[Proceeding] Effect of slip flow on the pressure drop in fibrous filters

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VOLUME II

CONTENT VOLUME I

CONTENT VOLUME II

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October 13 – 15, 2009

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15.00 – 16.15	**S2** Survey Lecture 2	**L2** Sedimentation Analysis in the Centrifugal Field	**M2** Produced Water Treatment	**G2** Air Filter II
16.45 – 18.00	**S3** Survey Lecture 3	**L3** Sedimentation and Flotation for Sorting	**M3** Combined Processes	**G3** Surface Filtration

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Tuesday – October 13, 2009

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Plenary Lecture 10:30 - 11:30

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S1 Survey Lecture 13:15 - 14:30

Advances in Pore Structure Evaluation by Porometry, Dr. Krishna Gupta, Porous Materials, Inc - USA I-21

L1 Sedimentation Analysis in the Gravity Field 13:15 - 14:30

Evaluation of consolidation-sedimentation properties in batch gravity sedimentation of concentrated suspension, N. Katagiri*, T. Hashimoto, E. Iritani, Nagoya University, Japan I-95

Modeling the settling velocity of flocs using fractal geometry, A. Vahedi*, B. Gorczyca, University of Manitoba, Canada I-103

Laboratory scale evaluation of inclined settling, T. Sobisch*, D. Lerche, LUM GmbH, Germany I-112

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Processing and characterization of ceramic membranes for efficient removal of lignin from bleaching effluents, M. Ebrahimi*, S. Kerker, A. Wienold, University of Applied Sciences Giessen-Friedberg; H. Neul, A. Ante, Bamag GmbH; M. Hilpert, Sappi Fine Paper Europe; P. Mund, Atech Innovations GmbH, Germany; P. Czermak, Kansas State University, USA II-485

Electro-ultrafiltration of liposomal dispersions for the removal of trace micropollutants, H. Saveyn*, M. Hakimhashemi, B. De Bock, P. Saveyn, P. Van der Meeren, Ghent University, Belgium II-491

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The effect of pleat count and air velocity on the initial pressure drop and fractional efficiency of HEPA filters, I. S. Al-Attar*, E. S. Tarleton, Loughborough University; R. J. Wakeman*, Consultant Chemical Engineer, UK; A. Husain, Kuwait Institute for Scientific Research KISR, Kuwait II-19

Interaction of fluid with porous structure in filtration processes: Modelling and simulation of pleats deflection, H. Andrä, O. Iliev, M. Kabel*, Z. Lakdawala, K. Steiner, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; V. Starikovicius, Vilnius Gediminas Technical University, Lithuania II-27

Importance of mechanical filtration in HVAC bags and panel air filter applications, A. Boni*, Hollingsworth & Vose Europe, Germany; J. Manns, D. Healey, S. Cox, Hollingsworth & Vose, USA II-32

S2 Survey Lecture 15:00 - 16:15

Membrane Pore Characterization Techniques - Status Quo and Future Development, Prof. Kuo-Lun Tung, Chung Yuan Christian University, Taiwan II-37

L2 Sedimentation Analysis in the Centrifugal Field 15:00 - 16:15

Sedimentation and consolidation behaviour of flocculated suspensions characterized by different methods measuring transmission, T. Sobisch*, A. Zierau, D. Lerche, LUM GmbH; A. Bjeoumikov, IFG GmbH; M. Holke, IAP e.V., Germany **I-117**

The use of analytical centrifugation for the assessment of particulate matter compressibility, P. Van der Meeren*, D. Curvers, H. Saveyn, Ghent University, Belgium; P. J. Scales, University of Melbourne, Australia **I-123**

Characterization of sedimentation and consolidation behaviour of kaolin suspensions in presence of dispersant, C. Le Coeur*, O. Larue, E. Vorobiev, University of Compiègne, France; T. Detloff, T. Sobisch, A. Zierau, D. Lerche, LUM GmbH, Germany **I-131**

