R.-P. Busse, Busse GmbH, Germany

Research & development in microfiltration technology (MF) at KISR, II-607
A. Alsaffar*, S. Bou-Hamad, A. Alsairafi, M. Alshimmiri, H. Alnaser, Kuwait Institute for Scientific Research, Kuwait

G4 **Poster Session I**

08:30 -09:45

Simulation of DPF media, soot deposition and pressure drop evolution, II-74
K. Schmidt*, S. Rief, A. Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM, S. Ripperger, Germany

Modeling of particle layer detachment under consideration of transient kinetic effects, Q. Zhang*, E. Schmidt, University of Wuppertal, Germany II-81

Theoretical considerations on optimization of fibrous filters structures for removal of fractal-like nanoaggregates, A. Podgórski*, M. Goszczynska, Warsaw University of Technology, Poland II-89

Inertial deposition of aerosol particles in fibrous filters at low and intermediate Reynolds numbers, V. A. Kirsch*, Frumkin Institute of Physical Chemistry and Electrochemistry; D. A. Pripachkin, A. K. Budyka, Karpov Institute of Physical Chemistry, Russia II-92

Theoretical study of the efficiency of nano-sized aerosol particles in a single fiber, J. M. Silva, F. O. Arouca*, J. A. S. Gonçalves, J. R. Coury, Federal University of São Carlos, Brazil II-99

Experimental investigations of electrostatic precipitators with high flow velocities, M. Kaul*, E. Schmidt, University of Wuppertal, Germany II-106

Investigation of regeneration mode in a compact granular bed filter for high temperature filtration, K. Pathmanathan*, J. E. Hustad, O. K. Sønju, NTNU Norwegian University of Science and Technology, Norway II-110

Particle and H₂S removal of ceramic filter system, K. S. Lim*, H.-S. Park, S. J. Park, KIER Korea Institute of Energy Research, Korea II-118

Recovery of VOCs using small scale prototype unit based on electrically conducting carbon monolithic adsorbents, P. Sklenickova, S. Tension, MAST Carbon International Ltd.; A. Wheatly, P. Row, Wellman Defense Ltd., UK II-123

Venturi scrubber venturi efficiency for collection of particulate pollutants emitted by the burning vegetal biomass fuel, M. A. Martins Costa, F. de Almeida Filho, S. Pupo de Moraes, B. de Araújo Lima, B. Santos Ferreira, D. Aparecido Silva Lopes, Paulista State University; M. Lopes Aguiar, N. A. Gómez-Puentes*, Federal University of São Carlos, Brazil II-128

Trajectory of the liquid jet into the throat of a pease-anthony venturi scrubber, N. A. Gómez-Puentes*, V. G. Guerra, J. R. Coury, J. A. S. Gonçalves, Federal University of São Carlos, Brazil II-136

L6 Filter Media Characterization 11:00 -12:15

Cartridge bubble point tester, A. Jena, K. Gupta*, Porous Materials Inc., USA I-218

A new method of measuring pore size distributions using multi-modal particle size standards, G. R. Rideal*, J. Storey, Whitehouse Scientific, UK; B. Schied, BS-Partikel, Germany I-226

Microstructure simulation of virtual woven filter media, E. Glatt*, S. Rief, A. Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM, Germany I-231

L7 Cake Filtration Analysis I 11:00 -12:15

Determination of pressure dependence of permeability characteristics from single constant pressure filtration test, E. Iritani*, N. Katagiri, Nagoya University, Japan I-239

Characterization of packed beds obtained by filtration of colloidal suspensions, M. Hieke*, H. Anlauf, H. Nirschl, Karlsruhe University, Germany I-247

Continuous pressure or discontinuous press filtration to separate slurries of very small particles – A theoretical comparison, H. Anlauf*, M. Hieke, Karlsruhe University, Germany I-252

M5 Deposition Control 11:00-12:15

Improved deposition control for membrane bioreactors with immersed flat sheet membrane modules, H. Prieske, L. Böhm*, A. Drews, M. Kraume, Technical University Berlin, Germany **II-615**

Effects of water quality and antiscalants on silica scaling of reverse osmosis membranes, W. Hater, C. zum Kolk, P. Izquierdo, BKG Water Solutions; G. Braun*, T. Götz, C. Ependiller, Cologne University of Applied Sciences, Germany **II-623**

Particle deposition in rotating filter disks, Y. Taamneh*, Tafila Technical University, Jordan; L. Steinke, S. Ripperger, University of Kaiserslautern, Germany **II-640**

G5 Industrial Gas Cleaning 11:00-12:15

Enhanced energy efficiency solutions for industrial baghouse filters, II-144 G.-M. Klein*, T. Schrooten, T. Neuhaus, R. Esser, F. Ott, T. Daniel, Intensiv-Filter GmbH & Co. KG, Germany

Conical lamina filter elements for higher filtration and energy efficiency and micro-fiber membrane filter media, K. Schumann*, Schumann Kompaktfilter, Germany **II-152**

Improved performance of bag filters through fabric surface modification, II-157 A. K. Choudhary*, A. Mukhopadhyay, National Institute of Technology, India

S4 Survey Lecture 13:15-14:30

Development history and system integration aspects of diesel particle filters in commercial vehicles, Dr. Achim Dittler, Daimler AG, Germany **I-64**

L8 Cake Filtration Analysis II 13:15-14:30

Constant pressure filtration of fibre/particle mixtures, K. Chellappah*, E. S. Tarleton, R. J. Wakeman, Loughborough University, UK **I-260**

Multi-staged creep effect in consolidation of tofu and okara as soft colloids, E. Iritani*, T. Sato, N. Katagiri, Nagoya University, Japan **I-268**

Filtration-consolidation analysis of solid/liquid expression from biological tissue, N. Grimi*, E. Vorobiev, Technical University of Compiègne, France; N. Lebovka, National Academy of Sciences of Ukraine, Ukraine; J. Vaxelaire, University of Pau and Pays de l'Adour, France **I-276**

M6 Membrane Fouling 13:15-14:30

Use of surface interaction free energy in the prediction of organic fouling of reverse osmosis (RO) membrane, R. Bai*, J. Miao, C. Liu, P. Tay, National University of Singapore, Singapore **II-638**

Fouling transition in high molecular weight flexible polymer cross-flow ultrafiltration, L. Béguin*, IFTS Institute of Filtration and Techniques of Separation; H. Duval, M. Rakib, Ecole Centrale Paris, France **II-646**

Effect of air-sparging on the performance of cross-flow microfiltration of yeast suspension, K.-J. Hwang*, C.-E. Hsu, P.-Y. Si, Tamkang University, Taiwan **II-654**

