ISSN 1746-7659, England, UK
Journal of Information and Computing Science
Vol. 2, No. 2, 2007, *pp*. 111-118

Effect of Different Particle Shapes on the Modelling of Woven Fabric Filtration

M.A. Nazarboland [1], X. Chen [1+], J. W. S. Hearle [1], R. Lydon [2] and M. Moss [2]

[1] School of Materials, University of Manchester, Manchester, UK
[2] Clear Edge Group, Haslingden, UK

(*Received 4 October 2006, accepted 4 February 2007*)

Abstract. A computer simulation model, based on theoretical analysis, has been developed to investigate and quantify how variation of particle shapes can affect the resulting filtration performance. The software tool geometrically models 3D woven fabrics, interfaces with CFD tools to numerically determine the fluid flow paths, implements particles of various shapes and sizes, and employs a force model as the foundation of its capture and positioning mechanisms. When a particle is intercepted by the fabric, the various forces exerted on it are utilized to predict the particle's movement over the fabric surface. These forces are derived from particle-fabric interactions such as friction and normal contact force, as well as particle-fluid interactions such as drag, buoyancy and particle weight. When these forces are in equilibrium, the particle is consequently deposited on the fabric. However, the subsequent motion of the particle is also controlled by particle-particle interactions due to collision and the van der Waals forces between such particles. The identical filtration process scenario are simulated in this work with different particles of spherical, ellipsoid, discus and needle shapes. By using the predicted results as the comparison criteria, it is revealed that the particle shape is a significant parameter that influences the filtration characteristics and the transient behaviour of cake formation.

Keywords: Filtration, Woven Fabric, CFD, Fabric modelling, Particle packing, Particle shapes

1. Introduction

Filtration is a process widely used in numerous industrial applications, especially in chemical, medical, food and paper industries. Developing an accurate theoretical model of filtration is difficult because of the nature of the filtration process, which involves particle transport in a fluid moving through complex fabric geometry. The fluid and suspended particles flowing through the maze of yarns follow a tortuous path controlled by the fluid dynamics and equations of motion for particles. Since the geometry and porosity of the fabric filter is determined by the weave pattern and the various parameters of the yarns constituting the fabric [1], it is important to optimize its structure to achieve the most efficient filtration. The past practice relied on the practical skill and experience of the fabric designers and on empirical trials.

Simulation and modelling offers excellent methods in quantitative and qualitative understanding of the filtration process. Costs of experimentation can be substantially reduced if these are combined with theoretical modelling investigations. Furthermore, these investigations provide an accelerated perception of the methodology required to breakdown the process into its fundamental physical phenomena. Once a model has attained a significant level of confidence, it can be successfully utilized as a design tool for new processes in filtration or optimization of existing ones.

The work and research carried out, contributing to the construction of *UniverFilter™* [2], has focused on the development of a woven fabric filter model, an interface to a finite volume element modelling tool that acquires the fluid flow paths, and introduction of particles with different size and shapes to follow such paths. A force-based model is then used to simulate the positioning and movement of such particles over the fabric and deposited particles. The results are utilized in simulation of the initial stages of cake formation and determining the filtration properties that can lead to the most efficient filtration. One particular aspect magnified through this paper is the magnitude of the effect particle shapes can play in the final results of the

+ Corresponding author. Tel.: +44-161-306 4113; fax: +44-161-9558164.
E-mail address: Xiaogang.Chen@manchester.ac.uk

simulation. It will be shown that for different particle shapes, filtration characteristics such as the cumulative filtrate volume, cake porosity, cake thickness and dry cake mass are not the same due to a varying particle configuration and packing.

2. Simulation Method

2.1. Fabric Geometrical Modelling

One of the main properties of woven media employed in filtration is their specific geometrical opening that ensures selective particle cut off. The woven fabric should filter all the contaminant particles larger than its pore size and practically none of the smaller dimensions. Construction of a software tool to simulate the filtration process through woven fabric filters entails two major stages. The first stage focuses on the creation of the 3D woven structure and the second on modelling of the filtration process.

