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Simulation in the field of gas filtration and separation

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FILTECH 2011

CONFERENCE PROCEEDINGS

VOLUME I

CONTENT VOLUME I

Scientific Committee	I-2
Session Survey	I-3
Conference Programme	I-4
Keyword List (Session Indicator)	I-15
Session Chairmen	I-17
Survey Lectures	I-19
Papers L-Sessions	I-94
Keyword List (Page Indicator)	I-668

CONTENT VOLUME II

Scientific Committee	II-2
Session Survey	II-3
Conference Programme	II-4
Keyword List (Session Indicator)	I-15
Session Chairmen	II-17
Papers G-Sessions	II-19
Papers M-Sessions	II-465
Keyword List (Page Indicator)	II-628

Conference Dates:

March 22 – 24, 2011

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

Tuesday, March 22, 2011				
8.30 – 9.45		Registration		
9.45 – 11.30		Opening Session / Plenary Talk		
11.30 – 12.15		Walk Around – Fair		
12.15 – 13.15		Lunch – Fair		
13.15 – 14.30	S1 Survey Lecture 1	L1 Filter Media – New Developments I	L2 Centrifugal Sedimentation Technology I	G1 Measurement Techniques
15.00 – 16.15	S2 Survey Lecture 2	L3 Filter Media – New Developments II	L4 Centrifugal Sedimentation Technology II	G2 Filter Test Systems I
16.45 – 18.00	S3 Survey Lecture 3	L5 Filter Media – Modelling, Simulation, Design	L6 Mechanical Liquid-Liquid Separation	G3 Filter Test Systems II

Wednesday, March 23, 2011				
8.30 – 9.45	L7 Filter Media – Characterization and Porometry	L8 Poster Session I	M1 Poster Session I	G4 Poster Session I
9.45 – 11.00	Coffee Break - Fair	Poster Viewing	Poster Viewing	Poster Presentation
11.00 – 12.15	L9 Wet Particle Classification	L10 Cake Filtration – Cake Formation and Cake Consolidation	M2 Cross Flow Techniques	G5 Particle Deposition
12.15 – 13.15		Lunch		
13.15 – 14.30	S4 Survey Lecture 4	L11 Cake Filtration – Washing and Extraction	M3 Membrane Bio Reactor	G6 Modelling and Simulation
15.00 – 16.15	S5 Survey Lecture 5	L12 Cake Filtration – Deliquoring	M4 Waste Water Treatment	G7 Surface Filtration
16.45 – 18.00	S6 Survey Lecture 6	L13 Cake Filtration Technology	L14 Electrostatic & Electrokinetic Effects in Separation Processes	G8 Mist and Droplet Separation

Thursday, March 24, 2011				
8.30 – 9.45	L15 Depth Filtration – Modelling and Simulation I	L16 Rotary Cake Filtration Technology	M5 New Membranes	G9 Poster Session II
9.45 – 11.00	Coffee Break - Fair	Poster Viewing	Poster Viewing	Poster Viewing
11.00 – 12.15	L17 Depth Filtration – Modelling and Simulation II	L18 – Non-&Regenerable Filters for Cleaning of Low Concentrated Liquids I	M6 Special Applications	G10 HEPA/ULPA Filters
12.15 – 13.15		Lunch		
13.15 – 14.30	L19 Depth Filtration – Modelling and Simulation III	L20 – Non-&Regenerable Filters for Cleaning of Low Concentrated Liquids II	G11 Cabin Air Filters	G12 Filter Media Characterization
15.00 – 16.15	L21 Separation Enhancement by Coagulation	L22 Removal of Particles and Scales from Surfaces	G13 Industrial Air/Gas Cleaning I	G14 Special Filter Media I
16.45 – 18.00	L23 Separation Enhancement by Flocculation	L24 – Removal of Pollutants from Water by Catalytic, Biological & Enzymatic Treatment	G15 Industrial Air/Gas Cleaning II	G16 Special Filter Media II

Tuesday, March 22, 2011

Plenary Talk	10:30 - 11:30	
New developments in the field of filtering dust separation techniques Prof. Dr. Wilhelm Höflinger, Vienna Technical University - Institute of Chemical Engineering, Austria		I-19
S1 Survey Lecture	13:15 - 14:30	
International standardization in the field of filtration and separation Prof. Dr. Chikao Kanaoka, Ishikawa National College of Technology, Japan Dr. Hisao Makino, Central Research Institute of Electric Power Industry, Japan Takeshi Yoneda, Yoneda Professional Engineer Office, Japan		I-22
L1 Filter Media - New Developments I	13:15 - 14:30	
Filter belts for vacuum belt filters – trends and new developments , C. Maurer*, SEFAR AG, Switzerland		I-94
Innovative low pressure plasma coatings for gas and liquid filter media , F. Legein*, Europlasma N.V., Belgium		I-99
Clean and easy union of filter materials by using ultrasonic , F. Weber, M. Pasternak*, Herrmann Ultraschalltechnik GmbH & Co. KG, Germany		I-107
L2 Centrifugal Sedimentation Technology I	13:15 - 14:30	
Using numerical flow and particle simulation to predict the separation performance of a centrifuge , X. Romani Fernández*; H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany		I-114
Effect of critical process parameters on the operation of a decanter centrifuge , T. Kinnarinen*, M. Louhi-Kultanen, A. Häkkinen, Lappeenranta University of Technology, Finland; E. Meshcheryakov, Saint Petersburg State Technological University of Plant Polymers, Russia		I-122
Selective separation of magnetic particles by magnetic field enhanced centrifugation , J. Lindner*, K. Wagner, H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany		I-130
G1 Measurement Techniques	13:15 - 14:30	
Large drop re-entrainment from an oil-mist filter , D. Kampa*, J. Meyer, G. Kasper, Karlsruhe Institute of Technology (KIT), Germany; B. Mullins, Curtin University of Technology, Australia		II-19
Monitoring and control of particulate matter emitted by biomass burning using scrubber venturi , M.A. Martins Costa*, F.A. Filho, S.P. Morais, B.A. Lima, R.A.D. Ribero, University Estadual Paulista - UNESP; N.A. G. Puentes, University São Carlos - UFSCAR, Brazil		II-26
Portable instrument for real time monitoring of airborne dust and nanoparticles , H. Grimm*, M. Pesch, F. Schneider, Grimm Aerosol Technik GmbH & Co KG, Germany		II-34
S2 Survey Lecture	15:00 - 16:15	
Membrane processes for the treatment of water and wastewater , Dr. Thomas Peters, Consulting for Membrane Technology, Germany		I-35
L3 Filter Media – New Developments II	15:00 - 16:15	
Monolithic melt blown process and applications , R.A. Steele*, Oerlikon Neumag, Germany		I-138
Development of innovative fiber materials for technical applications – fine polyvinylidene-fluoride filaments and fabrics , S. Walter, W. Steinmann*, G. Seide, T. Gries, G. Roth, RWTH Aachen University, Germany		I-146

New lube & fuel media technology increases element lifetime, D. Guimond*, T. Lawson, I-153
G. Jeide, P. Wijns, Hollingsworth & Vose, Germany

L4 Centrifugal Sedimentation Technology II 15:00 - 16:15

Innovative technology for produced water treatment, M.H. Lean*, J. Seo, A. Kole, A.R. I-160
Völkel, N. Chang, B. Hsieh, K. Melde, PARC Palo Alto Research Center, Inc., USA

Spiral plate technology with soft discharge system, H.A. Boele*, Evodos B.V., Netherlands I-168

Particles trajectories in a hydrocyclone measured by PEPT, Y.F. Chang*, C.G. Ilea, Ø.L. I-173
Aasen, A.C. Hoffmann, University of Bergen, Norway

G2 Filter Test Systems I 15:00 - 16:15

**Data analysis of agglomerate filtration measurements for polydisperse diesel chal- II-41
lenging aerosol**, J. Wang*, ETH Zurich University, Switzerland; D.Y.H. Pui, University of
Minnesota, USA; S. Haep, H. Fissan, Institute for Energy and Environmental Technology (IUTA),
Germany

Influence of the dust on the filter efficiency and emissions of cleanable filter media, II-48
M. Schmidt*, Palas® GmbH, Germany

**Effects of post-coating by generating a thin secondary particle layer on surface fil- I-56
tration**, Q. Zhang*, E. Schmidt, University of Wuppertal, Germany

S3 Survey Lecture 16:45 - 18:00

Particle (size) characterization I-45
Prof. Dr. Bernd Sachweh, BASF SE, Germany

L5 Filter Media - Modelling, Simulation, Design 16:45 - 18:00

CFD simulations for better filter element design, O. Iliev*, Z. Lakdawala, R. Kirsch, K. Steiner, I-181
E. Toroshchin, Fraunhofer ITWM; M. Dederig*, IBS Filtran, Germany; V. Starikovicius, Vilnius
Gediminas Technical University, Lithuania

Applications of simulation processes in filter media, P. Jungbecker, T. Klietzing, H. Krieger, I-189
G. Seide*, T. Gries, RWTH Aachen University, Germany

Structure and pressure drop of real and virtual metal wire meshes, E. Glatt, S. Rief, A. I-196
Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM; M. Knefel*, E. Wegenke, GKD
- Gebr. Kufferath AG, Germany

L6 Mechanical Liquid-Liquid Separation 16:45 - 18:00

**Analysis of impact parameters on the water/diesel separation process with filter ele- I-203
ments**; S. Schütz*, D. Winkler, K. Kissling, University of Stuttgart; P. Trautmann, J. Reyinger, M. Veit,
K. Brodesser, U. Staudacher, MANN+HUMMEL GmbH, Germany

Nanocoated filter media for oil-in-water emulsion separation, S. Bansal*, V. von Arnim, I-211
T. Stegmaier, H. Planck, Institute for Textile Technology and Process Engineering Denkendorf (ITV),
Germany

Laboratory scale evaluation of inclined creaming, T. Sobisch*, D. Lerche, LUM GmbH, I-219
Germany

G3 Filter Test Systems II 16:45 - 18:00

**New device for In situ testing of filter media in pulse jet filter plants concept - Details II-65
and experimental results**, F. Popovici, G. Gasparin*, Evonik Fibres, Austria

Test procedure to determine fine dust emissions of dust reduced street sweepers, D. II-70
Renschen*, J. Schamberg, E. Andrae, D. Glätzer, DMT GmbH & Co. KG; B. Schröer, AWISTA Gesellschaft
für Abfallwirtschaft und Stadtreinigung mbH, Germany

Novel test rig for adsorption of toxic substances, H. Finger*, G. Lauber, W. Mölter-Siemens, S. Haep, Institute for Energy and Environmental Technology (IUTA); D. Bathen, University Duisburg-Essen, Germany **II-78**

Wednesday, March 23, 2011

L7 Filter Media – Characterization and Porometry 08:30 - 09:45

In situ cake formation and pore structure characterization of filtration media, A. Jena, K. Gupta*, Porous Materials, Inc., USA **I-226**

Measuring the maximum pore size of small profile filter elements, G.R. Rideal*, J. Storey, A. Stewart, Whitehouse Scientific Ltd, UK **I-234**

How to reduce filtration costs of complex hydraulic systems, C. Peuchot*, IFTS Institute of Filtration and Techniques of Separation, France **I-242**

L8 Poster Session I 08:30 - 09:45

FILTER MEDIA - NEW DEVELOPMENTS

Next generation filter media containing electrospun nanofibers - pathway for improved filtration properties, J. Macak*, P. Popp, M. Vanicek, Elmarco Ltd., Czech Republic **I-249**

CENTRIFUGAL SEDIMENTATION TECHNOLOGY

Innovative platform technology for selective removal of suspended particles from raw waters, M.H. Lean, J. Seo, A. Kole, A.R. Völkel*, N. Chang, B. Hsieh, K. Melde, PARC Palo Alto Research Center, Inc., USA **I-255**

CAKE FILTRATION TECHNOLOGY

Novel BASP biotech filtration system for commercial scale "High density microbial fermentation biomass" - commercial scale, H. Katinger, University of Natural Resources and Applied Life Sciences, Austria; B. Patil*, V. Patil, BASP Industries, India **I-261**

WISY filter for separation of solids from water - Presentation of a new and unique filter system, J. Maurer*, WISY AG, Germany **I-269**

SEPARATION ENHANCEMENT BY CHEMICAL ADDITIVES

Compaction of multiwalled carbon nanotubes at high centrifugal acceleration and in the presence of a surfactant, N. Lebovka, M. Loginov, E. Vorobiev*, University of Compiègne, France **I-273**