G6 Filter Test Systems I 13:15-14:30

Comparison of differently generated soots used for filter testing, S. Haep*, H. Fissan, H. Kaminski, C. Asbach, B. Stahlmecke, H. Finger, Institute of Energy and Environmental Technology (IUTA), Germany **II-165**

Filtration of nanoparticles: presentation of FANA test bench, N. Michielsen*, T. Lelandais, C. Brochot, S. Bondiguel, IRSN Institute for Radiological Protection and Nuclear Safety, France **II-172**

Portable filtertester for nanometer and micrometer sized particles - the new all in one solution, lightweight no consumeables, no emissions, II-178
R. Hagler, M. Pesch, Grimm Aerosoltechnik GmbH, Germany

L17 Depth Filtration Processes 15:00 -16:15

The difficulty with filtering gel particles when producing man-made fibers and optical films, I-479
S. Strasser*, K. Brandt, Lenzing Technik GmbH, Austria

Development and characteristics of a new ion exchange filter cartridge made of phosphorylated hemp fibre yarn, I-486
B. Gemende*, N. Pausch, H. Mueller, A. Gerbeth, University of Applied Sciences Zwickau; M. Leiker, Produktions- und Umweltservice GmbH; J. Hofmann, U. Freier, K. König, Universität Leipzig; M. Feustel, A. Richter, Textilforschungsinstitut Thüringen-Vogtland e.V., Greiz, Germany

Media for water separation from biodiesel-ultra low sulfur diesel blends - comparison with super absorbant monitor media, I-494
C. M. Stanfel*, F. Diani Pangestu, Ahlstrom Filtration, LLC, USA

L9 Cake Filtration Processes I 15:00 -16:15

Experimental study on the influence of process variables on the performance of a horizontal belt filter, I-284
M. Huhtanen*, A. Häkkinen, J. Kallas, Lappeenranta University of Technology; B. Ekberg, Larox Corporation, Finland

Design of a new high performance drum filter for the chemical industry, I-292
T. Langeloh, Bokela GmbH, Germany

Plate and frame pressure filter optimisation using plant load cell data: Advantages, challenges and outcomes, I-300
R. G. de Kretser*, H. Saha, C. Biscombe, P. J. Scales, University of Melbourne, Australia

M7 Modelling and Simulation 15:00 -16:15

Modeling of enzymatic synthesis of fructooligosaccharides in continous membrane reactors, II-669
Z. Kovacs*, L. Engel, K. Grau, T. Hahn, M. Ebrahimi, University of Applied Sciences Giessen-Friedberg, Germany; P. Czermak, Kansas State University, USA

Modelling the separation of protein solutions by means of cross flow filtration, II-678
T. Grein*, S. Ripperger, University of Kaiserslautern; A. Piry, W. Kühnl, U. Kulozik, Munich University, Germany

3D reconstruction of ultrafiltration cakes from binarised images, II-686
F. Bourgeois*, M. Clifton, M. Meireles, Laboratoire de Génie Chimique UMR 5503, France

G7 Filter Test Systems II 15:00 -16:15

Filtration performance down to nano-particles, II-183
P. Tronville*, Politecnico di Torino, Italy; R. Vijayakumar, AERFIL LLC, USA

Essential improvements for a reliable fractional efficiency testing of air filters, II-191
M. Schmidt*, L. Mölter, Palas® GmbH, Germany

Investigation of the filtration behaviour of an artificial filtration test rig in comparison to an industrial filter unit – Differences and possibilities of scale up, II-199
G. Gasparin*, Evonik Fibres GmbH, Austria

L10 Depth Filtration Analysis I 16:45 -18:00

Advanced fibrous media simulations based on 3D structural data of real filter media, I-308
M. J. Lehmann*, S. Hiel, E. Nißler, P. Trautmann, MANN+HUMMEL GmbH, Germany

Analysis of the behaviour of an automotive fuel filter using a Brinkman-Darcy approximation and a probability density function for the two-phase flow, L. Valiño, R. Mustata, J. Hierro, Laboratorio de Investigación en Tecnologías de la Combustión, J. L. Hernández*, C. Blasco, Robert Bosch España Gasoline Systems S.A., Spain I-316

On coupled particle level and filter element level simulation for filtration processes, Z. Lakdawala*, O. Iliev, S. Rief, A. Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM, Germany I-324

L11 Cake Filtration Processes II 16:45 -18:00

Ultra-fine coal dewatering with hyperbaric disc filters, G. Krammer*, J. Kappel, R. Raberger, Andritz AG, Austria I-329

Saving of wash liquid at filtration, R. Bott*, T. Langeloh, Bokela GmbH, Germany I-337

Secondary-Dewatering of solid-liquid separation in sodium bi-carbonate separation applications, D.-E. Keller*, KMPT AG, Germany I-345

M8 Special Membranes 16:45 -18:00

Catalyst crosslinked membranes for use in solvent resistant nanofiltration, K. T. Cliff*, S. Tarleton, Loughborough University, UK II-678

Optimization of the channel form geometry of porous ReSiC ceramic membrane modules, S. Alexopoulos*, G. Breitbach, B. Hoffschmidt, University of Applied Sciences Aachen, Germany II-686

Textiles for the filtration of activated sludge in membrane bioreactors (MBRs), L. Böhm*, V. Iversen, S. Hermann, A. Drews, J. Münz, M. Kraume, TU Berlin, Germany; E. Fatarella, Next Technology Tecnotessile, Società Nazionale di Ricerca Tecnologica r.l., Italy; B. Lesjean, Berlin Centre of Competence for Water, Germany II-694

G8 Hot Gas Cleaning 16:45 -18:00

Use of CFD-software with simulation of particle formation and precipitation in high temperature processes, T. van der Zwaag*, C. Asbach, S. Haep, Institute of Energy and Environmental Technology IUTA; E. Kruis, University of Duisburg-Essen; K. Reuter-Hack, Karlsruhe University, Germany II-205

Evaluation of filtration and recleaning performance of hot gas filter media, R. Mai*, H. Leibold, H. Seifert, Forschungszentrum Karlsruhe GmbH, P. Gäng, Fil T Eq GmbH, Germany II-213

High Temperature Filtration of Pyrolysis Gases from Biogenic Feedstocks, H. Leibold*, R. Mai, J. Sitzmann, H. Seifert, Forschungszentrum Karlsruhe GmbH, Germany; A. Hornung, Aston University, UK; Y. Solantausta, VTT, Finland II-219

Thursday – October 15, 2009

L12 Washing of Particles and Cleaning of Media 08:30 -09:45

Flushing – Cleaning of debris and filter cakes from organic solvents, M. Wilkens*, U. A. Peuker, Technical University Bergakademie Freiberg, Germany I-350

The impact of centrifugal force on the quality of cake washing, F. Ruslim*, A. Erk, T. Danner, BASF SE, Germany I-357