M2 Produced Water Treatment 15:00 - 16:15

Application of inorganic membrane technology in the efficient treatment of oilfield produced water, M. Ebrahimi*, D. Willershausen, L. Engel, University of Applied Sciences Giessen-Friedberg; P. Mund, P. Bolduan, Atech Innovations GmbH, Germany; P. Czermak, Kansas State University, USA **II-498**

Treatment of hypersaline oilfield produced water in a membrane sequencing batch reactor, A. Fakhru'l-Razi*, A. R. Pendashteh, D. R. A. Biak, C. A. Luqman, Z. A. Zurina, University Putra Malaysia, Malaysia; S. S. Madaeni, Razi University, Iran; W. M. Zahid, King Saud University, Saudi Arabia **II-504**

Peroxidase-peroxide system catalyzed the removal of phenol and total hardness from produced water, K. F. Mossallam*, F. M. Sultanova, N. A. Salimova, Azerbaijan State Oil Academy, Azerbaijan **II-512**

G2 Air Filter II 15:00-16:15

Experimental investigation on the particle distribution and rearrangement in filter media, T. Häusle*, A. Hammen, H. Sauter, Mahle Filtersysteme GmbH, Germany **II-39**

Fungal colonization of fibrous air filter media: Influence on filter's permeability and fungal particules release, J. C. Bonnevie-Perrier, L. Le-Coq*, Y. Andrès, Ecole des Mines de Nantes, France **II-45**

The Eurovent certification program of air filters, I. Bodenstaff*, AAF International, Netherlands **II-53**

S3 Survey Lecture 16:45 - 18:00

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L3 Sedimenation and Flotation for Sorting 16:45 - 18:00

Use of colloidal gas aphrons for separation of water based printing inks and impurities from paper stock suspensions, D. Voß*, S. Schabel, University of Darmstadt, Germany **I-139**

Separation of fibre fines and inorganic fines in recovered paper suspensions, G. Hirsch; S. Schabel, D. Voß*, University of Darmstadt; M. Feist; H. Nirschl, Karlsruhe University, Germany **I-145**

Tracer studies of the flow structure in a DAF pilot plant, L. Jönsson*, University of Lund; M. Lundh, Kretsloppskontoret, Sweden **I-153**

M3 Combined Processes 16:45 - 18:00

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

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

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G3 Surface Filtration 16:45 - 18:00

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

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

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

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

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

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

L5 Poster Session I 08:30 - 09:45

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

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

· Separation Enhancement by Physical and Chemical Slurry Treatment ·

Fundamentals of stability of sulfur in iron chelate, K. Forsat*, K. Mohammadbeigy, Research Institute of Petroleum Industry (RIPI), Iran **I-201**

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

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

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

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

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

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

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

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

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

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

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

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

M5 Deposition Control 11:00-12:15

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

M7 Modelling and Simulation 15:00 - 16:15

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

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

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

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Influence of experimental parameters on local and filtrate properties of kraft pulp displacement washing, K. Dingwell*, J. Lindau, M. Sedin, H. Theliander, Chalmers University of Technology, Sweden **I-370**

· Backwashing Filtration Processes ·

Enhancing classical effluent treatment plant efficiency by introducing BASP rotary wedge wire drum dewatering screens, B. Patil*, V. Patil, BASP Industries, India **I-378**

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· Depth Filtration Processes ·

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· Chromatography ·

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· Electrocoagulation ·

Removal of arsenic from wastewaters by batch airlift electrocoagulation, H. K. Hansen*, P. Nuñez, C. Guiterrez, L. M. Ottosen, Technical University Federico Santa Maria, Chile **I-404**

· Filter Media ·

Choice and optimization of technical woven wire meshes in the solid liquid separation, M. Knefel, P. Wirtz, GKD - Gebr. Kufferath AG, Germany **I-585**

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Liquid-Liquid extraction of ammonia using hollow fiber membrane contactors, M. Ulbricht*, J. Schneider, M. Stasiak, Membrana GmbH, Germany; J. Munoz, A. Sengupta, B. Kitteringham, Membrana Charlotte, USA **II-702**

Achieving cleaner solutions, H. Williams*, Serfilco International, Great Britain; J. H. Berg, Serfilco Ltd, USA **II-709**