SORTING OF DIFFERENT MATERIALS

Simulation of a liquid fluidized bed classifier for polydisperse suspensions of equal density solid particles: design and operation strategies, A.I. Garcia Alvear*, Universidad Católica del Norte; G. Lopez, Sierra Miranda S.C.M., Chile **I-278**

A technical interpretation of three-phase system diagrams for KCl separation from carnallite using MATLAB software, E.R. Borujeny*, S.N. Khorasani, F.T. Esfahani, Isfahan University of Technology, Iran **I-286**

WASHING AND EXTRACTION

Effective separation of cadmium and iron from phosphoric acid by solvent extraction with trioctylamine, M.H.H. Mahmoud* 1,2, M.M. Al-Qahtani 2, 1 CMRDI Central Metallurgical R&D Institute, Helwan, Cairo, Egypt; 2 Chem. Dept. College of Science, Taif University, KSA **I-296**

M1 Poster Session I 08:30 - 09:45

Electrically driven back flushing during membrane ultrafiltration of whey, J. Pridal*, J. Pridal, A. Urban, Mikropur s.r.o.; Z. Bubnik, V. Pour, ICT Institute of Chemical Technology Prague, Czech Republic **II-469**

Membrane filtration of hyaluronic acid solution in constant pressure cell, T.-W. II-469
Cheng*, C.-J. Hsu, Y.-L. Chiu, Tamkang University, Taiwan

Mass transfer of TransMembraneChemieSorption using microporous hollow fiber membrane contactors, M. Ulbricht*, J. Schneider, M. Stasiak, Membrana GmbH, Germany; J. Munoz, B. Kitteringham, Membrana Charlotte, USA

Drinking water, cryptosporidium, membrane filtration and the "long term 2 enhanced surface water treatment rule", U. Kolbe*, I. Lomax, Dow Water & Process Solutions, Germany; D.J. Gisch, The Dow Chemical Company Midland, USA

Effects of membrane pore size on the performance of cross-flow microfiltration of BSA/Dextran mixtures, K.-J. Hwang*, P.-Y. Sz, Tamkang University, Taiwan

Hollow fibre microfiltration membranes for long term application in aquaculture - stabilization of performance and comparison with alternatives, B. Gemende*, A. Gerbeth, M. Schwind, University of Applied Sciences Zwickau; A. von Bresinsky, Fischwirtschaftsbetrieb; R.-P. Busse, Busse GmbH; U. Meyer-Blumenroth, S. Krause, R. Voigt, Microdyn-Nadir GmbH

Extraction of polyphenols from grape seeds by high voltage electrical discharges and extract concentration by membrane process, D. Liu, E. Vorobiev*, J.-L. Lanoisellé, University of Compiègne; R. Savoie, ESCOM - Ecole Supérieure de Chimie Organique et Minérale, France

Dynamic cross-flow filtration for isolation of extracellular products, G. Grim*, KMPT AG, Germany

High-recovery reverse osmosis desalination using wastewater twice from Tigris river water, O.A. Mohamed*, The Pilot Project for Co-generation of Water and Electricity Using Solar Thermal Energy System, Iraq; A.O. Sharif, University of Surrey, Great Britain

G4

Poster Session I

08:30 - 09:45

Velocity influence on the filtration regeneration of filter media, S.M.S. Rocha*, Federal University of Espírito Santo; L.G.M. Vieira, J.J.R. Damasceno, Federal University of Uberlândia; M.L. Aguiar, Federal University of São Carlos, Brazil

Performance of cellulose filter in gas filtration at high pressure conditions, E.H. II-94
Tanabe*, M.L. Aguiar, J.R. Coury, Federal University of São Carlos, Brazil

Simulation of the dust cake build-up on regenerated surface filters, S.M.S. Rocha*, Federal University of Espírito Santo; E.R. Nucci, Universidade Federal de São João Del Rei; M.L. Aguiar, Federal University of São Carlos, Brazil

Evaluation of the influence of operational conditions on gas filtration cake removal, II-110
P.M. Barros*; A.L.R. Cezar, M.L. Aguiar, Federal University of São Carlos, Brazil

A study of the compressibility of gas filtration talc cakes on fabric filters, A.G. Fargnoli, II-118
M.L. Aguiar, E.H. Tanabe*, Federal University of São Carlos, Brazil

Oil repellent nano-coatings for increased filtration performance, S.R. Coulson, M. II-126
McCarthy*, D.R. Evans, P2i Ltd., UK

New functionalities for textile media with GEA Tex technology, T. Stoffel*, M. Sauer- II-133
Kunze, GEA Air Treatment GmbH, Germany

Filtration of gases using textile filters, V.K. Midha*, National Institute of Technology II-140
Jalandhar, India

Measuring the inline available adsorption capacity of Zorflex® activated carbon cloth using electro conductive techniques, A. Smith*, Chemviron Carbon Cloth Division, UK

L9	Wet Particle Classification	11:00 - 12:15
-----------	------------------------------------	----------------------

Wet particle classification below 1 μ m Challenge for basic research and technical development, H. Anlauf*, Karlsruhe Institute of Technology (KIT), Germany I-307

Screening of colloidal particles in centrifuges, L.E. Spelter*, H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany I-315

Nozzle disc stack disc centrifuge use in wet classification in the fine grain range, T. Hartmann*, GEA Westfalia Separator Process GmbH, Germany I-323

L10	Cake Filtration – Cake Formation and Consolidation	11:00 - 12:15
------------	---	----------------------

Downscaling cake-filtration - An investigation of a separation process for crystallized proteins, B. Cornehl*, H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany I-329

Local filtration properties for hard-to-filter compressible materials, T. Mattsson*, M. Sedin, H. Theliander, Chalmers University of Technology; M.E. Lindström, Wallenberg Wood Science Centre - Royal Institute of Technology, Sweden I-336

Dewatering behaviour of ultrafine particle packings, S. Stein*, W. Hintz, J. Tomas, Otto-von-Guericke-University Magdeburg, Germany I-344

M2	Cross Flow Techniques	11:00 - 12:15
-----------	------------------------------	----------------------

Process development, optimization and cycle-time reduction in cross flow filtration by applying a design of experiments approach, L. Mathe*, K. Kuss, GE Healthcare Europe GmbH, Germany II-523

Effect of colloidal interaction on the reversibility and structure of the concentration polarization layers probed by in-situ SAXS during crossflow separation process of Laponite clay dispersions, M. Abyan, F. Pignon*, A. Magnin, University Joseph Fourier Grenoble; M. Sztucki, European Synchrotron Radiation Facility, France II-530

Influence of experimental parameters on (electro) filtration of positively charged particles, M. Hakimhashemi*, H. Saveyn, A.Y. Gebreyohannes, P. Van der Meeren, Ghent University, Belgium II-537

G5	Particle Deposition	11:00 - 12:15
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Simulation and measurement of dust loading of pleated air filters, P. Hettkamp*, J. Meyer, G. Kasper, Karlsruhe Institute of Technology (KIT), Germany II-154

Numerical and experimental investigation of soot deposition in wall-flow diesel particulate filters, P. Kopf*, T. Deuschle, M. Piesche, University of Stuttgart, Germany II-162

Deposition-dependent particle collection efficiency of model filter fibers in parallel arrays, T.K. Müller*, G. Kasper, J. Meyer, Karlsruhe Institute of Technology (KIT), Germany II-170

S4	Survey Lecture	13:15 - 14:30
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Nonwovens in filtration, Dr. Jörg Sievert, Freudenberg Filtration Technologies KG, Germany I-50

L11	Cake Filtration – Washing and Extraction	13:15 - 14:30
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The influence of adsorption properties - effects on the filter cake washing, M. Wilkens*, U.A. Peuker, Technical University Bergakademie Freiberg, Germany I-352

Filter cake washing of mesoporous particles, S. Noerpel*, H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany I-360

The non-aqueous filtration of oil sand - recovery of bitumen by organic solvents, E. Schmidt*, S. Häder-Schmidt, U.A. Peuker, Technical University Bergakademie Freiberg; F. Schmidt, Siemens AG, Germany I-367

M3 Membrane Bio Reactor 13:15 - 14:30

Investigation of mechanical membrane cleaning for enhanced MBR application, S. II-546
Krause*, A. Rach, W. Lamparter, Microdyn-Nadir GmbH, Germany

Optimized hydrodynamics for membrane bioreactor with immersed flat sheet membrane modules, L. Al-Shamary*, L. Böhm, M. Kraume, Technical University of Berlin, Germany

Highly efficient, low-energy membrane method in MBR technology based on Berghof external tubular membranes, S. Goodwin, G. Catley, Aquabio Limited, Great Britain; E. Wildeboer*, Berghof Membrane Technology GmbH & Co KG, Netherland

G6 Modelling and Simulation 13:15 - 14:30

Studies of different numerical models for a turbulent particle flow in a square pipe with 90° bend, D. Schellander*, D. Kahrmanovic, S. Pirker, Johannes Kepler University Linz, Austria

Flow and particle simulations of air cleaner filter media on microscopic scales, C. II-184
Feuchter*, MAHLE Filtersysteme GmbH, Germany

Fugitive dust suppression by optimized bulk solids moistening, J. Faschingleitner*, W. II-193
Höflinger, Vienna University of Technology, Austria

S5 Survey Lecture 15:00 - 16:15

Equipment selection and process design for solid/ liquid separation processes I-61
Dr. Steven Tarleton, Loughborough University, Department of Chemical Engineering, UK

L12 Cake Filtration – Deliquoring 15:00 - 16:15

Experimental study of filter cake cracking during deliquoring, A. Barua*, F. Stepanek, I-375
Imperial College London; G. Giorgio, W. Eagles, GlaxoSmithKline Ltd., UK

Comprehensive characterisation of material properties for dewatering: How much is enough?, R.G. de Kretser, A. Stickland*, S. Usher, P.J. Scales, University of Melbourne, Australia

Experimental and numerical investigation of the dewatering process of sewage screenings, H. Gregor*, U. Janoske, University of Wuppertal; W. Rupp, University of Cooperative Education Mosbach; M. Kuhn, Kuhn GmbH, Germany

M4 Waste Water Treatment 15:00 - 16:15

Recovery of polyphenols from paper industry effluent using pretreatment assisted ultrafiltration, D. Trebouet*, S.K. Singh, S. Ghnimi, IPHC University of Strasbourg, France

Clever, economical solutions for process media and wastewater recycling with membrane technology, P. Messerli*, W. Hochstrasser, L. Solinger, VP-Hottinger AG, M. Haller, aqua-System AG, Switzerland

Membrane autopsy in paper industry water recycling: An efficient tool for optimising filtration and cleaning strategies, E. Meabe*, R. Gutiérrez, J. Lopetegui, Likuid Nanotek; J. Ollo, J. Echeberria, L. Sancho, CEIT, R. Ordóñez, D. Hermosilla, Universidad Complutense de Madrid; F. Pérez, HOLMEN Paper Madrid, Spain

G7 Surface Filtration 15:00 - 16:15

An L9 orthogonal design methodology to study the impact of operating parameters on pulse-jet filtration process, A. Mukhopdhyaya*, National Institute of Technology Jalandhar, India

Prediction of cake-structure and pressure-drop evolution during filtration of polydisperse nanoparticles, T.D. Elmøe*, Technical University of Denmark, Denmark; D. Werz, A. Tricoli, S.E. Pratsinis, ETH Zürich University, Switzerland

Investigation of filter cake removal with different puff-back cleaning modes in a panel bed filter, K.P. Gaarder*, L. Wang, O.K. Sønju, J.E. Hustad, Norwegian University of Science and Technology, Norway

S6 Survey Lecture 16:45 - 18:00

Simulation in the field of gas filtration and separation, I-78
Prof. Paolo Tronville, Politecnico di Torino, Dipartimento di Energetica, Italy

L13 Cake Filtration Technology 16:45 - 18:00

Pushing the limits - How to continue a success story - The BHS-high performance rotary pressure filter, I-399
D. Steidl*, BHS- Sonthofen, Germany

Hi-Bar steam pressure filtration of an organic acid-process simplification by a hybrid separation process, I-416
R. Bott*, T. Langeloh, E. Ehrfeld, BOLEKA GmbH, Germany

Exploring the influence of feed material properties on full cycle optimisation of fill, squeeze and blow plate and frame pressure filters, I-416
R.G. de Kretser, A. Stickland*, P.J. Scales, University of Melbourne, Australia

L14 Electrostatic & Electrokinetic Effects in Separation Processes 16:45 - 18:00

Electrokinetic flotation of wastewater in a kinetic model tank, I-424
J.Q. Shang*, Y. Xu, The University of Western Ontario, Canada; F. Yono, Chrysler Group LLC, USA