Dissolution of magnetite particles in acidic conditions, R. Salmimies*, A. Häkkinen, J. Kallas, Lappeenranta University of Technology; B. Ekberg, Larox Corporation, Finland I-362

· **Washing of Particles** ·

Influence of experimental parameters on local and filtrate properties of kraft pulp displacement washing, K. Dingwell*, J. Lindau, M. Sedin, H. Theliander, Chalmers University of Technology, Sweden

· **Backwashing Filtration Processes** ·

Enhancing classical effluent treatment plant efficiency by introducing BASP rotary wedge wire drum dewatering screens, B. Patil*, V. Patil, BASP Industries, India

Precious metal catalyst recovery in API processing, L. Vashishta, Diva Envitec Europe Ltd., Great Britain; D. Stöcker, GKN Sinter Metal Filters GmbH, Germany

· **Depth Filtration Processes** ·

Effects of Biodiesel By-Products on Interfacial Tension and Water Separation Properties of Biodiesel-Ultra Low Sulfur Diesel Blends, F. D. Pangestu*, C. M. Stanfel, Ahlstrom Filtration, LLC, USA

· **Chromatography** ·

Preparative separation and purification of plasmid DNA nano-vectors using anion exchange expanded bed chromatography, M. Ebrahimipour, M. Jahanshahi*, Babol University of Technology, Iran

· **Electrocoagulation** ·

Removal of arsenic from wastewaters by batch airlift electrocoagulation, H. K. Hansen*, P. Nuñez, C. Guiterrez, L. M. Ottosen, Technical University Federico Santa Maria, Chile

· **Filter Media** ·

Choice and optimization of technical woven wire meshes in the solid liquid separation, M. Knefel, P. Wirtz, GKD - Gebr. Kufferath AG, Germany

Liquid-Liquid extraction of ammonia using hollow fiber membrane contactors, M. Ulbricht*, J. Schneider, M. Stasiak, Membrana GmbH, Germany; J. Munoz, A. Sengupta, B. Kitteringham, Membrana Charlotte, USA

II-709

Achieving cleaner solutions, H. Williams*, Serfilco International, Great Britain; J. H. Berg, Serfilco Ltd, USA

Development and large scale testing of water reuse process technologies in waste water free houses and companies based on ultrafiltration membranes of Microdyn-Nadir, A. Huber*, SCAUT Forschungsgesellschaft mbH; D. Swaboda, GFI GmbH, Germany

Purification and recycling of water at a food-processing plant based on the example of natural sausage casing production using a physical-chemical-biological system with ultrafiltration membranes from Microdyn-Nadir, A. Huber*, SCAUT Forschungsgesellschaft mbH, Germany

Integrated membrane process for treating desulfurization effluent, N. Yin*, F. Liu, Z. Zhong, W. Xing, Nanjing University, P. R. China

Recycle effect on double-pass concentric circular mass exchanger with an idealized membrane inserted, C.-D. Ho*, J.-W. Tu, Y.-C. Chuang, Tamkang University, Taiwan

Organic solvent nanofiltration in the pharmaceutical industry, H. Beckers, A. Buekenhoudt, P. Vandezande, R. Vleeschouwers*, VITO, Belgium

Iron removal by membrane contactor for assisting ilmenite leaching, II-745
E. A. Abdel-Aal, M. H. H. Mahmoud, M. M. S. Sanad, Central Metallurgical R & D Institute, Egypt; A. Criscuoli, A. Figoli, E. Drioli, University of Calabria, Italy

Filtration of highly concentrated CaCO₃ suspensions using a rotating disk dynamic system, II-756
M. Loginov, O. Larue, L. H. Ding, E. Vorobiev*, University of Compiègne, France; N. Lebovka, National Academy of Sciences of Ukraine, Ukraine

Process intensification by using dynamic Krauss-Maffei Cross Flow Filtration (DCF) without recirculation of retentate, II-763
G. Grim*, KMPT AG, Germany

Bench-scale unit for characterisation of particle adhesion on ceramic membrane surfaces, II-766
T. Quadt*, E. Schmidt, University of Wuppertal, Germany

G9 Poster Session II 08:30 -09:45

Isobaric pressurised air filter testing under overpressure up to 10 bar in accordance with ISO 12500, II-223
S. Schütz*, L. Mölter, M. Schmidt, Palas® GmbH, Germany

Method of achieving more accuracy in testing air cleaners, II-232
A. G. Denysenko*, Kharkiv Petro Vasylenko National Technical University of Agriculture, Ukraine

Errors on measurements of size distributions of nano-sized aerosol particles using the SMPS spectrometer, II-237
F. O. Arouca*, N. R. Feitosa, J. R. Coury, Federal University of São Carlos, Brazil

Study of the behaviour of filter media used in high pressure filtration systems, II-244
E. H. Tanabe*, A. B. N. Brito, E. J. Ricco, J. R. Coury, M. L. Aguiar, University of São Carlos, Brazil

Determination of adhesion force of organic and inorganic particle in synthetic fiber fabric filters, II-252
M. M. Campos, E. H. Tanabe*, M. L. Aguiar, University of São Carlos, Brazil

Statistical study on the operational variables influence in the dust cake structure, II-260
S. M. S. Rocha, J. J. R Damasceno*, C. R. Duarte, Federal University of Uberlândia; M. L. Aguiar, Federal University of São Carlos, Brazil

Numerical investigations of a content on thallium in the filter ash, II-267
Chizhko*, Moscow Environmental Center, Russia

Study of the influence of the thickness of the dust cake in drainage of the fluid, II-273
S. M. S. Rocha, J. J. R. Damasceno, L. G. M. Vieira, Federal University of Uberlândia; M. L. Aguiar*, Federal University of São Carlos, Brazil

Experimental investigations into the effects of post-coating on surface filtration, II-281
Q. Zhang*, E. Schmidt, University of Wuppertal, Germany

Virtual cyclone as a pre-dust-collector of bag filters, II-287
H.-S. Park*, K. S. Lim, KIER Korea Institute of Energy Research, Korea

Collection efficiency of fiber filters on the filtration of nano-sized particles from aerosols, II-292
N. R. Feitosa, F. O. Arouca*, J. R. Coury, Federal University of São Carlos, Brazil

Investigations into the collection of fine dust by plants, II-299
H. Mölleken, E. Schmidt, University of Wuppertal, Germany