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Recycle effect on double-pass concentric circular mass exchanger with an idealized membrane inserted, C.-D. Ho*, J.-W. Tu, Y.-C. Chuang, Tamkang University, Taiwan **II-732**

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

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EFFECT OF SLIP FLOW ON THE PRESSURE DROP IN FIBROUS FILTERS

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ABSTRACT

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

KEYWORDS

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

1. Introduction

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

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

This work aims to get a deeper understanding of the slip flow in fibrous filters by considering the solutions for three simple geometries (sphere, cylinder and parallel plates), and comparing the resulting drag coefficient, $C_D = \frac{2F_D}{\rho U^2 \pi R^2}$, with the value obtained in case of no slip boundary conditions. These geometries are relevant both to the study of the flow field around fibers and to that of aerosol particles

displacement. However, they are extremely appealing also from a fundamental point of view because at such low Reynolds numbers (typically between 10^{-3} and 10^{-1}) [3] one has a purely creeping flow without a wake past the obstacle [4].
The analysis of the stationary Stokes problem shows that the total drag experienced by a sphere in slip-flow regime is equivalent to the Stokes total drag for continuum flow multiplied by a rarefaction coefficient dependent upon the Knudsen number. The rarefaction effects decrease the total drag experienced by a sphere below the continuum model prediction.

2. Flow around a sphere

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

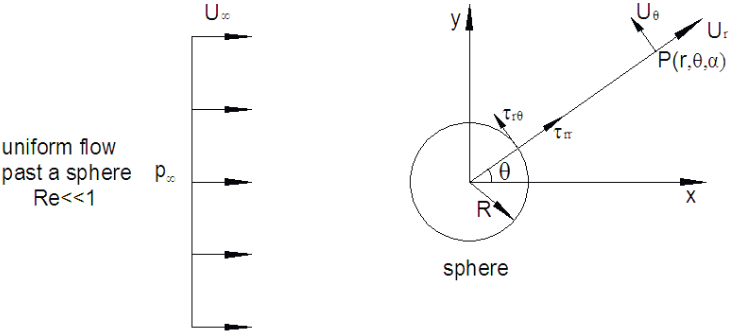

Figure 1 - Problem formulation for the flow around a sphere

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

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

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

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

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

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

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

$$u_r = 2\left(\frac{A}{r^3} + \frac{B}{r} + \frac{U_\infty}{2}\right)\cos\theta$$
$$u_\theta = \left(-\frac{A}{r^3} + \frac{B}{r} + U_\infty\right)\sin\theta \qquad (4)$$

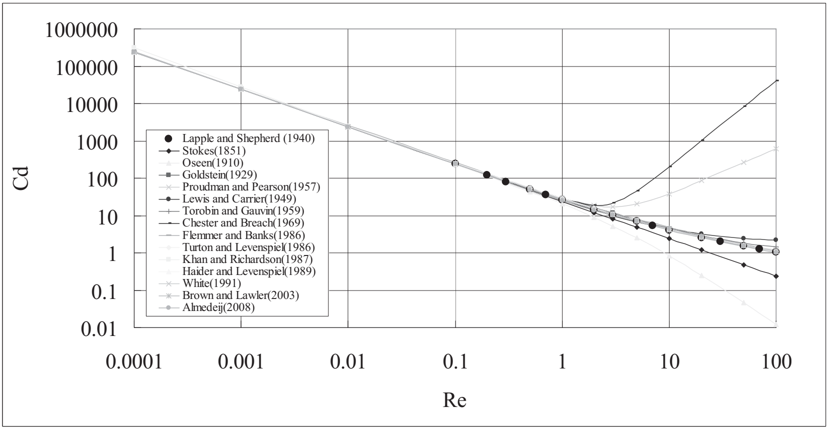

Figure 2 - Drag coefficient on the sphere: comparison between analytical solutions and experimental results available in the literature (case of no slip)