Sorptive deep bed filtration by the application of embedded ion exchangers in loose filter sheets, I-432
S. Lösch*, U.A. Peuker, Technical University Bergakademie Freiberg, Germany

G8 Mist and Droplet Separation 16:45 - 18:00

Method of testing metal working fluid mist separators, II-225
T. Laminger*, M. Stecher, W. Höflinger, Vienna University of Technology, Austria

Temporal evolution of the saturation profile of an oil-mist filter, II-233
D. Kampa*, Buzengeiger, J. Meyer, G. Kasper, Karlsruhe Institute of Technology (KIT), Germany; B. Mullins, Curtin University of Technology, Australia

The importance of drainage in mechanical fibrous filters, II-241
M. Dalemo*, Absolent AB, Sweden

Thursday, March 24, 2011

L15 Depth Filtration – Modelling and Simulation I 08:30 - 09:45

On some macroscopic models for depth filtration: Analytical solutions and parameter identification, I-440
O. Iliev, R. Kirsch*, Z. Lakdawala, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; V. Starikovicius, Vilnius Gediminas Technical University, Lithuania

A novel experimental method to determine dirt particle distribution inside filter material samples, I-448
G. Boiger*, ICE Strömungsforschung GmbH; G. Reiss, W. Brandstätter; University of Leoben, Austria

Nonwovens: Effect width fibre size distribution, I-457
H.H. Kleizen, Parker Filtration BV & Delft University of Technology, Netherlands

L16 Rotary cake filtration technology 08:30 - 09:45

Hyperbaric disc filter for dewatering of copper flotation concentrate, I-465
R. Raberger, G. Kammer*, Andritz AG, Austria

Continuous pressure filtration at high temperatures - Fundamentals and process design, I-472
R. Bott*, T. Langeloh, Bokela GmbH, Germany

Benefits of hi-bar filtration in counterpressure design, I-476
R. Bott*, T. Langeloh Bokela GmbH, Germany

M5	New Membranes	08:30 - 09:45
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Innovative coating technologies for membrane media, T. Kolbusch*, C. Dittrich, J. Hanel, II-590
Coatema Coating Machinery GmbH, Germany

Membranes in conjunction with functional water-soluble polymers to remove pollutant ions, B.L. Rivas, S.A. Pooley, E. Pereira*, M. Palencia, J. Sanchez, University of Concepción, Chile

Gas permeation of tubular buckypaper membrane, M.A. Davoodi, J. Towfighi, Tarbiat Modares University; M. Fotukian, A. Rashidi*, Research Institute of petroleum Industry RIPI, Iran

G9	Poster Session II	08:30 - 09:45
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Application of electrostatic precipitators on road sweepers for fine dust reduction, II-249
M. Kaul*, E. Schmidt, University of Wuppertal, Germany

Study of the electrostatic effect in the filtration of micrometer particles, M.V. Rodrigues*, Federal University of Alfenas; F.B. Fenara, M.L. Aguiar, University of São Carlos, Brazil

Measurement and simulation of nanoparticle deposition at microstructured filter media considering especially electrostatic, A. Hellmann*, K. Schmidt, S. Ripperger, Kaiserslautern University of Technology; S. Rief, A. Wiegmann, Fraunhofer Institute for Industrial Mathematics ITWM, Germany

Validating the simulation of diesel soot agglomerate deposition in microstructured filter media by means of microsieve examinations, K. Schmidt*, S. Ripperger, Kaiserslautern University of Technology; *formerly Fraunhofer ITWM, Germany

Comparison of loaded DPF backpressure from different engine cycles and the combustion DPF testing system, K. StJ Reavell*, G.I. Inman, T. Hands, M.G. Rushton, A.H. Bown, C. Nickolaus, Cambustion Ltd., Great Britain

Reduction of NO_x, SO₂ & mercury emission from coal fired fluidized bed boilers, M. Jedrusik*, M.A. Gostomczyk, A. Swierczok, Wroclaw University of Technology, Poland

Industrial sampling and gas emission monitoring in stationary source, F. de Almeida Filho, M. A. Martins Costa, UNESP - São Paulo State University; M.L. Aguiar*, E.H. Tanabe, F. Hiromitus, UFSCAR - Federal University of São Carlos, Brazil

Investigations into the collection of fine dust by facade greenery, D. Bracke*, G. Reznik, E. Schmidt; University of Wuppertal, Germany

A new approach to deriving particle size fractions from a laser optical dust cloud measurement, S. Bach*, E. Schmidt, University of Wuppertal; M. Weiß, Palas® GmbH, Germany

L17	Depth Filtration – Modelling and Simulation II	11:00 - 12:15
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Modelling and simulation of filter media loading and of pleats deflection, H. Andrä, I-480
O. Iliev, M. Kabel*, Z. Lakdawala, R. Kirsch, Fraunhofer Institute for Industrial Mathematics ITWM, V. Starikovicius, Vilnius Gediminas Technical University, Lithuania

The influence of filter material deformation on permeability and pressure loss, M. Mataln*, G. Boiger, ICE Strömungsforschung GmbH; W. Brandstätter, University of Leoben, Austria

Modelling of non-spherical dirt particle motion and deposition in fluid filtration processes, G. Boiger*, M. Mataln, ICE Strömungsforschung GmbH; W. Brandstätter, University of Leoben, Austria

L18	Regenerable and Non-Regenerable Filters for Cleaning of low concentrated Liquids I	11:00 - 12:15
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Experimental studies of the superposed filtration mechanisms in a candle filter, X. Romani Fernández*, H. Anlauf; H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany

New methods of boiler- and process water microfiltration form an economical alternative to replace traditional sand filters, S. Strasser*, J. Baumgartinger, R. Größwang, Lenzing Technik GmbH; Austria

Selection and Design a multi-purpose filter with existing resources and technology for cost effective utility and operation, K. Roy*, Suzikline Group, India

M6 Special Applications 11:00 - 12:15

Dynamic washing of highly concentrated suspensions of finest particles by means of rotating disc filters, D. Goldnik*, R. Weiler, S. Ripperger, Kaiserslautern University of Technology, Germany

Reduction of membrane biofouling through effective removal of primary biofouling contaminant: Transparent exopolymer particles (TEP), H. Mowers, R. Komlenic*, Ahlstrom Filtration LLC, USA

Resuspensions' characterisation of membrane filter cake particles in liquid media via particle counter during a regeneration process, T. Quadt*, E. Schmidt, University of Wuppertal, Germany

G10 HEPA/ULPA Filters 11:00 - 12:15

The effect face velocity, pleat density and pleat orientation on the most penetrating particle size, pressure drop and fractional efficiency of HEPA filters, I.S. Al-Attar*, R.J. Wakeman, E.S. Tarleton, Loughborough University, UK; A. Husain, Kuwait Institute for Scientific Research, Kuwait

Determination of integral and local efficiency of HEPA and ULPA filters by application of an automated scanning technique, S. Große*, C. Peters, A. Rudolph, Topas GmbH, Germany

Improvements in the quick and reliable determination of HEPA and ULPA filter classes, S. Schütz*, M. Schmidt; Palas® GmbH, Karlsruhe, Germany

L19 Depth Filtration – Modelling and Simulation II 13:15- 14:30

On the recent progress in predicting filtration efficiency for filter elements, Z. I-524 Lakdawala*, O. Iliev, Fraunhofer Institute for Industrial Mathematics (ITWM); M. Dederich*, IBS Filtran, Germany; V. Starikovicius, Vilnius Gediminas Technical University, Lithuania

Analysis of the filtration and dust retention process of a fuel filter simulated with a 3D model using an open source code, L. Valino, R. Mustata, J. Hierro, Laboratorio de Investigación en Tecnologías de la Combustión; J.L. Hernandez*, M. Busack, C. Blasco, M.J. Garcia, Robert Bosch España Gasoline Systems S.A., Spain

Fast media-scale multipass simulations, J. Becker, S. Rief*, A. Wiegmann, Fraunhofer Institute for Industrial Mathematics (ITWM); M. Lehmann, S. Pfannkuch, MANN+HUMMEL GmbH, Germany

L20 Regenerable and Non-Regenerable Filters for Cleaning of Low concentrated Liquids II 13:15- 14:30

Treatment of highly viscous lubricants by high gradient magnetic separation technique, K. Menzel*, J. Lindner, H. Nirschl, Karlsruhe Institute of Technology (KIT), Germany

Modeling and predicting clogging behavior of the filtration process with fibrous filter media for used engine lube oils, F. Gruschwitz*, M. Förster, N. König, MAN Diesel & Turbo SE; H. Nirschl, H. Anlauf, Karlsruhe Institute of Technology (KIT), Germany

New tools to manage and optimize management of cleanliness requirement of fluid systems, C. Peuchot*, IFTS Institute of Filtration and Techniques of Separation, France

G11 Cabin Air Filters 13:15-14:30

Cabin air filter media with bicomponent spunbond support layer, A. Maltha*, E. II-343
Berkhout, P. Zuuring, M. Koerntjes, Colbond B.V., Netherlands

Efficiency of electret cabin air filters using different test aerosols, A. Breidenbach*, F. II-349
Schmidt, University of Duisburg-Essen, Germany

**Loaded adsorption filter - a solution for purgeable, volatile components and odours II-357
in automotive interiors?**, F. Diederich*, TAG COMPOSITES & CARPETS GmbH, Germany

G12 Filter Media Characterization 13:15-14:30

**Comparing the operating behaviour of pulse cleaned filter bags with that of flat media II-364
in a VDI tester**, O. Kurtz*, J. Meyer, G. Kasper, Karlsruhe Institute of Technologie (KIT), Germany

Novel test rig for compressed air filters: background, layout, first results, W. Moelter- II-372
Siemens*, G. Lauber, H. Finger, S. Haep, Institute for Energy and Environmental Technology IUTA; D.
Bathen, University Duisburg-Essen, Germany

Optimising life cycle costs - Sandler AG's new synthetic pocket filter media, U. II-379
Hornfeck*, Sandler AG, Germany

L21 Separation Enhancement by Coagulation 15:00-16:15

Numerical simulation of agglomeration and filtration of colloidal suspensions, H. I-570
Nirschl*, F. Keller, C. Eichholz, B. Schäfer, Karlsruhe Institute of Technologie (KIT), Germany

**Effect of some additives on enhancing filtration rate of new valley oxidized phos- I-578
phate concentrate**, E.A. Abdel-Aal*, Central Metallurgical R&D Institute; E.A. Abdel Rahman,
Egypt Phosphate Company; A.T. Kandil, Helwan University, Egypt

Metal (Al, Fe)-hydroxide sols formation in the coagulation, I. Licsko*, Budapest University I-590
of Technology and Economics, Hungary

L22 Removal of Particles and Scales from Surfaces 15:00-16:15

Removal of calcium scales from the surface of a ceramic filter medium, R. Salmimies*, I-599
A. Häkkinen, Lappeenranta University of Technology; B. Ekberg, Outotec (Filters) Oy; Finland; J.
Kallas, Tallinn University of Technology, Estonia; J.-P. Andreassen, R. Beck, Norwegian University of
Science and Technology, Norway

**Investigations on the cleaning behaviour of polymer woven filter media in solid liquid I-607
separation**, C. Leipert*, H. Nirschl, Karlsruhe Institute of Technologie (KIT), Germany

Cross-flow filtration: Influences on the cleanability of woven polymer filter media, M. I-615
Ulmer*, K. Sommer, Technical University Munich (TUM), Germany

G13 Industrial Gas/Air Cleaning I 15:00-16:15

**Maximize turbine efficiency while minimizing service costs using innovative air inta- II-384
ke systems**, M. Sauer-Kunze*, M. Grochowski, GEA Air Treatment GmbH - Branch GEA Delbag
Lufttechnik, Germany

Air Filtration System at the M5 East Tunnel Sydney, E. Deux*, B. Markmann, FILTRONtec I-392
GmbH, J. Chapman, FILTRONtec Pty Ltd., Australia

**Influence of gas distribution and field velocity on separation efficiency at ESP's with II-398
regards to different power supply techniques**, D. Steiner*, M. Lisberger, M. Lengauer,
Scheuch GmbH; W. Höflinger, Vienna University of Technology, Austria

G14 Special Filter Media I 15:00 - 16:15

Comparison of the various filter media used in bag filters, M. Sikka*, National Institute of Technology Jalandhar, India II-406

Material for high temperature gas filtration, A.K. Choudhary*, A. Mukhopadhyay, National Institute of Technology Jalandhar, India II-413