L14	Separation Enhancement by Magnetic Forces	11:00 -12:15
	Selective magnetic separation – A revolution in solid-liquid separation? I-411 H. Nirschl*, C. Wagner, C. Eichholz, University of Karlsruhe, Germany	
	DEM-Simulation of magnetic field effects in solid-liquid-separation, I-419 C. Eichholz*, H. Nirschl, University of Karlsruhe, Germany	
	Removal of pesticides and benzene from water by using nanomagnetic filtration, I-427 S. Alfadul*, A. Alabdulaa'aly, M. Kahn, KACST King Abdulaziz City for Science and Technology; M. Abdalla, Saud University, Saudi Arabia	
L15	Depth Filtration Analysis II	11:00 -12:15
	Comparing fibre composition of nonwovens: Filtration performance and sustainability potential, I-433 H. H. Kleizen*, Parker Filtration BV, Delft University of Technology, The Netherlands	
	Advanced CFD simulation of filtration processes, I-440 M. Dederig, IBS Filtran; O. Iliev*, Z. Lakdawala, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; R. Ciegis, V. Starikovicus, Vilnius Gediminas Technical University, Lithuania; P. Popov, Texas A&M University, USA	
	Filtering of clay colloids in MX-80 d etritis material, I-445 T. Richards*, Chalmers University of Technology; I. Neretnieks, Royal Institute of Technology, Sweden	
G10	Monitoring and Control	11:00 -12:15
	Monitoring and control of emission of particulate materials in industrial production of alcohol, II-306 M. A. Martins Costa, F. de Almeida Filho, M. L. Aguiar, F. Hiromitus, São Paulo State University; E. H. Tanabe*, Federal University of São Carlos, Brazil	
	Online quality controll in for road tunnel air filters - the new dimension in performance and air quality, II-313 F. Schneider*, Grimm Aerosoltechnik; E. Deux, FILTRONtec GmbH, Germany	
	Fast online efficiency testing and emission measurement of cleanable filter elements, II-319 G. Lindenthal, Ingenieurbüro für Partikeltechnologie und Umweltmesstechnik; M. Weiß*, M. Schmidt, Palas® GmbH, Germany	
G11	Filter Media Clogging	11:00 -12:15
	Clogging of industrial high efficiency particulate air filter in case of fire, II-325 F.X. Ouf*, V.M. Mocho, Institute for Radiological Protection and Nuclear Safety, France	
	Effect of air humidity on the clogging of mini-pleated and plane HEPA filters by hygroscopic and non-hygroscopic and particles, II-333 A. Joubert*, J. C. Laborde, L. Bouilloux, IRSN; D. Thomas, S. Callé-Chazelet, Nancy University, France	
	Clogging mechanisms involved in the aging of cleanable filter media, II-341 J. Schubert*, G. Mauschitz, W. Höflinger, Vienna University of Technology, Austria	
L16	Separation Enhancement by Physical and Chemical Slurry Treatment	13:15-14:30
	Removal of colloidal particles from colloidal waste by use of particle immobilization in gel, I-453 M. Iwata*, Suzuka National College of Technology, Japan; M. S. Jami, International Islamic University Malaysia, Malaysia	
	Peroxidase catalyzed the removal of phenol from synthetic waste water, I-461 K. F. Mossallam*, F. M. Sultanova, N. A. Salimova, State Oil Academy, Azerbaijan	
	Eshidiya industrial wastewater treatment, I-471 S. Emeish*, Al-Balqa' Applied University, Jordan	

S5	Survey Lecture	13:15-14:30
Membrane bioreactors in waste water treatment - Status and trends, I-80 Prof. Matthias Kraume, Berlin Technical University, Germany; Dr. Anja Drews Oxford University, Great Britain		
G12	Ab- and Adsorption	13:15-14:30
Fugitive dust suppression using water spraying systems with low water consumption in enclosed systems, II-349 J. Faschingleitner*, G. Mauschitz, W. Höflinger, Vienna University of Technology, Austria		
Odour reduction by means of textiles – innovative coatings, II-357 H. Finger*, F. Schmidt, St. Haep, D. Bathen, Institut für Energie- und Umwelttechnik e. V. (IUTA), Germany		
The truly custom-made adsorbent system, II-364 S. Fichtner*, S. Kaemper, J.-M. Giebelhausen, B. Boehringer, A. Arnold, M. Mueller, Blücher GmbH, Adsor-Tech GmbH, Germany		
G13	Nanofibre Filter Media	13:15-14:30
Fabrication and performance evaluation of nano-fibrous filters for filtration of sub-micron aerosols, II-370 W. W.-F. Leung*, C.-H. Hung, P.-T. Yuen, The Hong Kong Polytechnic University, P. R. China		
Improved filterefficiency through integrated nanofibers, II-377 W. Rupertseder*, T. Ertl, A. Seeberger, A. Jung, IREMA-Filter GmbH, Germany		
Development of nonwoven composites air filters based on micro and nano-fibers, II-383 J. Payen*, P. Vroman, M. Lewandowski, A. Perwuelz, Ecole Nationale Supérieure des Arts et Industries Textiles (ENSAIT), France		
L18	Backwashing Filtration Processes	15:00-16:15
RFF – Backwash fibre filter innovation in depth filtration, I-502 J. Baumgartinger*, Lenzing Technik GmbH, Austria		
Internal filter for fischer-tropsch wax/catalyst separation, I-506 M. A. Khodagholi*, A. A. Rohani, M. R. Hemmati Mahmoudi, Research Institute of Petroleum Industry, Iran		
Filtration and particle analysis for heavily contaminated engine lube oil, I-514 F. Gruschwitz*, M. Förster, N. König, MAN Diesel SE; H. Nirschl, H. Anlauf, Karlsruhe University, Germany		
L19	Precoat Filtration	15:00-16:15
Filtration of high density microbial fermentation biomass using BASF biotech filter, I-522 V. Patil*, B. Patil, BASP Industries, India; H. Katinger, University of Natural Resources and Applied Life Sciences, Austria		
Filtration system for isolation of decoquinat bio molecules, I-530 B. Patil*, V. Patil, BASP Industries, India		
Organic precoat filter aids - Update on current statur and future developments, I-539 E. Gerdes*, J. Rettenmaier & Söhne, Germany		
G14	Modelling and Simulation I	15:00-16:15
Simulation of particle separation at woven wire filters, II-391 H. Rieger*, H. Sauter, Mahle Filtersysteme GmbH, Germany		
Simulation of fluid flow and particle deposition in three dimensional nonwoven structures, II-399 T. Warth*, M. Piesche, University of Stuttgart, Germany		

Penetration of aerosol particles through polydisperse fibrous filters – II-406
Model and experiment, A. Podgórski*, A. Jackiewicz, Warsaw University of Technology, Poland

G15 Special Filter Media 15:00-16:15

Nano filtration media - Challenges of modelling and computer simulation, II-413
L. Cheng*, S. Rief, Fraunhofer Institute for Industrial Mathematics ITWM, Germany

Investigation of filter service life increased by collating high efficiency media, II-420
P. P. Tsai*, The University of Tennessee, USA