Over the last century, various techniques have been employed to model woven fabrics, specifically, yarn paths. The simplest approach was by Peirce [3] in which the yarn path, in the case of plain weave, is represented by two arcs tangentially connected by a straight-line segment. The Peirce technique is regarded as an idealized approximation and recent methods employ splines to formulate the yarn paths and surfaces. A spline curve can mathematically be described as a piecewise cubic polynomial function whose first and second derivatives are continuous across the various curve sections. In computer graphics, spline refers to any composite curve formed with polynomial sections satisfying specified continuity condition at the boundary of the pieces. B-splines are the most widely used class of approximating splines and are utilized in several texts [4,5] for simulating woven fabrics.

UniverFilter™ is used to create 3D geometrical models on the provision of fabric weave, yarn and fabric structural parameters. The software uses both Peirce's woven fabric model and the more realistic Spline model for creating the yarn path in the fabric. The paths in real fabrics are complicated and their shapes depend upon many factors including the yarn mechanical properties. The shape of the yarn path is finalized when the minimum energy is achieved in the yarns [6]. The B-Spline function represents the yarn paths by defining control points rather than coordinate points to allow a better representation of the yarn paths by taking into consideration of energy minimization of the constituent yarns in the fabric. *UniverFilter*™ uses three idealized yarn cross-sectional shapes for both warp and weft yarns, which are circular, racetrack, and lenticular.

2.2. Boundary conditions of fluid flow

The second stage of the simulation software development focuses on the filtration aspect. Prior to this, the effects of woven fabrics on fluid flow behaviour need to be analyzed and integrated to the system.

Fluid flow is classified into laminar and turbulent flows and is described by a set of equations based on conservation of mass and momentum. Generally, two different approaches have been employed in previous investigations on fluid flow through woven fabrics, one being simplifying the fabric into an assembly of orifices and the other the use of fabric models. The former was proposed by Backer half a century ago suggesting that the inter-yarn pores in a fabric to be represented by an assembly of orifices or nozzles through which passes the major portion of the flow [7]. Others [8, 9] used the second approach for numerical analyses of the size and shape of pores using Computational Fluid Dynamics (CFD).

Having already designed the filter, the next step requires establishing the fluid flow paths. However, due to the high complexity of fluid dynamics, there is no other choice than to obtain the approximation solution numerically by the use of a computational fluid dynamics (CFD) program.

Powerful commercial CFD software, Fluent is utilized for analysis. The method used in such software is to discretize the fluid domain into small cells to form a volume mesh or grid, and then apply iterative methods to solve the equations of motion governed by the Navier-Stokes equations. The method devised in this work is to export the fabric geometry, usually one weave repeat, into the CFD software. The fabric is placed inside a rectangular chamber. The specific position of the fabric inside the chamber is dependant to fabric dimensions and the physical properties of the fluid. This is a separate topic and is not discussed here. The two planes of the chamber parallel to the fabric are the inlet and outlet pressure boundaries. The cross-sectional area of the chamber is related to the size of fabric repeat. The four walls of the chamber are regarded as symmetry surfaces so that the results indicate a better depiction of real situations (experiment scale-up).

The resulting volume of the structure is then meshed using tetrahedral elements. A denser grid cell distribution is applied to areas on the fabric surface to account for the large gradients that occur in these areas. All the corresponding parameters are set and the simulation is run until the data is converged. The results of fluid flow paths, the fluid pressure and velocity in the chamber downstream and all relevant data are imported by *UniverFilter*™ for further analysis.

2.3. Introduction of Particles

The next stage involves introduction of the particles, suspended in the fluid. According to the defined particles distribution, they are placed randomly at a starting position corresponding to the starting points for elements of fluid flow paths at the inlet pressure plane of the chamber. Particles of various size and shapes can be used in the system. The particle shapes considered are spherical, discus shaped, ellipsoid and needle shaped. This is in contrast with most other similar tools that consider only spherical [10-13] or sometimes ellipsoids [14] as particle shapes. The simulation is then run with the particles following the fluid flow paths.