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

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

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

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

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

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

$$\tau_{r\theta} = \mu\left(\frac{1}{r}\frac{\partial u_r}{\partial \theta} - \frac{1}{r}u_\theta + \frac{\partial u_\theta}{\partial r}\right)$$

$$\tau_{rr} = 2\mu\frac{\partial u_r}{\partial r} \qquad (7)$$

$$p = p_\infty + 2\mu\cos\theta\frac{B}{r^2}$$

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

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

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

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

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

3. Flow in circular tubes

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

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

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

$$u = -\lambda_f\frac{2-\sigma}{\sigma}\frac{du}{dr} \qquad (11)$$

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

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

The mean velocity is defined as:

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

so that the volumetric flow rate is:

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

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

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

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

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

For isothermal flow, the product of pressure and the Knudsen number is constant and one can write $pKn = p_0 Kn_0$. Then, the mass flow rate can be re-written as:

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

and setting $p_z = p_0$ yields:

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

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

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

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

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

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

4. Flow around a cylinder

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

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

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

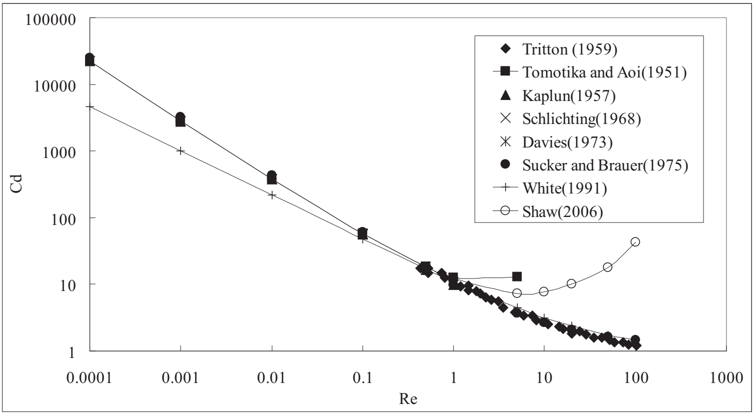

Figure 3 - Drag coefficient on the cylinder: comparison between analytical solutions and experimental results available in the literature (case of no slip)

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

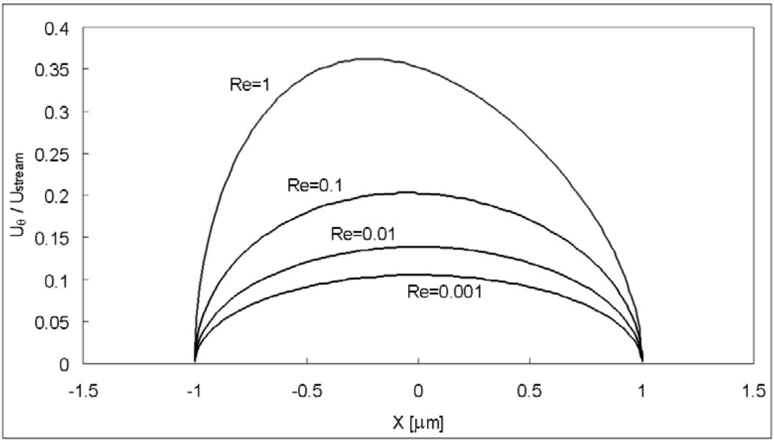

Figure 4 - Tangential velocity on the cylinder wall

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

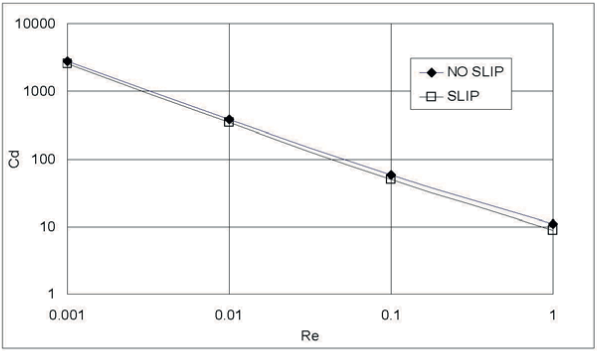

Figure 5 - Drag coefficient on a cylinder in cross-flow: comparison between slip flow and no-slip flow

5. Conclusions

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

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

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