High-performance spunlace filter media for process air and liquid filtration, II-429
V. Lorentz*, Norafin GmbH, Switzerland

L20 Filter Media Development and Application 16:45-18:00

Influence of filter cloth behaviour on the layout of cake forming filters, I-542
E. Ehrfeld, Bokela GmbH, Germany

Comparison of pore size distribution of non-woven fibrous filter evaluated by computer simulation with the distributions measured by DFM and microscopic observation, I-550
K. Matsumoto*, K. Nakamura, Yokohama National University; T. Yunoki, Tritec Corporation, Japan

Continuous welding and simultaneous edge sealing of pleated filter media, I-557
A. Korz*, K. Herzer, Textile Fusion Technologies GmbH, T. Westermann, Pfaff Industriesysteme und Maschinen AG, Germany

L21 Selective Separation and Classification 16:45-18:00

"Bubble bobble" in the lauter tun – A new way for mash separation in the brewhouse, I-561
J. Tippmann*, H. Scheuren, J. Voigt, K. Sommer, Munich University, Germany

Performance of dynamic filtration in particle classification, I-569
L. Steinke*, Y. Taamneh, S. Ripperger, University of Kaiserslautern, Germany

Modeling sieving filtration using simple network models, I-577
U. Beuscher*, W. L. Gore & Associates Inc., USA

G16 Modelling and Simulation II 16:45-18:00

Influence of an oscillating flow on single fibre efficiency, II-435
P. Kopf*, M. Piesche, University of Stuttgart, Germany

Deposition of nanoparticles in the composites of nano- and micro-sized fibers. The electrostatic effects, II-443
L. Gradon*, Warsaw University of Technology, Poland

Effect of slip flow on the pressure drop in fibrous filters, II-449
Z. Bin, Tongji University, P.R. China; V. Bertola, The University of Edinburgh, UK; E. Cafaro, P. Tronville*, Politecnico di Torino, Italy

G17 Mist and Droplet Separation 16:45-18:00

Collection of oil droplets from pyrolysis gases by an electrostatic precipitator, II-457
A. Bologna*, H.-R. Paur, H. Seifert, K. Woletz, Forschungszentrum Karlsruhe, Germany

Measurements of metal working fluid mist emissions at high concentrations, II-465
T. Laminger*, W. Höflinger, Vienna University of Technology, Austria

A model for steady-state oil transport and saturation in a mist filter, II-473
D. Kampa*, J. Meyer, B. Mullins, G. Kasper, Karlsruhe University, Germany

The Programme lists countries and regions and is subject to amendments. Errors and omissions expected.

SESSION CHAIRMEN

TUESDAY, OCTOBER 13, 2009

S1 - Survey Lecture: Advances in Pore Structure Evaluation by Porometry	13:15-14:30 h
Chairman: Harald Anlauf	
L1 - Sedimentation Analysis in the Gravity Field	13:15-14:30 h
Chairman: Dietmar Lerche	
M1 - Waste Water Treatment	13:15-14:30 h
Chairman: Siegfried Ripperger	
G1 - Air Filter I	13:15-14:30 h
Chairman: Thomas Caesar	
S2 - Survey Lecture: Membrane Pore Characterization Techniques – Status Quo and Future Development	15:00-16:15 h
Chairman: Richard Wakeman	
L2 - Sedimentation Analysis in the Centrifugal Field	15:00-16:15 h
Chairman: Dietmar Lerche	
M2 - Produced Water Treatment	15:00-16:15 h
Chairman: Steve Tarleton	
G2 - Air Filter II	15:00-16:15 h
Chairman: Thomas Caesar	
S3 - Towards predicting filtration and separation - Progress and challenges	16:45-18:00 h
Chairman: Siegfried Ripperger	
L3 - Sedimentation and Flotation for Sorting	16:45-18:00 h
Chairman: Harald Anlauf	
M3 - Combined Processes	16:45-18:00 h
Chairman: Jaroslav Pridal	
G3 - Surface Filtration	16:45-18:00 h
Chairman: Wilhelm Höflinger	

WEDNESDAY, OCTOBER 14, 2009

L4 - Sedimentation in Centrifuges/Hydrocyclones	8:30-9:45 h
Chairman: Michael Kopf	
L5 - Poster Session I	8:30-9:45 h
Chairman: Graham Rideal	
M4 - Poster Session I	8:30-9:45 h
Chairman: Kuo-Lun Tung	
G4 - Poster Session I	8:30-9:45 h
Chairman: Gerd Mauschitz	
L6 - Filter Media Characterization	11:00-12:15 h
Chairman: Christophe Peuchot	
L7 - Cake Filtration Analysis I	11:00-12:15 h
Chairman: Urs Peuker	
M5 - Deposition Control	11:00-12:15 h
Chairman: Kuo-Lun Tung	
G5 - Industrial Gas Cleaning	11:00-12:15 h
Chairman: Takeshi Yoneda	
S4 - Development history and system integration aspects of diesel particle filters in commercial vehicles	13:15-14:30 h
Chairman: Eberhard Schmidt	
L8 - Cake Filtration Analysis II	13:15-14:30 h
Chairman: Peter Scales	
M6 - Membrane Fouling	13:15-14:30 h
Chairman: Thomas Peters	
G6 - Filter Test Systems I	13:15-14:30 h
Chairman: Gerhard Kasper	
L17 - Depth Filtration Processes	15:00-16:15 h
Chairman: Hermanes Kleizen	

L9 - Cake Filtration Processes I Chairman: Gernot Krammer	15:00-16:15 h
M7 - Modelling and Simulation Chairman: Thomas Peters	15:00-16:15 h
G7 - Filter Test Systems II Chairman: Gerhard Kasper	15:00-16:15 h
L10 - Depth Filtration Analysis I Chairman: Hermann Nirschl	16:45-18:00 h
L11 - Cake Filtration Processes II Chairman: Marja Oja	16:45-18:00 h
M8 - Special Membranes Chairman: Thomas Peters	16:45-18:00 h
G8 - Hot Gas Cleaning Chairman: Achim Dittler	16:45-18:00 h