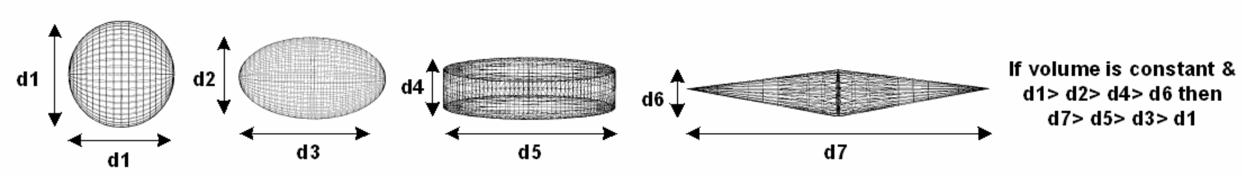

Fig. 1: Different shapes of spherical, ellipsoid, discus and needle compared

Fig. 1 shows the important aspect of particle shape variation. When various shapes with constant volume are considered, the dimension of these shapes change. As mentioned previously, woven fabric filters capture particles that are larger than its pore size. Thus, if one dimensionality of the particle increases, its other dimension decreases to keep the particle volume constant. This leads to more particles passing through the pores, changing the characteristics of the filter.

2.4. Particle Capture and Cake Formation

Solving the fluid flow behaviour surrounding the fabric filter determines the fluid flow paths. These govern the movement of particles. Thus, the next stage is the establishment and modelling of the particle capture. Most other encountered methods assume that when a particle collides with the fabric, it is deposited in the contact location. Settled particles are then used as the basis of stopping other particles. In general, a particle possesses translational and rotational motion, which can be described by:

$$F_p = m_p \frac{dv_p}{dt} \tag{1}$$

$$T_p = I_p \frac{d\omega_p}{dt} \tag{2}$$

where F_p, T_p, m_p, v_p, I_p and ω_p are the total force, torque, particle mass, translational velocity, moment of inertial and angular velocity, respectively.

As the particles move towards the locality of the fabric filter, particle capture rules are applied. It is normally expected that the particles that intercept the fabric, should be stopped. However, the particle location compared to the fabric filter is not the only criteria that should be used in stoppage of such particles. For instance, the particle velocities can affect some capture mechanisms such as diffusion and the fluid pressure can influence the interception mechanism. Another factor that will contribute to particle capture is the particle size and shape. It is expected that the woven fabric should filter all the particles larger than its pore size and practically none of the smaller dimensions. However, the fluid pressure and the force transmitted by particle drag on the fabric could transform the effective pore area. Such changes to the pore structure need to be considered and thus provisions be made in the program for implementing depth filtration in case particles are able to get through. As far as particle size is concerned, in case of colloidal particles, the Brownian energy governs the particle motion in the locality of the fabric.

Most techniques encountered for a particle approaching the fabric filter surface assume that the particle is deposited on the location of impact and not much further investigation is carried out. However, since it is these deposited particles on the fabric that are the basis of capturing other particles, the particle movement over the fabric surface needs to be thoroughly investigated and modelled. The forces on the particle at this location are the drag (*FD*), weight (*FW*), buoyancy (*FB*), friction (*fr*) and the normal (*N*) force exerted from the fabric surface:

$$FD = \frac{1}{2} C_d A \rho v^2 \quad (3)$$

$$FW = m_p g \ , \quad (4)$$

$$FB = \rho V_p g \quad (5)$$

$$fr = adh.N \quad (6)$$

where A is the effective area of the particle, v is the difference in velocity between the particle and the fluid, V_p is the particle volume and *adh* is the adhesivity factor of the particle to the fabric.The normal force is perpendicular to the surface of the fabric (see Fig. 2a) and can be calculated from the other forces mentioned, owing to the fact that the resultant force in the direction of the normal force should equate to zero. C_d is the drag coefficient and can be calculated from [15]:

$$C_d = \frac{24}{\text{Re}}(1 + b_1 \text{Re}^{b2}) + \frac{b_3 \text{Re}}{b_4 + \text{Re}} \quad (7)$$

$$\text{Re} = \rho D_p \mid u_p - u_f \mid / \mu$$

$$b_1 = \exp(2.3288 - 6.4581\phi + 2.4486\phi^2)$$

$$b_2 = 0.0964 + 0.5565\phi$$

$$b_3 = \exp(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3)$$

$$b_4 = \exp(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3)$$

and $\phi = s / S$ is the particle sphericity with s being the surface of sphere having the same volume as the particle and S is the actual surface area of the particle, μ is the molecular viscosity of the fluid and D_p is the particle diameter.