Investigating the effect of degree of crystallinity on the charge retention behavior on electrostatically-charging polyester nonwovens, P. P. Tsai*, The University of Tennessee, USA; Y. Yan, South China University of Technology, P.R. China II-423

L23 Separation Enhancement by Flocculation 16:45 - 18:00

FlocFormer technique - best conditioning for best dewatering and separation results, C. Schroeder*, aquen aqua-engineering GmbH, Germany; D. Takao, Tsukishima Kikai Co., Ltd (TSK), Japan I-623

New laboratory developments for belt thickener optimization, P. Ginisty*, C. Peuchot, IFTS Institute of Filtration and Techniques of Separation, France I-631

Relation between particle size distribution and filtration performance in biomass separation, P. van Hee, A.M.C. Janse*, J. Vente, H. Robers, T. Verkaik, DSM Biotechnology Center, Netherlands I-640

L24 Removal of Pollutants from Water by Catalytic, Biological and Encymatic Treatment 16:45 - 18:00

Catalytic manganese removal in the neutral pH range, U. Fischer*, C. Höfer, Rheinkalk Akdolit GmbH & Co. KG; H. Vedder, AWA-Institut, Gesellschaft für Angewandte Wasserchemie mbH I-645

Removal of ammonia from vacuum-II stripper wastewater in Jordan Petroleum Refinery (JPR), S. Emeish*, M. Tal, A. Khalil, S. AL-Muhteseb, Al-Balqa' Applied University, Jordan I-652

The effect of petroleum oil content on the enzymatic treatment of produced water, K.F. Mossallam, N. A. Salimova, Azerbaijan State Oil Academy, Azerbaijan I-660

G15 Industrial Gas/Air Cleaning II 16:45 - 18:00

Optimized cleaning systems for industrial baghouse filters, P. Bai*, T. Neuhaus, T. Schrooten, G.-M. Klein, Intensiv-Filter GmbH & Co. KG, Germany II-429

New filter lines for bulk solid handling in plastic, petrochemical and alumina industry, C. Soretz*, P.J. Erasmus, Coperion GmbH, Germany II-437

The Hybrid ESP-BF dust collector in China - Can be a substitute for ESP and BF?, L. Wang*, G. Fengnian, Chindias Environment & Energy Technologies, Ltd., P.R. China II-445

G16 Special Filter Media II 16:45 - 18:00

Investigation of the filtration properties of on-line laminated meltblown fibers/membrane, P.P. Tsai*, C. Woods, J. Wyrick, The University of Tennessee, USA II-453

Layers of submicron fibers produced by melt electrospinning, C. Hacker*, P. Jungbecker, G. Seide, T. Gries, H. Thomas, RWTH Aachen University, Germany II-459

Energy efficiency vs. electrostatics - requirements for new synthetic filter media, A. Seeberger*, A. Jung, T. Ertl, W. Rupertseder, IREMA-Filter GmbH, Germany II-462

KEYWORD LIST SESSION INDICATOR

Activated Carbon; G04-09, G11-3, G13-2
Adhesive Forces; G04-04, M06-3
Adsorption; G03-3, G04-09, G09-06, G11-3, L04-1, L11-2
Aerosol; G08-3, G09-04
Aerosol Spectrometer; G02-2, G10-3
Agglomerates; G02-1, L21-1
Air Cleaning; G03-3
Air Filters; SL - 6, G03-3, G10-1, G11-3, G13-2
Air Intake Systems; G13-1
Air Pollution; G09-07
Air Pollution Control; G03-2
Alumina; G15-2
Ammonia; L24-2
Anodizing Plant; M04-2
Antibiotics; L13-1, M01-08
Aquaculture; M01-06
Automatic Filter; L18-2
Automotive; G11-3, L03-3
Autopsy; M04-3
Backflushing; L18-3, L22-2, M01-01, M06-3
Backwash filter; L18-2
Baffle plate; G07-1
Bag Filter; SL - 1, G03-1, G14-1, G14-2
Baghouse Filter; G12-1, G14-1, G15-3
Belt Closure; L01-1
Belt Filter; L01-1
Bicomponent Spunbond Nonwoven; G11-1
Biodiesel; L03-3, L06-1
Biofouling; M06-2
Biomass; G01-2, G13-3, L23-3
Biomass Separation; L08-04, M01-06
Bioreparation; M01-05
Biotechnology; L08-04
Blocking Filtration; L18-1
Boiler Feed Water; L18-2
Boycott Effect; L06-3
Buckypaper; M05-3
Bulk Material; G09-09
CFD; SL - 6, G07-2, G16-2, L05-2, L19-3
CFD-Simulation; G04-01, G05-1, G06-2, G09-04, G13-3, L02-1, L05-3
CIP; L08-04
CMC; L13-1
Cabin Air; G11-2, G11-3
Cake Filtration; L10-1, L10-2, L18-1, L18-2
Cake Formation; L07-1, L10-2
Cake Press Device; L13-1
Cake Resistance; G15-1, L23-3
Cake Structure; L07-1
Cake Wash; L11-3, L13-1
Calcium; L22-1
Candle Filter; L18-1
Carbon Nanotube; L08-06, M05-3
Carnallite; L08-08
Catalytic Manganese Removal; L24-1
Cellulose Filter; L14-2
Centrifugal Separator; L02-2, L04-2, L04-3
Centrifugation; L02-3, L08-04, L08-06
Ceramic Filter Media; L22-1
Ceramic Membrane; M04-3, M06-3
Challenge Test; L07-2
Charged Particles; G09-02
Charging; L03-1
Chemical-free Separation; L04-2
Chemicals; G15-2
Clarification; M02-1
Classification; L08-07, L09-1, L09-2, L09-3
Cleanability; L22-2, L22-3
Cleaning; M03-1, M04-3
Clogging; L18-1
Coagulation; L21-3
Coalescence; L06-2
Coalescence Filter; G01-1, G08-2, L06-1
Coating; G02-3, M05-1
Colloid; L21-1
Colloidal Particles; M04-1
Colloidal Systems; M02-2
Compaction; L08-06
Composite Membrane; M05-3
Compressed Air Filters; G12-2
Compressibility; G04-05
Compressible Filter Cakes; L10-2
Compressive Yield Stress; L12-2
Computational Fluid Dynamics; G16-2, L05-1
Computer Simulation; L15-1, L17-1
Computer Software; L05-1
Concentration; M01-07, M02-1
Concentration Polarization; M01-02
Concentration Profile; L11-1
Conditioning; G02-3, G09-06, L23-1, L23-2
Consolidation; L10-3
Constant Pressure Cell; M01-02
Constant Pressure Filtration; L11-1
Copper Flotation Concentrate; L16-1
Counter Current Washing; L13-1
Creaming Velocity; L06-3
Cross-Flow Filtration; L22-3, M01-05, M01-08, M02-1, M02-3, M06-3
Cross-Flow Separation; M02-2
Cryptosporidium; M01-04
Cut Off Size; L09-1
Cycle Time; G07-1
DEHS; G11-2
DEM simulation; L17-3
DI Water; L18-2
DLVO Theory; L10-3
Dead-End Filtration; L10-2, L23-3
Deep Bed Filtration; L14-2
Deliquoring; L12-1
Deposition; G09-03
Depth Filtration; G09-02
Desalination; L08-02, M01-09
Desaturation; L13-3
Design; L08-07
Dewatering; L02-2, L12-3, L16-1, L23-1
Diafiltration; M01-02, M06-1
Diesel Oil; L06-1
Diesel Particulate Filter; G05-2, G09-05
Diesel Soot; G09-04
Disc Filter; L22-1, M06-1
Disc Separators; M06-1
Dissolved Substances; L04-1
DoE; M02-1
Downscaling; L10-1
Drainage; G08-3, G12-2
Drinking Water; M01-04
Drop Re-Entrainment; G01-1
Dust Cake; G05-1
Dust Emission; G02-2, G03-2, G12-1
Dust Filtration; G03-1, G05-1
Dust Loading; G05-3
Dust Separation; Plenary, G06-3, G09-08
Dust Suppression; G03-2, G06-3
Dye; L11-2
Dynamic Washing; M06-1
EN 1822; G10-3
Efficiency Tests; G03-2, L15-1
Effluent Treatment; M04-2
Electret; G11-2, G14-3
Electro-Hydrodynamic Flow; G13-3
Electroadhesion; M06-2
Electrofiltration; M02-3
Electrokinetic Flotation; L14-1
Electrophoresis; L14-1
Electrospinning; G16-2, L08-01
Electrostatic; G09-03, G16-3, L03-1
Electrostatic Charges; G14-3
Electrostatic Discharge; M01-07
Electrostatic Effects; G09-01, G09-02
Electrostatic Precipitation; G09-01, G09-06, G13-2, G13-3, G15-3
Emission; G07-1
Emission Control; G01-2
Emission Measurement; G02-2
Emulsion; G08-1, L06-1, L06-2, L18-3
Emulsion Stability; L06-1, L06-3
Energy Efficiency; G12-3, G15-1, G16-3, M03-2
Energy Reduction; M03-1
Energy Saving; L01-3
Environmental Protection; G01-2
Enzymatic Treatment; L24-3
Expression; L13-3
Fabric Filter; G04-01, G04-05, G14-1
Fermentation; L08-04, M01-08
Fibre Size Distribution; L15-3
Fibrous Filter; SL - 6, G08-3, G09-02
Fibrous Media; G05-3, L03-3, L20-2
Filter Cake; G04-04, L05-3
Filter Cake Discharge; G02-3
Filter Cake Structure; G07-2
Filter Cake Wash; L11-1, L11-2, L11-3
Filter Cleaning; G02-3
Filter Clogging; L20-2
Filter Control; G03-3
Filter Design; L05-3, L15-2, L17-3
Filter Efficiency; G03-3, G08-1, G10-2
Filter Layout; G13-2
Filter Loading; L17-1
Filter Media; G04-02, G04-08, G06-2, G11-1, G11-3, G12-3, G16-1, L01-2, L03-3, L05-3, L17-1, L22-3, M05-1
Filter Performance; G09-02, G13-2
Filter Scanning Test Rig; G10-2
Filter Sheet; L14-2
Filter Test; G08-1, L07-2
Filter Test Equipment; G02-2, G10-3, L07-1
Filter Test Rig; G02-2, G03-1, G03-3
Filtration; SL - 4, G04-06, G04-07, G04-09, G05-2, G08-3, G09-03, L03-1, L08-01, L12-1, L13-3, L17-2, L18-3, L19-2, L21-1, M05-2
Filtration Efficiency; G16-1, L17-2, L19-1
Filtration Mechanism; G09-02
Filtration Performance; SL - 6, G03-1, L15-3
Filtration Properties; L12-2, M02-3
Filtration Rate; G04-01, L21-2
Filtration Resistance; L10-2
Filtration Simulation; G07-2, L05-1, L19-3
Fine Dust Precipitation; G09-01, G09-08
Fine Filtration; L20-2
Fine Particle; G01-2
Flat Sheet Membranes; M01-06
FlocFormer; L23-1
Flocculation; L23-1, L23-2
Flow Instabilities; L04-3
Flow Simulation; L19-1
Fluid Mechanics; L09-2
Fluid-Structure Interaction; L17-1
Fluidized Bed; L08-07
Flux Enhancement; M02-3
Fouling; M01-02, M04-3
Fractional Efficiency; G10-1
Fractionation; L09-1
Fuel-Water Separation; L06-1
Fuelcell-Membranes; M05-1
Fugitive Dust; G06-3
Functionalized Surfaces; G03-3, G12-2
Gas Cleaning; G02-2, G10-1
Gas Cyclone; SL - 6
Gas Filtration; G03-3, G04-01, G04-02, G04-03, G04-04, G04-05, G04-08, G05-3, G12-1, G15-2
Gas Filtration Cakes; G02-3, G04-05
Gas Permeation; M05-3
Glass Fiber; G10-1
Grade Efficiency; L09-1
Gravity Separation; L06-3
Gypsum Morphology; L21-2
HEPA Filter; G10-1, G10-2, G10-3
High Efficient Air Filters; G13-1
High Gradient Magnetic Separation; L02-3, L20-1
High Pressure Filtration; G04-02
High Temperature Filtration; G14-2
High throughput experimentation; L23-3
Hollow Fiber Membrane; M01-06
Hot Gas Cleaning; G07-3
Hyaluronic Acid; M01-02
Hybrid Model; G06-1
Hydraulic Oil; L15-3