THURSDAY, OCTOBER 15, 2009

L12 - Washing of Particles and Cleaning of Media Chairman: Urs Peuker	8:30-9:45 h
L13 - Poster Session II Chairman: Hans Theliander	8:30-9:45 h
M9 - Poster Session II Chairman: Kuo-Jen Hwang	8:30-9:45 h
G9 - Poster Session II Chairman: Hans-Joachim Schmid	8:30-9:45 h
L14 - Separation Enhancement by Magnetic Forces Chairman: Karsten Keller	11:00-12:15 h
L15 - Depth Filtration Analysis II Chairman: Eugène Vorobiev	11:00-12:15 h
G10 - Monitoring and Control Chairman: Hans-Joachim Schmid	11:00-12:15 h
G11 - Filter Media Clogging Chairman: Markus Lehner	11:00-12:15 h
L16 - Separation Enhancement by Physical and Chemical Slurry Treatment Chairman: Eiji Iritani	13:15-14:30 h
S5 - Membrane bioreactors in waste water treatment - Status and trends Chairman: Eberhard Schmidt	13:15-14:30 h
G12 - Ab- and Adsorption Chairman: Markus Lehner	13:15-14:30 h
G13 - Nanofibre Filter Media Chairman: Gernot Krammer	13:15-14:30 h
L18 - Backwashing Filtration Processes Chairman: Martin Lehmann	15:00-16:15 h
L19 - Precoat Filtration Chairman: Christophe Peuchot	15:00-16:15 h
G14 - Modelling and Simulation I Chairman: Gernot Krammer	15:00-16:15 h
G15 - Special Filter Media Chairman: Wallace Leung	15:00-16:15 h
L20 - Filter Media Development and Application Chairman: Reinhard Bott	16:45-18:00 h
L21 - Selective Separation and Classification Chairman: Harald Anlauf	16:45-18:00 h
G16 - Modelling and Simulation II Chairman: Martin Lehmann	16:45-18:00 h
G17 - Mist and Droplet Separation Chairman: Gerd Mauschwitz	16:45-18:00 h

EFFECT OF SLIP FLOW ON THE PRESSURE DROP IN FIBROUS FILTERS

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ABSTRACT

Slip occurs when the gas velocity at flow boundaries is not zero. As a step toward deriving the effects of slip flow on the pressure drop in fibrous filters, we examine slip flow solutions for relatively simple geometries (sphere, cylinder, parallel plates and circular tube). Whilst the analytical approach is available for the sphere, parallel plate and tube geometries, a CFD solution is necessary for the cylindrical geometry. The results show that slip flow causes a pressure drop reduction in comparison to the no-slip case for all these cases. Since fibrous filters are essentially combinations of these geometric elements, the inclusion of slip conditions in fibrous filter flow analyses will predict lower filter media pressure drops, and improve prediction agreement with measured pressure drops.

KEYWORDS

Fibrous Filter, Pressure Drop, Slip Flow, CFD-Simulation, Incompressible flow

1. Introduction

Fibrous filters are widely used in air cleaning and HVAC applications because they ensure high filtration efficiencies and lower pressure drops in comparison with other types of filter. However, the random distribution of the fibers determines extremely complex paths for the fluid flow, so that currently the design of fibrous filters is essentially based on empirical criteria.

A major issue that makes modeling fibrous filters difficult is the occurrence of slip flow within narrow gaps among fibers, which affects both semi-empirical models and the implementation of numerical algorithms [1, 2]. This happens whenever the gap size or fiber diameter, L , becomes of the same order as the mean free path of fluid elements, λ_f (i.e., when $Kn = \lambda_f/L \leq 1$). Thus, understanding the characteristics of slip flow at low Reynolds numbers is essential to describe the fluid dynamic behavior of fibrous filters, hence to estimate pressure drops. A full characterization of slip flow around fibers would bring a significant advantage to the numerical solution of the flow field: in fact, if one can calculate a priori the thickness of the fluid layer around fibers which is affected by slip flow, then the computational domain can be divided accordingly, with obvious advantages in terms of time and accuracy of the results.

This work aims to get a deeper understanding of the slip flow in fibrous filters by considering the solutions for three simple geometries (sphere, cylinder and parallel plates), and comparing the resulting drag coefficient, $C_D = \frac{2F_D}{\rho U^2 \pi R^2}$, with the value

obtained in case of no slip boundary conditions. These geometries are relevant both to the study of the flow field around fibers and to that of aerosol particles

displacement. However, they are extremely appealing also from a fundamental point of view because at such low Reynolds numbers (typically between 10^{-3} and 10^{-1}) [3] one has a purely creeping flow without a wake past the obstacle [4].

The analysis of the stationary Stokes problem shows that the total drag experienced by a sphere in slip-flow regime is equivalent to the Stokes total drag for continuum flow multiplied by a rarefaction coefficient dependent upon the Knudsen number. The rarefaction effects decrease the total drag experienced by a sphere below the continuum model prediction.

2. Flow around a sphere

The creeping flow around a sphere was first investigated by Stokes [5], who derived the well-known formula for the drag coefficient named after him. Whilst inertia is completely neglected in this approach, its effects become significant at large distances, regardless of how small the Reynolds number is. This was taken into account by Oseen, who added a linearized acceleration term to the momentum equation [6], and Goldstein, who derived the exact solution of Oseen's equations [7].

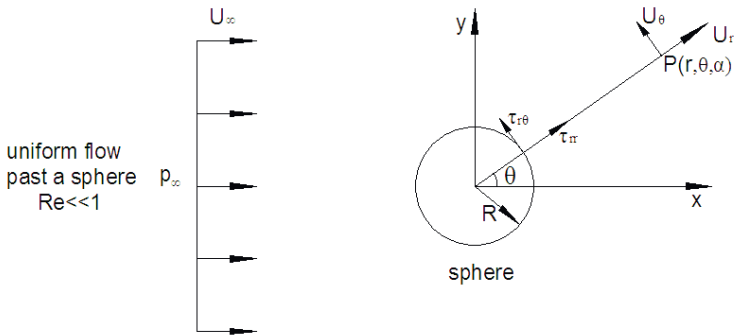


Figure 1 - Problem formulation for the flow around a sphere

An expression for the drag coefficient at small Reynolds numbers can also be obtained by means of the perturbation method [8]. The stream function for creeping flow in a spherical polar coordinate system (sketched in Figure 1) satisfies the biharmonic equation [9, 10]:

$$\nabla^4 \psi = \nabla^2 (\nabla^2 \psi) = 0 \tag{1}$$

The solution of Eq. (1) can be written in the form:

$$\psi(r, \theta) = \left(\frac{A}{r} + Br + Cr^2 + Dr^4 \right) \sin^2 \theta \tag{2}$$

where A, B, C and D are constants. Because the stream function at $r \rightarrow \infty$ is

$$\psi(\infty, \theta) = \frac{U_\infty}{2} r^2 \sin^2 \theta \tag{3}$$

where U_∞ is the free stream velocity, one can conclude that $D = 0$ and $C = U_\infty/2$. The velocity components resulting from this solution are:

$$u_r = 2 \left(\frac{A}{r^3} + \frac{B}{r} + \frac{U_\infty}{2} \right) \cos \theta$$

$$u_\theta = \left(-\frac{A}{r^3} + \frac{B}{r} + U_\infty \right) \sin \theta$$
(4)