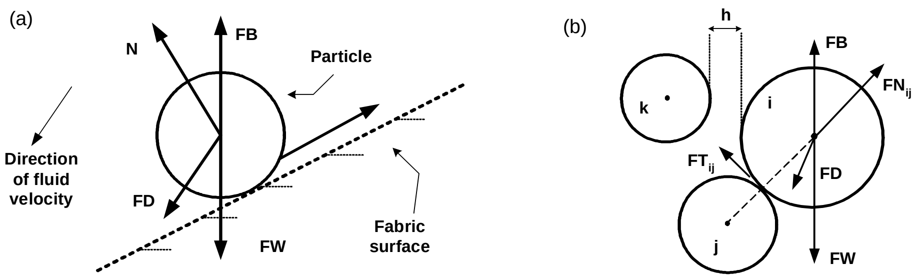

Fig. 2: Forces on a particle (a) particle-fabric interaction, (b) particle-particle interaction

A sphere gives an extreme in terms of the volume-to-surface area ratio, which impacts both motion and reaction of a particle. For a non-spherical particle, an additional lift force becomes important, and generally hydrodynamic forces introduce a torque on the particle, as the centre of pressure does not coincide with the centre of mass [16].

When the forces on the particle reach equilibrium (i.e., zero in all directions), the particle is deposited. This is unless it is influenced by other particles, which is subsequently used in calculating its new position. Forces exerted on a particle by other particles are show in Fig. 2b. When a particle collides with another, two forces of tangential (FT) and normal (FN) contact force are imposed. These can be calculated using [17, 18]:

$$FN_{ij} = [\frac{2}{3} E \sqrt{R} \xi_n^{\ 3/2} - \gamma_n E \sqrt{R} \sqrt{\xi_n} (v_i . \hat{n}_{ij})] \hat{n}_{ij} \quad (8)$$

$$FT_{ij} = -\text{sgn}(\xi) \mu \mid FN_{ij} \mid [1 - (1 - \frac{\min(\xi_s, \xi_{\max})}{\xi_{\max}})] \quad (9)$$

where $E = Y / (1 - \sigma^2)$ and Y is Young's modulus, σ is Poisson ratio, $\xi_s, \xi_{\max}$ are the total and maximum tangential displacement, $\hat{n}_{ij}$ is the unit vector and ξ_n is the overlap between particle *i* and *j*. Even though it can be very insignificant in most cases, the van der Waals force is also considered [19]:

$$FV_{ik} = -\frac{Ha}{6}.\frac{64R_i^3R_k^3(h+R_i+R_k)}{(h^2+2R_ih+2R_kh)^2(h^2+2R_ih+2R_kh+4R_iR_k)^2}.\hat{n}_{ik} \qquad (10)$$

where Ha is the Hamaker constant and h is the separation of surfaces. For particles migrating on cake surface or within formed cake, the drag can be estimated by [20]:

$$FD = -4\pi\mu u_f \frac{(D_p/2)(3+2\gamma^5)}{2-3\gamma+3\gamma^5-2\gamma^6} \qquad \text{where} \qquad \gamma = \sqrt[3]{1-\varepsilon} \qquad (11)$$

To decrease the computational time and increase the overall simulation efficiency, a two-dimensional grid is designed to store the location of each particle. Moreover, the grid can also hold other important data, such as the fluid velocity, normal vector to the fabric surface and cake related parameters. Basically, the fabric area is divided into small lattices. Grid dimensions are dependent to the size of the smallest component of a particle. In this experiment, for the highest level of accuracy, the least dimension of the smallest particle is divided so that it fills a 9x9 grid. This will give a highly accurate representation of particle packing. This is in contrast with some other modelling techniques, which considers each layer or grid dimension to have the particle size as its thickness [21].

3. Results and Discussions

The ultimate aim of the *UniverFilter*™ software program is that in a particular filtration dilemma, the tool should be able to predict the most efficient structural geometry of the fabric filter. By varying the parameters of the fabric, including fabric density, yarn linear density, crimp and cross-sectional shape of the yarns, a study [22] was carried out to see how changes in structural parameters of the fabric affect fluid flow and eventually the filtration process.