Hydrocyclone; L04-3, L08-03
Hydroxamides; L04-1, L04-2
Hydrogen-Bond; L21-3
Hydrophilic Nanocoating; L01-2
Hydrophobic; L01-2
Hygienic Design; L22-2
Hyperbaric Filtration; L16-1
ISO 25000; G12-2
ISO 29463; G10-3
ISO Guidelines; L15-2
Impregnation; L03-3
In Situ Testing; G03-1
Increased Turbine Efficiency; G13-1
Industrial Waste Water; M04-1
Interfacial Tension; L06-1
Ion Exchange; L14-2, M06-2
Iron; L08-09, L22-1
Iron Removal; L24-1
Jet Clean Filter; G15-2
Jet Pulse; G15-1
Jordan Petroleum Refinery (JPR); L24-2
Kaolin; L02-2
Laboratory Device; L06-3
Lamination; L01-3, M05-1
Life Cycle Cost; G12-3
Light Scattering; G05-3
Liquid Storage; G08-1
Local Measurement; L10-2
Lube oil; L03-3
Lubricant Treatment; L20-1
Lysozyme Crystals; L10-1
MATLAB; L08-08, L15-2
MBR; - 2, M03-1, M03-3, M04-2
MPPS; G10-3
Magnetic Filtration; L02-3
Maintenance Costs; G13-1
Mass Transfer; L22-2, L22-3
Meltblown Filter Media; L03-1
Membrane; M01-01, M05-2
Membrane Filtration; M01-04, M01-07, M04-2
Membrane Fouling; M01-05, M01-09
Membrane Separation; M01-05, M02-3
Membrane Technology; SL - 2
Mesoporous Particles; L11-2
Metal Working Fluids; G08-1
Metal-Hydroxide Sols; L21-3
Micro Structure; G09-04
Microfiltration; SL - 2, L10-1, L18-2, M01-05, M01-06, M02-3
Microporous Membrane; G16-1
Microstructure; G06-2
Mineral; L16-1
Mineral Suspensions; L12-2
Mist Filtration; G01-1, G08-2
Mist Separation; G04-07, G08-1
Modelling; SL - 6, L05-1, L15-1, L20-2
Motion Trajectory; L04-3
Multi Layer Filtration; L24-1
Multi Pass Test; L15-3, L19-3
Multiphase Flow; L02-1
Multiphase Simulation; L08-07, L12-3
Multiple Stage Filters; G13-1
Nanofibers; G16-3, L08-01
Nanofibre Nonwovens; L05-2
Nanofiltration; SL - 2, M04-2
Nanoparticles; G01-3, G09-03, L06-1, L09-1, L09-3
Nanotechnology; G03-3
Natural Gas; G04-02
Nonwoven Filters; L20-2
Nonwovens; SL - 4, G04-08, L01-3, L15-3
Nozzle Centrifuge; L09-3
Numerical Simulation; L21-1
Oil Filtration; L03-3, L07-1, L19-3, L20-1
Oil Removal; L04-1
Oil Sand; L11-3
Oleophobic Nanocoating; L01-2
Online Monitoring; G03-3
OpenFOAM®; L17-2, L17-3
Operating Temperature; G14-2
Optical Particle Counter; G03-2
Optical Particle Measurement; G01-1
Optimal Nozzle Parameters; G06-3
Organic Contaminants; L04-1
Organic Solvents; L11-3
PM2.5; G03-2, G07-1
PTA; L13-1
Panel Bed Filter; G07-3
Paper Industry; M04-1, M04-3
Parameter Identification; L15-1
Particle Charging; G09-01
Particle Concentration; L08-02, L19-1
Particle Deposition; G05-3, G09-02, G09-08
Particle Detection; L04-3
Particle Generation; G09-05
Particle Interaction; G06-1, L17-3
Particle Separation; G06-2
Particle Shape; L17-3
Particle Simulation; G06-1
Particle Size Distribution; L19-2, L23-3
Particle Sizing; G01-3, L09-2, M06-3
Particulate Emissions; G13-3
Particulate Material; G09-07
Patchy Cleaning; G04-03
Pathogens; M01-04
Penetration; L15-2
Peptiser; M02-2
Permeability; G04-01, G10-1, L05-2, L07-1, L08-01, L12-2
Peroxidase; L24-3
Pharmaceuticals; M01-08
Phosphate Concentrate; L21-2
Phosphoric Acid; L08-09
Pinholes; L01-3
Plasma; G04-06, L01-2
Plasma Coating; L01-2
Plastics; G15-2
Pleatability; G11-1
Pleated Filter; G05-1, L17-1
Polarization Layers; M02-2
Pollutant Ions; M05-2
Polydisperse Particles; G02-1, G07-2
Polymers; L08-01, L23-2
Polymethylmethacrylate; L15-2
Polyphenol; M01-07
Polyvinylidene-Fluoride Fabrics; L03-2
Pore Blocking; G07-2
Pore Size; L01-1, L06-2, L07-1, L07-2, L08-01
Pore Size Distribution; L07-1
Porosity; G04-01, G04-05, L06-2, L23-3
Potassium Chloride; L08-08
Power Consumption; L01-3
Precoat Filtration; L08-04
Pressure Drop; G04-07, G06-2, G08-3, G09-05, G10-1, G11-1, G15-1, L17-2, L19-1, L19-2
Pressure Filtration; L10-3, L13-2, L16-2, L18-3
Pressure-Drop Evolution; G07-2
Pretreatment; L08-02, M04-1
Process Design; SL - 5, L16-2, M04-2
Process Filter; G15-2
Process Optimisation; M02-1, M03-2, M04-2
Produced Water Treatment; L04-1, L24-3
Pulp and Paper; L10-2
Pulse Jet Cleaning; G12-1
Punch Density; G07-1
Reactor; G09-06
Recovery; M01-09
Recycling; M04-3
Reduced Volume Filters; L03-3
Regression Analysis; L02-2
Removal Efficiency; L24-2
Removal Tension; G04-04
Reverse Osmosis; SL - 2, G04-08, M01-09, M05-1
Road Tunnel; G13-2
Rotary Pressure Filter; L08-04, L13-1
Rotating Disc Membrane; M01-08
Reactor; G09-06
Recovery; M01-09
Recycling; M04-3
Reduced Volume Filters; L03-3
Regression Analysis; L02-2
Removal Efficiency; L24-2
Removal Tension; G04-04
Reverse Osmosis; SL - 2, G04-08, M01-09, M05-1
Road Tunnel; G13-2
Rotary Pressure Filter; L08-04, L13-1
Rotating Disc Membrane; M01-08
SAXS; L11-530
SDI Reduction; I-255
SMPS; L11-398
Salt Induced Flocculation; I-219
Sand Filter; I-512
Sandwich Systems; L11-590
Saturation; L11-233
Scalant Removal; I-160
Scale; I-599
Scale-up; I-545
Scattered Light Particle Sizer; L11-310
Selective Adsorption; I-352, I-432
Selective Bioseparation; I-130
Selectivity; I-307
Self Adjusting Interface Level; I-168
Self Cleaning; I-518
Separation; I-19, I-255, I-269, I-286, I-416, I-623
Service Costs; L11-384
Service Life; I-94
Sewage Screenings; I-391
Sewage Sludge; I-383
Shrinkage Cracks; I-375
Simulation; I-78, I-189, I-487, I-532, L11-162, L11-265
Single Fiber Efficiency; L11-70
Slitting of Filter Materials; I-107
Sludge; I-631
Sodium Chloride; L11-349
Sol-Gel; I-590
Solid bowl centrifuge; I-114
Solid-Liquid Separation; I-61, I-269, I-344, I-399, I-424, I-518, I-590
Solvent; I-296
Soot; L11-349
Spiral Plate Pack; I-168
Spunbond; L11-423
Starch; I-399
Static Filter; L11-437
Stirring; L11-469
Submicron Particles; L11-272
Sugar; L11-26
Surface Filtration; L11-56, L11-65, L11-154, L11-364, L11-459
Surface Modification; I-99, L11-126
Surfactants; I-273, I-578
Suspension; I-278, L11-605
TIC and TIM Adsorption; G03-3
TSS Removal; L04-1, L08-02
Tangential Flow Filtration; M01-08
Test Dust; G11-2, L15-3
Test Rig; G09-05, G12-2
Testing Procedures; SL - 1, L22-3
Textile Structures; L05-2
Thermal Stability; G14-3
Thermophilic Bacteria; L24-2
Thickening; L23-2
Three-dimensional Flow; G07-2
Titanium Dioxide; L02-2
Tornado Press; L23-1
Toxic Compounds; G03-3
Transmembrane Pressure; M01-08
Transparent Exopolymer Particles; M06-2
Transport in Porous Medium; G08-2
Tubular Bowl Centrifuges; L09-2
Tubular Membranes; M03-3
Tubular Module; M05-3
Tunnel Air Filtration; G13-2
Turbulent Flow; G06-1
Two Phase Flow; L19-2
ULPA Filter; G10-2, G10-3
Ultra Low Sulfur Diesel; L06-1
Ultrafiltration; SL - 2, G04-08, G13-2, M01-01
Ultrafiltration; M04-1, M04-2
Ultrasound; L01-3
VDI 3926; G02-2
VOC; G03-3
Vacuum; L01-1
Venturi Scrubber; SL - 6, G01-2
Viscosity; L20-1
Washing; L22-1, M06-1
Washing Press; L12-3
Waste Water; SL - 2, M01-09, M03-1
Water Separator; G15-2
Water Treatment; SL - 2, L14-1, L24-1, M01-03
Water-Functional Polymers; M05-2
Water-Spray; G06-3
X-Ray Tomography; G05-1, G06-2
Zeta Potential; L10-3

SESSION CHAIRMEN

TUESDAY, MARCH 22, 2011

Plenary Talk – Wilhelm Höflinger: New developments in the field of filtering dust separation techniques	10:30-11:30 h
S1 - Chikao Kanaoka: International standardization in the field of filtration and separation Chairman: Eberhard Schmidt	13:15-14:30 h
L1 - Filter Media - New Developments I Chairman: Krishna Gupta	13:15-14:30 h
L2 - Centrifugal Sedimentation Technology I Chairman: Sebastian Stahl	13:15-14:30 h
G1 - Measurement Techniques Chairman: Wilhelm Höflinger	13:15-14:30 h
S2 - Thomas Peters: Membrane processes for the treatment of water and wastewater Chairman: Kuo-Jen Hwang	15:00-16:15 h
L3 - Filter Media - New Developments II Chairman: Christoph Maurer	15:00-16:15 h
L4 - Centrifugal Sedimentation Technology II Chairman: Steve Tarleton	15:00-16:15 h
G2 - Filter Test Systems I Chairman: Chikao Kanaoka	15:00-16:15 h
L5 - Filter Media - Modelling, Simulation, Design Chairman: Steve Tarleton	16:45-18:00 h
L6 -Mechanical Liquid-Liquid Separation Chairman: Dietmar Lerche	16:45-18:00 h
G3 - Filter Test Systems II Chairman: Takeshi Yoneda,	16:45-18:00 h
S3 - Bernd Sachweh: Particle (size) characterization Chairman: Eberhard Schmidt	16:45-18:00 h

WEDNESDAY, MARCH 23, 2011

L7 - Filter Media – Characterization and Porometry Chairman: Christophe Peuchot	8:30-9:45 h
L8 - Poster Session I Chairman: Harald Anlauf	8:30-9:45 h
G4 - Poster Session I Chairman: Markus Lehner	8:30-9:45 h
M1- Poster Session I Chairman: Thomas Peters	8:30-9:45 h
L9 - Wet Particle Classification Chairman: Urs Peuker	11:00-12:15 h
L10 - Cake Filtration – Cake Formation and Consolidation Chairman: Hans Theliander	11:00-12:15 h
M2 - Cross Flow Techniques Chairman: Jaroslav Pridal	11:00-12:15 h
G5 - Particle Deposition Chairman: Wilhelm Höflinger	11:00-12:15 h
S4 - Jörg Sievert: Nonwovens in filtration Chairman: Eberhard Schmidt	13:15-14:30 h
L11 - Cake Filtration – Washing and Extraction Chairman: Urs Peuker	13:15-14:30 h
M3 - Membrane Bio Reactor Chairman: Jaroslav Pridal	13:15-14:30 h
G6 - Modelling and Simulation Chairman: Martin Lehmann	13:15-14:30 h
S5 - Steve Tarleton: Equipment selection and process design for solid/liquid separation processes Chairman: Harald Anlauf	15:00-16:15 h
L12 - Cake Filtration – Deliquoring Chairman: Anthony Stickland	15:00-16:15 h