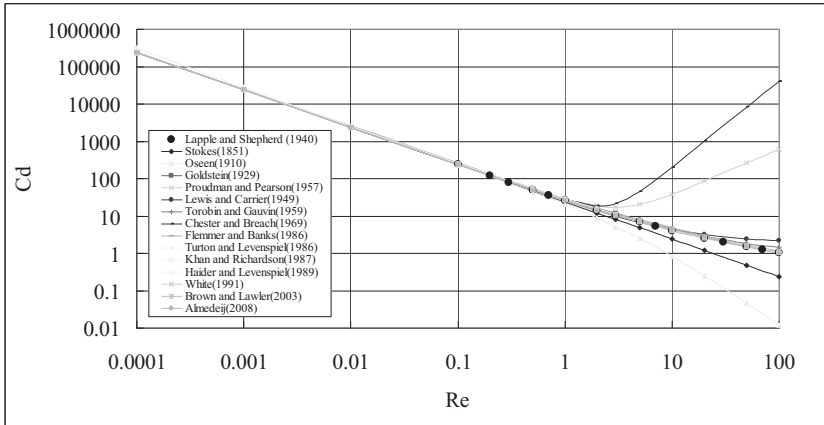


Figure 2 - Drag coefficient on the sphere: comparison between analytical solutions and experimental results available in the literature (case of no slip)

The remaining two arbitrary constants are determined by imposing the conditions on the radial and tangential components of the velocity on the sphere wall. In the case of no slip, $u_r = u_\theta = 0$, and one obtains $A = U_\infty R^3/4$ and $B = -3U_\infty R/4$. Figure 2 shows a comprehensive summary of the results available in the open literature.

In the case of slip flow, the boundary condition for the tangential velocity is proportional to the wall shear stress:

$$u_\theta = \frac{2-\sigma}{\sigma} Kn \frac{R}{\mu} \tau_\theta \quad (r = R, 0 \leq \theta \leq \pi)$$
(5)

where Kn is the Knudsen number and σ is the tangential momentum accommodation coefficient. The resulting expressions for the arbitrary constants are:

$$A = \frac{1}{4} U_\infty R^3 \frac{1}{1 + 3Kn^*}$$

$$B = -\frac{3}{4} U_\infty R \frac{1 + 2Kn^*}{1 + 3Kn^*}$$
(6)

where $Kn^* = Kn(2-\sigma)/\sigma$. The drag force on the sphere is the sum of skin-friction drag, normal stress drag, and pressure drag (or shape drag), which can be calculated by integrating on the sphere surface the tangential stress component $\tau_{r,\theta}$, the normal stress component τ_{rr} , and pressure, respectively, where the stress components are given by:

$$\begin{aligned}\tau_{r\theta} &= \mu \left(\frac{1}{r} \frac{\partial u_r}{\partial \theta} - \frac{1}{r} u_\theta + \frac{\partial u_\theta}{\partial r} \right) \\ \tau_{rr} &= 2\mu \frac{\partial u_r}{\partial r} \\ p &= p_\infty + 2\mu \cos\theta \frac{B}{r^2}\end{aligned}\tag{7}$$

The total drag force resulting from the integration of these stress components is:

$$F_D = 6\pi\mu U_\infty R \frac{1+2Kn^*}{1+3Kn^*}\tag{8}$$

Thus, Eq. (8) shows that the effect of slip flow is to decrease the total drag experienced by the sphere. A non-dimensional drag coefficient can be defined as the ratio between the drag force and the dynamic pressure acting on the projected front area:

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 \pi R^2}\tag{9}$$

In case of no-slip flow, $F_D = 6\pi\mu U_\infty R$, so that $C_D \text{Re}/12 \rightarrow 2$. For slip flow, one finds that the drag coefficient is reduced significantly: for example, setting $Kn = 0.1$ and $\sigma = 1$ yields $C_D \text{Re}/12 \rightarrow 1.75$, which means a reduction of 12.5%.

3. Flow in circular tubes

The continuum flow momentum equation for the incompressible flow within smooth micro-tubes is:

$$\mu \left(\frac{d^2 u}{dr^2} + \frac{1}{r} \frac{du}{dr} \right) = \frac{dp}{dz}\tag{10}$$

where r is the radial coordinate, and z that in the flow direction. The boundary conditions are $u \neq \infty$ when $r = 0$ and:

$$u = -\lambda_f \frac{2-\sigma}{\sigma} \frac{du}{dr}\tag{11}$$

On the tube wall, where λ_f is the mean free path, and σ is the tangential momentum accommodation factor. Introducing the Knudsen number, where the characteristic length is the tube diameter, the velocity distribution is given by:

$$u = -\frac{1}{4\mu} \frac{dp}{dz} \left(R^2 - r^2 + \frac{2-\sigma}{\sigma} \cdot 4Kn \cdot R^2 \right)\tag{12}$$

The mean velocity is defined as:

$$\langle u \rangle = \frac{1}{A} \int u dA = \frac{1}{\pi R^2} \int_0^R 2\pi r u dr = -\frac{R^2}{8\mu} \frac{dp}{dz} \left(1 + \frac{2-\sigma}{\sigma} \cdot 8Kn \right)\tag{13}$$

so that the volumetric flow rate is:

$$\dot{G} = \pi R^2 \langle u \rangle = -\frac{\pi R^4}{8\mu} \frac{dp}{dz} \left(1 + \frac{2-\sigma}{\sigma} \cdot 8Kn \right)\tag{14}$$

and one can calculate the pressure drop in a tube of length L as:

$$\Delta p = \frac{8\mu L \dot{G}}{\pi R^4} \left(1 + \frac{2-\sigma}{\sigma} \cdot 8Kn\right)^{-1} \quad (15)$$

For an ideal gas at temperature T , the mass flow rate is given by:

$$\dot{m} = -\frac{\pi R^4}{8\mu K_{gas} T} \frac{dp}{dz} p \left(1 + 8 \frac{2-\sigma}{\sigma} Kn\right) \quad (16)$$

For isothermal flow, the product of pressure and the Knudsen number is constant and one can write $pKn = p_0Kn_0$. Then, the mass flow rate can be re-written as:

$$\dot{m} = \frac{\pi R^4 p_0^2}{16\mu RT \cdot z} \left[\frac{p_i^2}{p_0^2} - \frac{p_z^2}{p_0^2} + 16 \frac{2-\sigma}{\sigma} \cdot Kn_0 \left(\frac{p_i}{p_0} - \frac{p_z}{p_0} \right) \right] \quad (17)$$

and setting $p_z = p_0$ yields:

$$\dot{m} = \frac{\pi R^4 p_0^2}{16\mu RTL} \left[\frac{p_i^2}{p_0^2} - 1 + 16 \frac{2-\sigma}{\sigma} \cdot Kn_{z_0} \left(\frac{p_i}{p_0} - 1 \right) \right] \quad (18)$$

On the other hand, the mass flow rate for the continuum flow, i.e. with no slip, is given by:

$$\dot{m}_* = \frac{\pi R^4 p_0^2}{16\mu RTL} \left(\frac{p_i^2}{p_0^2} - 1 \right) \quad (19)$$

Thus, in case of slip flow the mass flow rate through the tube is larger than in case of no slip, because $\dot{m}/\dot{m}_* > 1$ for the same pressure difference between the two ends of the tube:

$$\frac{\dot{m}}{\dot{m}_*} = 1 + \frac{16 \frac{2-\sigma}{\sigma} \cdot Kn_0}{\frac{p_i}{p_0} + 1} \quad (20)$$

Since the flow rate for the slip case increases over the no-slip case, one can conclude that slip flow induces a reduction of frictional drag on the flow.