The differences in pressure and velocity on the two sides of the filter fabric reflect how the flow is affected by the structure of the filter fabric. The information can, for example, be used to engineer filter fabric structures with specific flow requirements. It is also useful to help establish particle capture rules and therefore to simulate the cake forming process. Assessing the fluid pressure distribution analysis on the surfaces of the fabric will provide information on yarn and fabric structures, which could be employed to more accurately predict transformations in the shape and size of the pores. This can also maximize the life cycle of the filter fabric. The shear stress can be utilized in the implementation of the particle capture rules. These values can assist in predicting the probabilities of particle attachment to the fabric. If a distribution of particle sizes was known, semi-empirical rules could be formulated to divide the particles into groups centred on some chance of the particles being stopped. Shear stress values on the surfaces of the fabric assist in defining these probabilities.

Particle factors can also influence the particle packing, which in turn manipulates the fluid flow paths. The overall effect is investigated to observe whether particle shape would alter the results of filtration in a significant way. A force model is used to facilitate the correct final location of particles. The force models are the most accurate method in determining the location of the particles near the fabric and also in the overall formed cake. From the outcome of the modelling and simulation, the tool is capable of reporting some very interesting filtration properties such as cumulative volume of filtrate and dry cake mass.

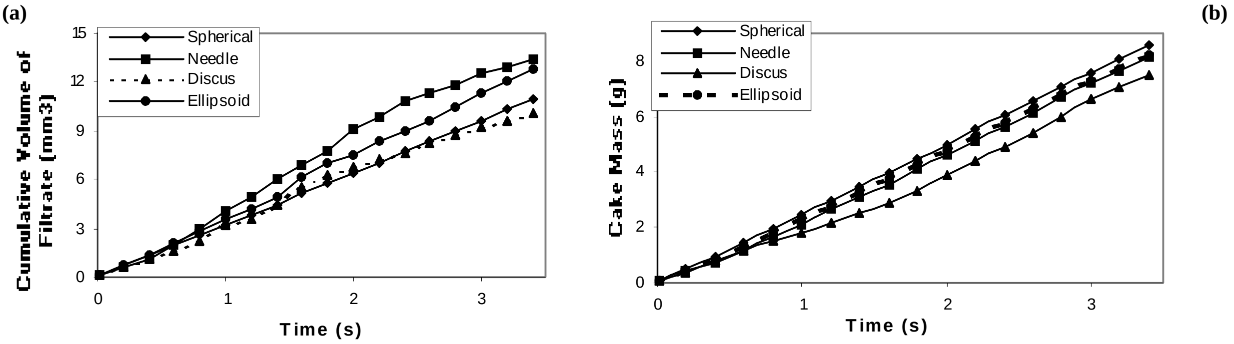

Fig. 3: (a) Cumulative volume of filtrate [mm^3] and (b) cake mass [g] vs. time [s]

Most tools simulating filtration, assume particle shape to be spherical. Fig. 3 shows how changing the particle shape, while keeping its volume constant, can produce different values for the cumulative volume of filtrate and dry cake mass in the early periods of cake formation. In this analysis, four particle shapes of spherical (diameter, 16 μm), needle shaped (breadth, 11.79μm and height, 58.9μm), discus shaped (diameter, 27.95μm and thickness, 3.49μm) and ellipsoid (height, 20.16μm and thickness, 10.08μm) were considered. Solid concentration is 1% and sand was used as particles (density, 1602 kg/m^3). One repeat of a plain-woven fabric (warp and weft diameter of 0.408mm, warp spacing of 0.476mm, weft spacing of 1mm and warp crimp of 17.6%) was used as the filter media. The testing was simulated with a constant input pressure of 3 bars. A plain woven fabric with warp density, 21 ends/cm, weft density 10 picks/cm, warp crimp of 17.6% and warp/weft yarns linear density of 100 tex was used as the filter media.

As the results demonstrate, the particle shapes play a significant role, since this corresponds to a change in their dimensionality. In case of particle capture, thinner but longer particles have a better chance of being captured. The same parameters also affect the particle packing, and obviously with the more squared shapes having better packing qualities.