M4 - Waste Water Treatment Chairman: Thomas Peters	15:00-16:15 h
G7 - Surface Filtration Chairman: Gerhard Kasper	15:00-16:15 h
L13 - Cake Filtration Technology Chairman: Gernot Krammer	16:45-18:00 h
L14 - Electrostatic & Electrokinetic Effects in Separation Processes Chairman: Eugene Vorobiev	16:45-18:00 h
G8 - Mist and Droplet Separation Chairman: Siegfried Ripperger	16:45-18:00 h
S6 - Simulation in the field of gas filtration and separation Presenter: Paolo Tronville	16:45-18:00 h

THURSDAY, MARCH 24, 2011

L15 - Depth Filtration – Modelling and Simulation I Chairman: Harald Banzhaf	8:30-9:45 h
L16 - Rotary Cake Filtration Technology Chairman: Harald Anlauf	8:30-9:45 h
M5 - New Membranes Chairman: Thomas Peters	8:30-9:45 h
G9 - Poster Session II Chairman: Hans-Joachim Schmid	8:30-9:45 h
L17 - Depth Filtration – Modelling and Simulation II Chairman: Harald Banzhaf	11:00-12:15 h
L18 - Regenerable and Non-Regenerable Filters for Cleaning of low concentrated Liquids I Chairman: Sebastian Stahl	11:00-12:15 h
M6 - Special Applications Chairman: Thomas Peters	11:00-12:15 h
G10 - HEPA/ULPA Filters Chairman: Arunangshu Mukhopadhyay	11:00-12:15 h
L19 - Depth Filtration – Modelling and Simulation II Chairman: Hermann Nirschl	13:15-14:30 h
L20 - Regenerable and Non-Regenerable Filters for Cleaning of low concentrated Liquids II Chairman: Siegfried Ripperger	13:15-14:30 h
G11 - Cabin Air Filters Chairman: Arunangshu Mukhopadhyay	13:15-14:30 h
G12 - Filter Media Characterization Chairman: Paolo Tronville	13:15-14:30 h
L21 - Separation Enhancement by Coagulation Chairman: Arunangshu Mukhopadhyay	15:00-16:15 h
L22 - Removal of Particles and Scales from Surfaces Chairman: Marja Oja	15:00-16:15 h
G13 - Industrial Gas/Air Cleaning I Chairman: Markus Lehner	15:00-16:15 h
G14 - Special Filter Media I Chairman: Martin Lehmann	15:00-16:15 h
L23 - Separation Enhancement by Flocculation Chairman: Christophe Peuchot	16:45-18:00 h
L24 - Removal of Pollutants from Water by Catalytic, Biological and Encymatic Treatment Chairman: Harald Anlauf	16:45-18:00 h
G15 - Industrial Gas/Air Cleaning II Chairman: Markus Lehner	16:45-18:00 h
G16 - Special Filter Media II Chairman: Hermanes Kleizen	16:45-18:00 h

Proceeding lists countries & regions

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SIMULATION IN THE FIELD OF GAS FILTRATION AND SEPARATION

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ABSTRACT

The paper surveys the history and present status of simulation of equipment to capture aerosols and gaseous air contaminants. Simulation of both industrial and effluent separation devices and fibrous filters are reviewed. Problems involved in simulating actual operating conditions, unusual atmospheres, turbulence and nano-scale filter structures are discussed, along with the computational limits of current CFD schemes. Suggestions are made for further refinement of simulation models to obtain better agreement between simulations and experimental data.

KEYWORDS

Air Filters, CFD, Fibrous Filters, Filtration Performance, Gas Cyclone, Modelling, Simulation, Venturi Scrubber

1. Introduction

Detailed calculation of the performance of gas phase separation equipment involves solutions of sets of differential equations which describe flow through the separation devices. The strength of computational fluid dynamics (CFD) in solving such equations has created a mindset which equates CFD with simulation. However, in gas filtration and separation technology, we find useful simulations which do not use CFD.

In the broadest sense, simulation includes all laboratory tests, where the tested device may be only part of an actual device, or a small-scale model of it. Tests try to mimic field conditions, but often use conditions far from those in actual applications.

A second type of simulation occurs when analyzing data from experiments. Before any mathematical description of a gas cleaning device can be made, some model for the performance of the device must be assumed. Indeed, one can devise mathematical models without any experimentation, or use them to guide experiments. The extent to which the mathematical model reflects the actual geometry of the device simulated, and the physics of its behavior, can determine how accurate its predictive equations will be.

Often the search for descriptive equations requires gross simplifications of the actual shapes and operating conditions to allow mathematical analysis. These results may be useful for selection of equipment or improving its design. But in many cases, the geometry of a device is too complicated for classic mathematical analysis. In CFD we have a means to overcome this barrier. It breaks our models into thousands of little pieces that can be digested by computer codes, and produces performance descriptions whose accuracy can at least be quantified. If CFD analysis gives performance predictions close enough to measured data, the model used for the verified CFD calculation can be extended to predict performance at other conditions, and for equipment optimization. If CFD fails, we revise the model, and try again.

We have some guidance in the simulation process, or at least warnings of troubles ahead, attributed to some great thinkers:

“A scientific theory should be as simple as possible, but no simpler” (A. Einstein);

“All models are wrong, but some are useful” (Statistician George Box);

“Correlation does not imply causation” (Somebody long before Aristotle).

With these understandings of the nature of simulations, let us examine how they have assisted the development of filtration and separation technology.

2. Venturi scrubbers

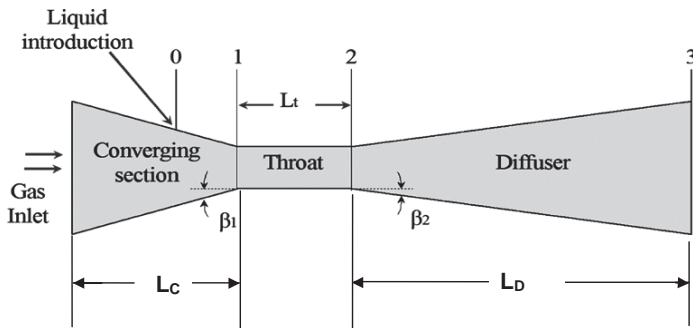


Figure 1 - Venturi Scrubber Schematic [adapted from Economopoulou (2007)]

Figure 1 shows a longitudinal section of a venturi. Although the geometry of the venturi is simple, analysis of its performance is not. At least the following parameters must be considered in to determine the pressure drop and efficiency of the venturi:

Gas flow volume	Liquid injection position	Particle concentration,
Liquid-flow rate	Gas and liquid properties	density, morphology
Venturi geometry	Droplet characteristics	and diameter

The venturi must be followed by a cyclone to capture the droplets bearing particles captured in the venturi. The efficiency and pressure drop of this cyclone are parameters in the overall system performance. The simulation of the cyclone portion of such a system is considered in the next section.

The equations listed below show the level of complexity involved in various analyses. Subscripts *G* and *L* refer to gas and liquid; subscripts *p* and *d* to particle and droplet.

2.1 Venturi Pressure Drop

There are many reports of test results on venturi scrubbers with wide ranges of the above parameters. Some of these test sets were used to develop predictive performance equations incorporating the physical phenomena considered pertinent by the authors. Examples of equations predicting venturi pressure drop are contained in Calvert (1970 and later), Boll (1973), Hesketh (1974), Yung (1977), and Leith et al. (1985). In spite of these years of study, the prediction of pressure drop by these analytical methods is poor. Figure 2 gives the agreement between the pressure drop predictions of Leith and measurements for a wide range of venturi sizes and operating conditions. At 0.59 kPa, the agreement ranges from -28% to +80%. If the velocity pattern, which determines pressure drops in a gas cleaning device, is based on an unreliable model, then modeling particle capture using that model is futile.

Clearly, something is needed beyond correlations of empirical data, even if the correlations are guided by what seem to be reasonable physical concepts. CFD might be that something.

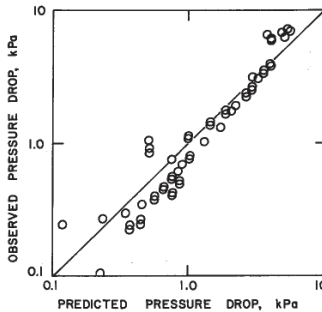


Figure 2 - Comparison, measured values of pressure drop to analytical predictions [from Leith et al. (1985)]

2.2 Venturi Particle Efficiency and Penetration

The analysis of particle capture is far more complicated, and the accuracy of prediction less reliable. In this discussion, we will list expressions for penetration, which measures the fraction of pollutant that passes a separator. [Penetration = (1 - Efficiency), both fractions].

An example of the limited use of predictive equations is shown in Hesketh (1973):

$$\text{Penetration} = C_o / C_i = \frac{95200}{V_f^{2.86} \rho_G^{1.43} A_f^{0.19} R_{LG}^{1.12}} \quad (1)$$

Unfortunately, this expression contains nothing related to dust properties, so is merely a correlation built on the data set Hesketh used.

A later example is from Costa et al. (2005), a correlation including both inertial and diffusion collection on water droplets in a venturi:

$$\text{Penetration} = \exp \left[-51.9 \left(\frac{Q_L (1 - F_r) \rho_L D_d}{A_f \mu_G} \right)^{0.19} \left(\psi^{0.169} + 2813 Pe^{-0.581} \right) \right] \quad (2)$$

Where

$$\psi = \frac{\rho_p d_p^2 V_G C}{18 \mu_G D_d} \quad (\text{inertial parameter}) \quad (3)$$

$$Pe = \frac{3\pi V_G D_d \mu_G d_p}{K_B T C} \quad (4)$$

These expressions gave remarkably good fits to experimental data when only a single variable was considered (e.g. particle diameter), but penetration by Equation 2 including all variables gave predictions of penetrations of 1% to 7% for measured values in the range of 0.1% to 9%. Penetration is, admittedly, a demanding criterion for judging predictive equations.

Yung et al. (1977) and Boll (1973) both modified an earlier analysis by Calvert, eliminating some of the assumptions, which also eliminated some empirical constants. To display Yung's efficiency equation set takes almost a whole page; Boll's expression is in differential form, and must be solved by numerical methods.

Rudnick et al (1986) applied the expressions developed by Yung and Boll to efficiency test data on three venturis. Plots of predicted vs. measured penetration results are shown in Figure 3 which shows that these regression equations for penetration, hence efficiency, essentially predict nothing, in spite of their complexity.

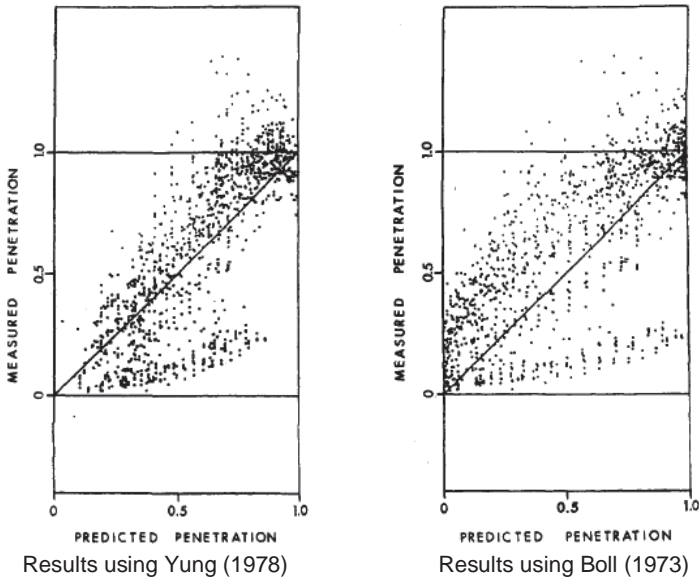


Figure 3 - Comparison of venturi penetrations predicted by Yung and Boll equations to measured data [from Rudnick et al. (1986)]

2.3 Venturi CFD Simulations

CFD analyses of various aspects of venturi performance include studies by: Anathanarayanan and Viswanathan (1999); Ravi et al. (2003); Ahmadvand and Talaie (2009); Pak and Chang (2006).

Analysis of particle capture by venturis must include, in addition to the above list of items needed for pressure drop calculation, particle wettability. A great deal of attention has been given to the particle size distribution of the droplets created in the venturi throat, and to their spreading across the throat area. Each of the authors of these CFD studies assures us that the agreement between measurement and CFD simulation was excellent. It would be interesting to have the kind of comparison made by Rudnick et al. on a wide array of venturi scrubber designs. The labor involved would, however, be immense.