4. Flow around a cylinder

The flow around a cylinder is important not only in the context of fibrous filters, but also in many other engineering applications, both from the fluid dynamics and from the heat transfer points of view [11]. Unfortunately, for the uniform viscous flow around a circular cylinder, Stokes proposed that there was no analytic solution, which is known as Stokes' paradox [5, 9]. Technically speaking, this happens because uniform flow around a cylinder does not satisfy a certain consistency condition [12]. More recently, the corresponding necessary condition for the existence of a solution was found assuming that there is a slip on the surface of the cylinder [13].

Several Authors have proposed asymptotic solutions for the creeping flow around a cylinder with no-slip boundary condition [10] and drag coefficient correlations [14-17], including a recent work suggesting a solution for the Stokes paradox [18]. Experimental data are available in the range of Reynolds numbers from 0.06 to 0.5

[19] as well as for higher Reynolds numbers [20]. Figure 3 summarizes different results for the drag coefficient on a cylinder in case of no-slip (both theoretical and experimental) available in the literature.

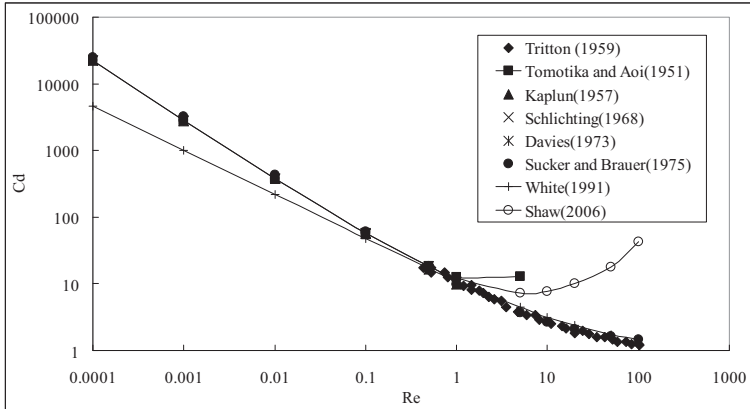


Figure 3 - Drag coefficient on the cylinder: comparison between analytical solutions and experimental results available in the literature (case of no slip)

To investigate the effect of slip flow on a cylinder, we carried out numerical simulations of the flow field using the commercial code Fluent v6.3. From this the drag coefficient could be obtained. The results were then compared with the CFD solution for the no-slip problem. The slip-flow condition is the same used above for the spherical geometry, given by Eq. (5), and was implemented as a user-defined function. To allow updating the boundary condition as the flow field solution converges, the problem is solved as a transient flow instead of a steady-state flow.

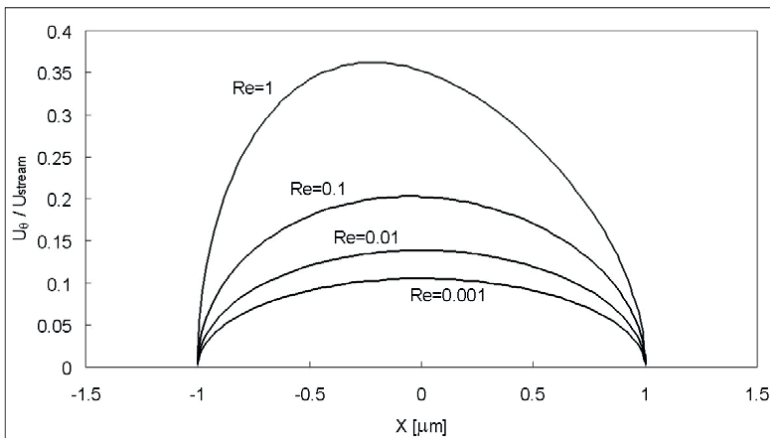


Figure 4 - Tangential velocity on the cylinder wall

Figure 4 shows an example of the tangential velocity on the cylinder wall in case of slip flow, while Figure 5 shows the comparison between the drag coefficients obtained with slip and no-slip boundary conditions, setting $Kn = 0.1$ and $\sigma = 1$. One can observe a clear reduction of the drag coefficient for slip flow of the order of 10%, which is consistent with the value calculated analytically for the spherical geometry

above, using the same values for the slip parameters Kn and σ .

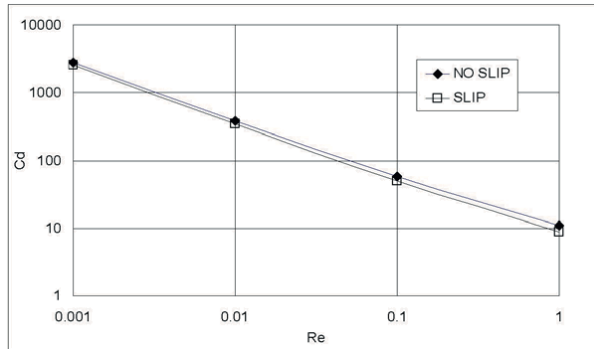


Figure 5 - Drag coefficient on a cylinder in cross-flow: comparison between slip flow and no-slip flow

5. Conclusions

The problem of laminar (creeping) flow with slip flow boundary conditions was studied for both external flow (sphere, cylinder) and internal flow (circular tube), and compared with the solutions obtained in case of no-slip boundary condition. The study of slip flow in these geometries is the first step towards a better understanding of slip flow in fibrous filters: in fact, they are the simplest representation of fibers (the cylinder), of pores within the filter (the tube), and of particles or aerosols (the sphere). In two cases (sphere and tube), the solution for slip flow can be found analytically, while for the cylinder a numerical solution obtained with a commercial CFD code is provided. In all cases, slip flow causes a reduction of the drag exerted by the wall on the flow, which results into a reduction of the drag coefficient (in case of external flow) or of pressure drops (in case of internal flow).

On the basis of these results, one can tackle the investigation of more realistic systems, where several of these basic elements are combined together.

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