Other filtration characteristics such as cake thickness and porosity (see Fig. 4) are also obtained for different particle shapes. Assessment of cake porosity shows interesting results. After a few seconds, when the porosity values stabilise, it is observed that the porosity increases for particle shapes from spherical to discuss to ellipsoid to needle. This is due to the structural packing of particles. It should be noted that particle compressibility is not formulated into the tool at this stage. This could change the results, especially for needle shaped particles. In the needle shaped particles, the fact that the particle has sharp sides and with the aid of particle compressibility, the particle packing will be different. Basically, this type of particle can be more easily forced and lodged into pores formed between other particles.

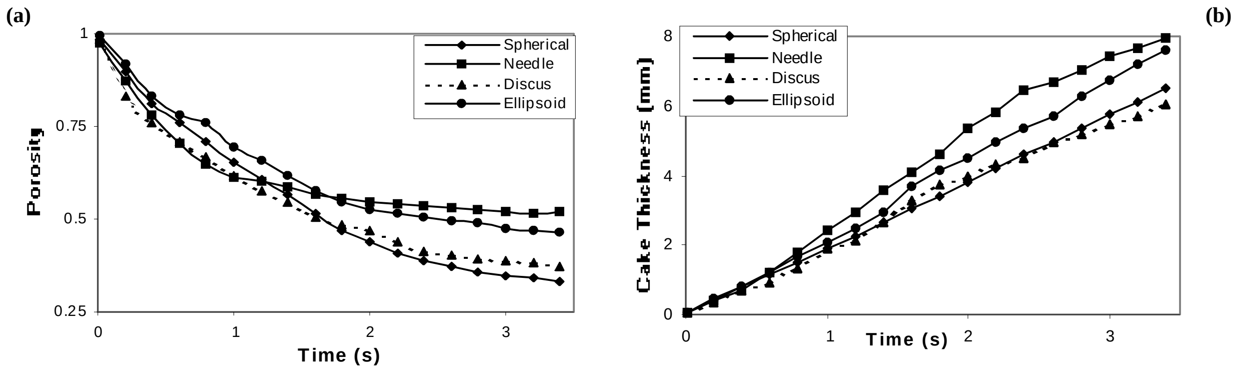

Fig. 4: (a) Cake porosity and (b) cake thickness [mm] vs. time (s)

To confirm the accuracy of results, they need to be compared with empirical data. However, the cake compressibility is not currently implemented in the system and that could affect the results. Also, since the foundation of most of the modelling is based on the early stages of cake formation, it is near impossible to measure or visualise (at the early stages of) the cake formation experimentally in the lab. The graphical user interface employed can be utilized to observe these phenomena but data validation is still another step, which need to be fully considered.

4. Conclusions

Establishment of a software tool to model filtration through woven fabric filters is explained. Its first module is modelling a 3D woven fabric. This model along with the physical parameters regarding the particular filtration scenario is then exported to a CFD tool, to calculate fluid pressure and velocity in the locality of fabric and attaining the fluid flow paths. The tool then imports these results. Particles of various sizes and shapes are introduced to follow the fluid flow paths, and since the fluid flow governs their movement, the imported paths are employed.

As the particles come into contact with the fabric surface, a force model is employed to control the particle movement over such surface. Similar force model governs how particles interact with each other.

This is the major contributing factor in particle packing and thus in cake formation. The tool has the capability to record some interesting filtration properties quite accurately, as time progresses. Using the same filtration scenario, keeping all its parameters constant while varying the particle shapes, it is observed that at the early stages of cake formation, the output parameters (filtration characteristics) are different for various shapes. This proves the significance of particle shapes when simulating filtration through woven media. Essentially, shape of the particles lead to various particle packing, and it is this different packing, which changes the fluid flow and pressure profiles through the formed cake.

Evidently, the work carried out in this paper forms the foundations in establishing a software tool that can be used to test and improve fabric filter designs for more efficient filtration and improved cake release properties. Even at this early stage, the results generated by the computer model are encouraging. The advantage of predictive modelling can be significant in terms of system optimization and the design of new processes, although the model requires further development before this can be realized.