What we do know is that every CFD analysis needs to include verification studies. The ideal CFD solution to its sets of differential equations would use infinitesimal steps of time and space coordinates. We must do with finite steps, but there are techniques for extrapolating the results to "zero" scale of the computational mesh used. A reliable CFD analysis requires at least three runs using successively smaller mesh scales in order to perform the extrapolation to zero scale. The paper of Herman et al. (2006) illustrates this process. The internet site of the US space agency NASA offers an extensive tutorial on this and other recommended procedures for

verification and validation of CFD calculations. (See www.grc.nasa.gov/www/wind/valid/homepage.html)

3. Cyclones

The first patent for a dust-collecting cyclone was apparently issued to J.M. Finch in 1885. Although his cyclone little resembles present-day designs, the germ of the cyclone concept was there. Dirty gas entered a cylinder tangentially at high velocity, and the bulk of the flow exited axially. In Finch's design, dust was expelled by centrifugal force through slots in the wall of the cylinder, a more complicated and less effective scheme than the flow reversal and bottom dust drop-out of current cyclone designs. The configuration of Figure 4 uses Finch's tangential entry, but the swirling flow reverses at the bottom of the cyclone cone, and dust drops out of the cyclone cone into a hopper. This design was widely used by the early 1900s, and is still important.

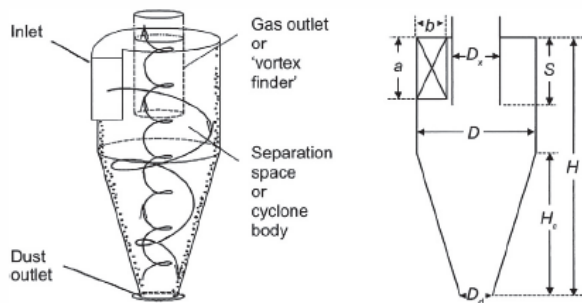


Figure 4 - Tangential-inlet cyclone and defining dimensions [from Gronald (2011)]

Efforts toward improved performance produced many modifications to the basic cyclone concept, with elements inserted into the cyclone to channel flows and counter-flows of gas and dust. The cyclonic, centrifugal concept is available in a wide array of sizes, from tiny sampling instruments to units a meter or more in diameter. In addition, there are designs which substitute a spin-generating helix in the inlet air flow for the tangential inlet. These are called axial-flow cyclones.

Mathematical analysis of what was happening inside cyclones was rather limited in the 19th century. Some pieces of the puzzle were available then. We speak of "Newtonian fluids" because the great polymath produced the first serious understanding of viscosity, in the mid-17th century. (Most analysis of the motion of small particles in cyclones is pure Newtonian mechanics, and there is a lot of use of Newton's calculus, also). Bernoulli, Euler, d'Alembert, Lagrange, and Laplace all made significant contributions to the necessary mathematics, still used in our CFD codes. Navier made his contribution to the laws governing fluid flows in 1822, and Stokes his in 1842. By 1851 Stokes had also derived the expression for the aerodynamic drag on a small particle, fundamental to the simulation of particle motion in a cyclone. Other early advances came from: Hagen and Poiseuille (laminar pipe flow, 1839); Darcy (porous-bed flow, 1856); Rayleigh (convection, 1880s).

Most of the great advances in fluid mechanics which form the basis of our present simulations took place after 1900. Reynolds published his first work shedding some

light on turbulent flow a little earlier, in 1895. To name a few other contributors: Prandtl (boundary-layer theory, 1904); Buckingham (dimensional analysis, 1914); G. I. Taylor (turbulence, 1923); von Karman (turbulence, boundary layer theory, supersonic flow, 1930s); Kolmogorov (turbulence, 1940); Spalding (turbulence, CFD, 1970s).

The parameters defining cyclone operation include those in the venturi list above, including parameters related to liquids when the cyclone collects liquid particles. The cyclone geometry must of course be defined, along with any “bleed air” flow withdrawing the separated dusty portion of the flow. The more sophisticated studies include the effects of boundary layer conditions at the surface of the cyclone cone.

3.1 Empirical Correlations of Cyclone Performance

An excellent review of cyclone modeling is given by Zhao (2007). He identifies three model forms: “equilibrium orbit”; “timed flight”; and hybrids of these. He then notes that there are three approaches to obtaining expressions for cyclone pressure drop and efficiency/penetration from these models.

The first method uses detailed definition of the physical mechanisms present in the model, and mathematical description of these. The second method uses dimensionless groups, and seeks the combinations of these groups and exponents applied to them which best fit measured performance data. Finally, there is CFD.

Zhao’s paper describes rigorous means to optimize predictive equation parameters using the dimensionless group method. His results appear to provide a substantial improvement over earlier attempts to correlate empirical data obtained on cyclones.

The regression equations compared in Zhao’s paper are representative of the work on cyclone performance that has appeared in the literature: Barth (1956); Leith and Licht (1971); Dietz (1981); Mothes and Löffler (1988); Li and Wang (1989); Iozia and Leith (1990); Clift et al. (1991). Citations for these studies are given by Zhao.

3.2 CFD Predictions of Cyclone Performance

In most cases, cyclone flow will be turbulent, and a turbulence model with its parameters must be chosen. The Reynolds stress model for turbulence (RSM) has proved to be the most reliable. Equations calculating the level of gas “slip” at the cyclone walls and at the surface of particles must be supplied.

Boysan et al. (1982); Zhou et al. (1990); Ogawa (1997); Meier and Mori (1999); Witt et al. (1999); Zhao et al. (2004); Martignoni et al. (2007); Bernardo et al. (2006) present analyses of cyclone performance using CFD. Shalaby (2007) is essentially a tutorial on the application of CFD to cyclones, with explanations of many CFD problems. Figure 5 is an example of the velocity patterns obtained in his study. The tangential inlet flow is not shown, but the velocity differences between outer (blue) and inner (red) vortices are shown. The boundary layer on the inside the discharge pipe appears, graded from blue (low velocity) through green and yellow to red (high velocity). The color image appears in the thesis.

Comparisons between CFD predicted and measured values of cyclone performance are rare in published literature. Figure 6 is one example, from Crosby and Frye (2008). The results from Shepherd and Lapple (1940), long before CFD, are closer to measured values than Crosby and Frye’s CFD results. The measurements of efficiency at 1/6 normal gravity were made on an aircraft on a parabolic flight path, which simulates zero gravity for about 30 seconds. Validating CFD can be difficult.

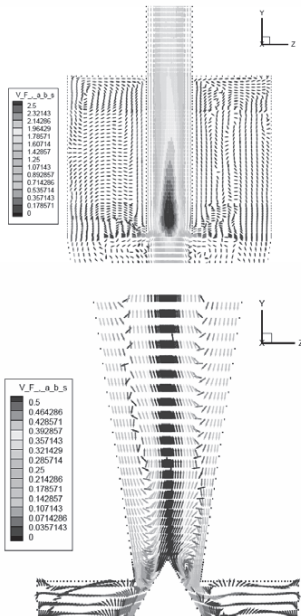


Figure 5 - CFD-generated pattern of velocity vectors for tangential-inlet cyclone [from Shalaby (2007)]

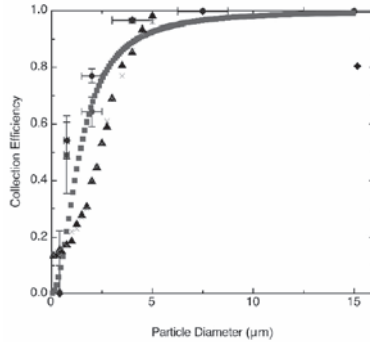


Figure 6 - Cyclone Efficiency Dependence on Particle Diameter [from Crosby and Frye (2008)]

Predicted:

- Shepherd & Lapple (1940)
- ▲ Crosby & Frye (CFD, normal gravity)
- x Crosby & Frye (CFD, zero gravity)

Measured:

- ◆ Crosby & Frye (normal gravity)
- Crosby & Frye (CFD, 1/6 normal gravity)

4. Louvers

We have found a limited number of references for simulations of this form of inertial separator. Figure 7 shows the geometry of a flat-blade louver separator.

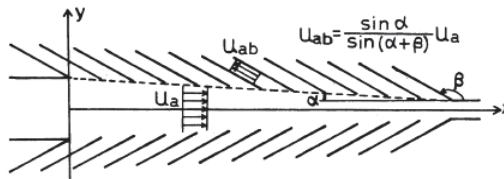


Figure 7 - Geometry Used for CFD Simulations of Louver Performance [from Hiyoshi (1988)]

Hiyoshi traced large (12 µm to 102 µm mass mean diameter) particle paths through this simulation of a louver cross-section, using CFD methods. They obtained the results shown in Figure 8. By positioning a plate splitting the central chamber in half the performance was greatly improved, apparently holding impacting particles. At high inlet velocities, without a center plate, the CFD- calculated paths sometimes

showed particles bouncing back and forth between the opposite sets of lower blades. Enikeev (1995) modeled the paths of water droplets by CFD in similar structures.

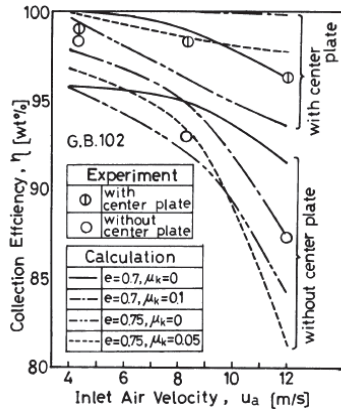


Figure 8 - CFD Simulations of Louver Efficiency [from Hiyoshi (1988)]

5. Electrostatic Precipitators

Electrostatic precipitators (ESP) have three quite different geometries: wire-tube, two-stage, and single-stage. The application of the wire-tube design is today largely limited to the capture of liquid particles, or those with other properties (such as very high electrical resistivity). These make wet operation of the units desirable. Two-stage precipitators, with a short ionizer section followed by a set of charged parallel plates, are used in ventilation systems, including residential applications. The single-stage design, with a row of discharge electrodes between parallel collector plates, is used in large-scale industrial applications, especially for capture of fly-ash from coal-fired power plants. The physical phenomena are similar in all three forms; we will discuss only the single stage form. A schematic section of this is shown in Figure 9.

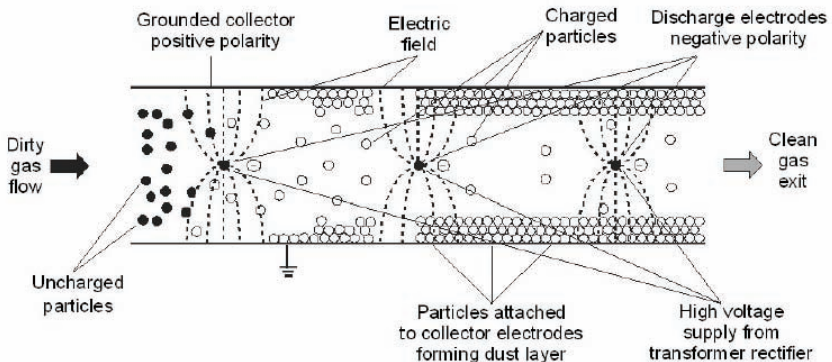


Figure 9 - Schematic Cross-Section of a Single-Stage Electrostatic Precipitator [from Parker and Plaks (2004)]

The figure is actually far simpler than reality, for the electric field lines actually fill the entire interior space. Discharge electrodes may be cylindrical wires as shown, or they may be complicated fluted or scalloped structures, or even carry rows of sharp points. The collector plates are not usually continuous as shown, but are divided into sections to allow motion when rapped. These collector plate sections are also formed into shapes which provide rigidity and spaces where collected particles are somewhat protected from being blown back into the passing gas stream.

The discharge electrodes are held at high negative voltage, either steady DC or pulsing, relative to the grounded collector plates. Excitation is typically 70 kV, which is sufficient to ionize the gas in a small diameter "corona" surrounding the discharge electrodes. Both (+) and (-) ions are present within the corona zone, but beyond it only (-) ions are found. Passing particles accumulate the (-) ion charges, and are driven toward the collector plates. These particles may adhere to the collector plates or to particles previously deposited on the plates, or they may rebound from the plates. If the particles are poor electrical conductors - if they have high resistivity - areas may form in the collected deposits which produce (+) ions. This is called "back ionization", and causes some particles to be driven back into the passing gas flow.

A realistic model of a single-stage ESP must simulate all of the phenomena just described, plus the flow of gas in the space between the collector plates. Fortunately, the electrostatic fields and ion creation and flow are little influenced by the gas flow velocity pattern (but are dependent in predictable ways on the thermo-physical properties of the gas). Hence the ion density pattern, and the charging rate of particles, can be defined. Less fortunately, the behavior of the gas is modified by the presence of ions in an electric field. And of course, the usual problems of modeling flow that may be viscous or turbulent are present. In addition, the flow is actually 3-dimensional, with some of what is called "sneakage" of dusty gas escaping treatment at the top and bottom of the collector plates.

The development of models has progressed from the very simple one-dimensional expression of Deutsch (1922), here shown in a general form applicable to both wire-in-tube and single-stage plate precipitators:

$$Penetration = \exp\left(\frac{A_p \cdot w_p}{Q}\right) \quad (5)$$

Where

A_p = area of the collector plates; w_p = particle migration velocity near the plates;
 Q = gas volumetric flow.

Through the years, the pieces of the ESP puzzle have been added to the Deutsch equation, with many laboratory and field studies providing the data to back up concepts. An understanding of ESP problems can be gained by browsing the 154-page training manual (Parker and Plaks, 2004) for the computer program ESPVI 4.0. Additional material on the concepts used in this code is available in chapters by Lawless and Altman and Lawless and Plaks in EPRI (1990a). ESPVI 4.0 includes a database defining particle properties based on field tests. The agreement between its predictions of efficiency and energy use are apparently sufficient for the US Environmental Protection Agency to approve its use in licensing electrical utilities.

Although ESPVI 4.0 is very detailed, it contains many simplifications not necessary with CFD modeling. There have been numerous applications of CFD to ESP modeling. Examples include: Soldati (2003); Talaie (2005); Lin and Tsai (2010).

6. Filters with Cleanable Surface-Loading Media

Cleanable media filters using tubular fabric bags and cartridge filters are widely applied in industrial exhaust pollution control. These devices rely for efficiency on the buildup of collected dust on the filter media surface, and intermittent removal of this dust “cake”. The most popular method of cleaning is the pulsejet, which uses pulses of compressed air to induce a reverse airflow through the filter media. This is applicable to both baghouses and cartridge type filters. For baghouses, however, cleaning can also be accomplished by flow reversing dampers, and by shaking the bags. Realistic simulation of cleanable-media performance needs to consider the parameters and processes listed below.

Media Type: Woven, nonwoven felted and laminated fabrics; pleated filter cartridges	Gas properties Gas humidity Flow volume	Particle concentration, density, morphology and diameter
Cleaning method: shaking, collapse, pulse-jet	Pulse-jet pressure, frequency, duration	Particle adhesion and release behavior
Media area	Pulse-jet venturi design & position	Particle load on fabric or cartridge media
Shaker acceleration		

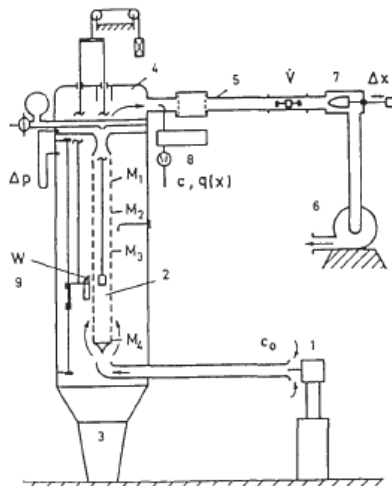


Figure 11 - Pulse-Jet Bag Filter Tester [from Schmidt and Löffler (1990)]

- 1: Dust Feeder; 2: Filter Bag; 3: Hopper; 4: Compressed Air Pulse System; 7: Flow Control; 8: Particle Counter; 9: Radioisotope Dust Cake Mass Scanner.**

Most literature on cleanable media filters consists of reports of field experience, with almost no quantitative determination of the impact of the above factors, or use of mathematical models. Schmidt and Löffler (1990) describe a single-tube fabric collector with pulse-jet cleaning, with simultaneous measurement of the pulse waveform and fabric acceleration. The thickness of deposited dust was measured by

adsorption of radioisotope emissions. They also report attempts to define the internal structure of the dust cake. Cleanable filter behavior is a topic ripe for study.

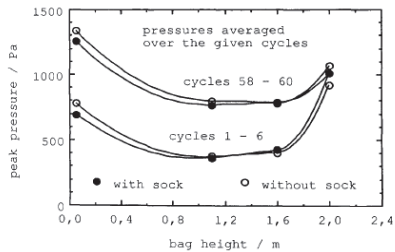


Figure 10 - Peak excess pressure inside bag during cleaning pulses, as a function of position above lower end of bag [from Schmidt and Löffler (1990)]

7. Simulation of Fibrous Air Filters

In a few forms of fibrous air filters the air flow approaches the filter medium at full duct velocity, perpendicular to the medium. In most filter designs filter medium is pleated; to increase media area and lower media velocity. In another design, filter medium is formed into pleated panels which are also arranged in larger-scale “pleats”. Analysis of flow through filters with pleats must consider the flow through the filter medium per se, and also through the inlet and outlet regions upstream and downstream of the filter medium. Let us first examine the modeling of filter media.

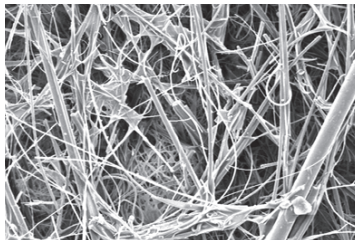


Figure 12 - SEM image of a typical air filter medium, showing a wide range of fiber diameters, random structure, and binder bridges

7.1 Classic Models for Filter Media

Figure 12 is a SEM image of a typical air filter medium. We repeat this familiar image because it shows the randomness of fibers in most media, and also the web-like binder bridges joining the fibers. Few simulations of fibrous filter media have simulated this element of fibrous media, which sometimes makes up as much as 15% of the solids volume of filter media. Binder needs to be added to simulations, just as it must be added to real media.

Early attempts modeling fibrous filtration had to use very simple, orderly models. One was by Langmuir (1942). His model represented a filter by a single fiber sitting in lonely splendor, with gas flow at uniform velocity distant from the fiber. One might say that this model meets Einstein’s criterion for simplicity, and the remarkable thing is that it provided some useful information. Oseen and Lamb had solved the pattern of gas flow for this model in 1910-1911. Langmuir treated the case of viscous flow, and

included two particle-capture “mechanisms”: “direct interception” and “diffusion”. He also dealt with the problem of the effect of nearby fibers by introducing an empirical coefficient related to the fractional solids of the filter medium. He showed that for a given fiber diameter and fractional solids, there is a particle diameter which is removed with least efficiency. This particle diameter is what we refer to as the maximum penetrating particle size (MPPS). It the reason that HEPA filters are usually specified as having “> X% efficiency on 0.3 μm diameter particles”. Langmuir suggested the 0.3 μm diameter as the appropriate MPPS for the HEPA filters then in use, at their usual operating conditions.

Problems arise in modeling filter media with a range of fiber diameters. The model requires that one determines an “effective fiber diameter” experimentally, along with the empirical correction for fractional solids. Such approach tells very little about how to design a sheet of filter media.

Numerous investigators developed the theoretical behavior of various regular arrays of uniform-diameter fibers. Geometries analyzed included rectangular and staggered rows of fibers, and a few with more than one fiber diameters. Brown’s book (1993) describes these studies in great detail. Kuwabara made a major contribution in 1959 with a way around the problem of nearby fibers. His concept (expressed for a 2D section cut through the filter medium) was that each fiber was at the center of an imaginary circle, now called a “Kuwabara Cell”. The outer diameter of the cell was set so that the ratio of the fiber cross-section to the cell cross-section equals the fractional solids for the filter medium. Boundary conditions for the fiber and the outer cell were adjusted to allow analytical solutions, avoiding the need for finite-difference calculations not readily available in 1959.

The Kuwabara cell is a fine example of a model which is completely wrong, but produces some useful results. Kuwabara cells joined together to simulate a significant piece of filter media must overlap. Simulations closer to actual filter media geometries had to await the development of computational fluid dynamics.

7.2 CFD Simulations of Fibrous Filter Media

It is possible to analyze models simulating filter media performance in 3 dimensions (3D) even using something less than a supercomputer. The group at the Fraunhofer Institute, e.g. Cheng et al. (2009) and others investigating woven and nonwoven fabrics, see Wang et al. (2006), have modeled media with random fiber diameters located randomly in 3D spaces. Other studies have been satisfied with 2D sections through media. This allows random fiber diameters and full media depth to be simulated without heavy computational burdens, see Tronville and Rivers (2005), Herman et al. (2006). These studies allow evaluation of the proper boundary conditions at the surface of both the fibers and particles, which may have diameters as low as a few hundred nanometers. At those boundaries, gas may have zero velocity, or different levels of “slip”. For filter media with fiber diameters still smaller, the usual Navier-Stokes equations describing the flow may need to be replaced with the Burnett equations, or entirely different computational procedures, such as the Lattice Boltzmann method and Direct Monte Carlo Simulation (DMCS). DMCS mimics the detailed molecular motions of gases.

Predicting particle capture from physical fundamentals, whether by classic analysis or CFD, is more difficult than just predicting pressure drop caused by the air flow resistance. One must first get a reliable flow model to get reliable solutions of particle motion. Including electrostatic effects adds complexity. The buildup of particles on filter fibers has been simulated in 2D and 3D, but with inevitable simplification of

models, more so in 2D than 3D. There is always a trade-off between realistic modeling and computation time.

7.3 CFD Simulations of Complete Filters

For CFD determination of the gas velocity pattern, pressure drop and particle capture in a pleated filter, the filter medium may be replaced with a region of the same thickness and uniform, isotropic permeability K_M . The assumptions here are that the filter medium is uniform, with thickness s_M and pressure drop Δp_M proportional to velocity v_M :

$$K_M = \frac{v_M \cdot \mu \cdot s_M}{\Delta p_M} \quad (6)$$

In similar fashion, for these determinations on multi-panel filters the panels may be represented by regions of the panel thickness s_P and uniform and isotropic permeability K_P . In this case, the panel pressure drop is not linear with panel velocity v_P , but a function of v_P . Usually, a quadratic in v_P is adequate, hence panel permeability K_P is:

$$K_P = \frac{(av_P + bv_P^2) \cdot \mu \cdot s_P}{\Delta p_P} \quad (7)$$

The simplest way to determine a and b in Eq. (7) is to measure the pressure drop across a single panel for a range of velocities v_P , with flow perpendicular to the panel face. Existing CFD codes allow the insertion of this information into flow analysis where some zones in the calculation domain are identified as porous media.

8. Devices for Gaseous Contaminant Capture

Adsorption is the separation of unwanted gaseous components (pollutants) from a gas stream by trapping on the surface of a solid. Adsorption is the dissolving of such components within the body of a solid or liquid. Adsorption is greatly intensified when the surface of the solid is expanded by pores of microscopic size. Both adsorption and absorption have been studied in great detail by chemical engineers, and are described in established texts like Bird et al (2002). With some simplifying assumptions, sorption processes are often well described by analytical solutions to differential equations, so that numerical approaches are not needed.

There are, however, complexities. The speed of a sorption process is dependent on the thermo-physical properties of each gas molecular species involved, and especially on the concentrations of each in the carrier gas. If more than one contaminant species (including water vapor) is present, each may interfere with the separation of others from the carrier gas. Captured contaminant molecules may be released from the sorptive material by temperature changes, adsorption of other species, or the continued passage of unpolluted carrier gas. As contaminant molecules accumulate on or within the sorptive material, the rate of molecular transfer from the carrier gas decreases.

The literature on sorption is immense. Of special value in the separation of contaminants from breathable air is the series by Nelson et al. (1976) which applies to gas masks and building ventilation. CFD is not much needed in studies of deep granular beds. However, the flow characteristics of so-called tray adsorbers and pleated media containing adsorptive material can be treated as described above for particulate filters of multi-panel mini-pleat and pleated forms. Venturi scrubbers and baghouses are sometimes used as contactors for absorption and chemisorption.

Chemisorbers incorporate reactive chemicals on the surfaces of their carrier bodies or in scrubbing liquids. There are no universally reactive substances, so specific pollutants must be targeted, and reaction rates added to the parameter list. The literature on chemisorption is, therefore, much devoted to specified pollutants.

9. Conclusions

Empirical, analytical, and numerical means exist to simulate the performance of gas flow separation equipment, with CFD being the most recent development.

Meaningful predictions can only be made when all significant phenomena are incorporated in the models assumed for analysis. When a predictive method is developed, its accuracy should be tested on a broad array of measured data before it is used to design or optimize separation systems.

A validated database of fully defined systems and their performance results would be useful to verify the accuracy of future predictive methods.

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