5. References

[1] S. Backer. The relationship between the structural geometry of textile and its physical properties. Part IV: Interstice geometry and air permeability. *Text. Res. J.* 1951, **21**: 703-714.

[2] M. A. Nazarboland, X. Chen, J. W. S. Hearle, R. Lydon and M. Moss. Computer simulation of filtration process through woven fabrics. *CESA 06*, Beijing, China.

[3] F. T. Peirce. The Geometry of Cloth Structure. *J. Textile Inst.*, 1937, **28**: T45.

[4] T. J. Lahey. Modelling hysteresis in the bending of fabrics. *MASc Thesis in systems design engineering*. University of Waterloo. Canada. 2002.

[5] H. Y. Lin and A. Newton. Computer Representation of Woven Fabric by Using B-Splines. *J. Text. Inst*. 1999, **90**(1): 59-72.

[6] Y. Jiang, and X. Chen. Geometric and algebraic algorithms for modelling yarn in woven fabrics. *JOTI*. 2005, **96**(4): 237-245.

[7] S. Backer. The relationship between the structural geometry of textile and its physical properties, I: Literature review. *Text. Res. J*. 1948, **18**: 650-658.

[8] W. Lu, K. Tung and K. Hwang. Fluid Flow Through Basic Weaves of Monofilament Filter Cloth. *Text. Res. J*. 1996, **66**: 311-323.

[9] K. C. Ting, R. J. Wakeman and V. Nassehi. Modelling flow in monofilament cloths – Prediction of pressure loss. *Filt. Soc. Meeting*. May 2005.

[10] W. S. Jodey and E. M. Tory. Computer simulation of close random packing of equal spheres. *Phys. Rev. A*. 1985, b(4): 2347-2351.

[11] K. J. Dong, R Y. Yang, R. P. Zou, A. B. Yu, G. Roach and E. Jamieson. Simulation of the cake formation and growth in sedimentation and filtration. *3rd Int. Conf. CFD in the Minerals and Process Ind.*, CSIRO, Melbourne, Australia, Dec. 2003.

[12] W. Lu and K. Hwang. Mechanism of cake formation in constant pressure filtration. *Sep. Tech*., 1993, 122-132.

[13] R. Y. Yang, R. P. Zou and A. B. Yu. Computer simulation of the packing of fine particles. *Phys. Rev. A*, 2000, **62**(3).

[14] K. Hwang, Y. Wu and W. Lu. The surface structure of cake formed by uniform-sized rigid spheroids in cake filtration. *Powder Tech*. 1996, **87**: 161-168.

[15] C. Yin, L. Rosendale, S. K. Kaer and H. Sorenson. Modelling the motion of cylindrical particles in a nonuniform flow. *Chem. Eng. Sci*. 2003, **58**: 3489-3498.

[16] A. Haider and O. Levenspiel. Drag coefficient and terminal velocity of spherical and nonspherical particles. *Powder Tech*. 1989, **58**: 63-70.

[17] N. V. Brilliantov, F. Spahn, J. M. Hertzsch and T. Poschelt. Model for collisions in granular gases. *Physics Review E*. 1996, **53**.

[18] P. A. Langston, U. Tuzun and D. M. Heyes. Discreet element simulation of granular flow in 2D and 3D hoppers: dependence of discharge rate and wall stress on particle interactions. *Chem. Eng. Sci*. 1995, **50**.

[19] J. N. Israelachvili. *Intermolecular and Surface Forces*. London: Academic. 1991.

[20] W. Lu, K. Tung and K. Hwang. Effect of woven structure on transient characteristics of cake filtration. *Chem. Eng. Sci*., 1997, **52**: 1743-1756.

[21] A. J. Walker and L. Svarovsky. Development of a computer model for predicting the filtration characteristics of a suspension. *Filt. & Sep*. 1994, 57-65.

[22] M. A. Nazarboland, X. Chen, J. W. S. Hearle, R. Lydon and M. Moss. Analysing the effect of woven fabric filter on fluid using CFD. *Meeting of the Filtration Society.* Loughborough Univ.

JIC email for contribution: editor@jic.org.uk