19th International Congress on Modelling and Simulation, Perth, Australia, 12–16 December 2011
http://mssanz.org.au/modsim2011

Modelling the Influence of Filter Structure on Efficiency and Pressure Drop in Knitted Filters

B.J. Mullins [a b c], **A.J.C. King**[a], **R.D. Braddock** [c]

[a]*Fluid Dynamics Research Group, Curtin University, GPO Box U1987, Perth WA 6845*
[b]*Curtin Health Innovation Research Institute, Curtin University, GPO Box U1987, Perth WA 6845*
[c]*Atmospheric Environment Research Centre, Griffith University, Nathan QLD, 4111*
Email: b.mullins@curtin.edu.au

Abstract: Fibrous filters are used extensively in a range of applications, including process engineering, automotive filtration and for worker (respiratory) protection. These filters are usually a felted, nonwoven structure of randomly arranged fibres. However, a special class of such filters exists - knitted filters. These filters are advantageous for many applications, as their knitted structure imparts significant mechanical strength. The structure of the fibres in such filters can be described by the classical strophoid equation.

There has been relatively little study on the pressure drop and efficiency of such filters. This work has developed a geometric model of a knitted metal filter, by applying the strophoid equation. The geometric model thus allows a range of geometries to be generated, based on the strophoid variables, and also fibre/wire diameter, then the knits layered at a given bulk porosity (packing density), to create a geometry of desired properties.

The geometric model outputs can then be coupled with a novel computational fluid dynamics (CFD) model for fibrous filtration (developed by the authors). This then allows, the relationship between the aforementioned structural properties and critical filter properties such as particle capture efficiency and pressure drop to be investigated.

This work examined the pressure drop and efficiency of a knitted filter geometry at 3 different packing densities. The CFD results were compared to classical single fibre efficiency theory for conventional fibrous filters. The CFD results showed increased capture efficiency and pressure drop compared to fibrous filter theory.

Keywords: Filter; Knitted; Particle; Pressure drop; Efficiency; Optimisation; Computational fluid dynamics; Strophoid

1 INTRODUCTION

Fibrous filters are used extensively in a range of applications, including process engineering, automotive filtration, and for worker (respiratory) protection. These filters are usually a felted, nonwoven structure of randomly arranged fibres, though some woven filters are also in use.

However, a special class of such filters exists - knitted filters. These filters are advantageous for many applications, as their knitted structure imparts significant mechanical strength. As a result of this, such filters may be used for high temperature or high stress applications, such as filters in automotive supplementary restraint (SRS airbag) systems, to capture explosive particles during airbag detonation, which would otherwise damage the airbag or injure the vehicle occupant. Figure 1 shows an image of a filter used for such an application.

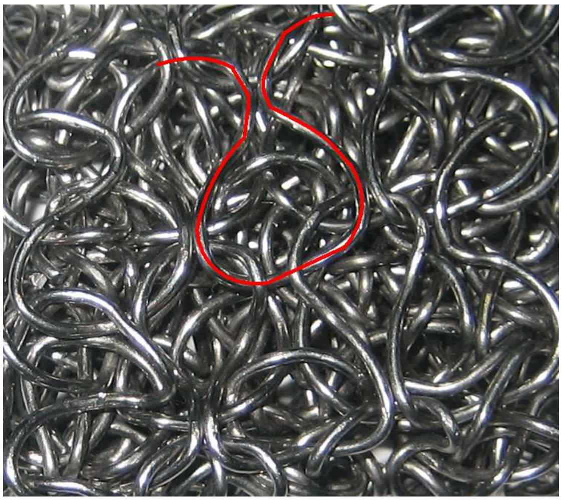


Figure 1. Image of compressed knitted metal filter showing strophoid-shaped knit loop. This particular filter would normally be used in an automotive SRS system

There has been relatively little previous study on the pressure drop and efficiency of such filters. Indeed the only work which can readily be found is that of Anand and Lawnton (1991), who conducted a highly empirical study into pressure drop and filtration efficiency for a selection of knitted filters.

This work will adopt a more fundamental approach, and use models to simulate the performance of idealised filter geometries of knitted (metal) filters.The geometric model thus allows a range of geometries to be generated, based on the strophoid variables, and also fibre/wire diameter, then the knits layered at a given bulk porosity (packing density), to create a geometry of desired properties. The geometries can also be artificially 'compressed' in order to increase the packing density (solidity) of the filter - this technique is often use in knitted filter manufacturing, and has been done to create the filter in Figure 1.

The general shape of the main fibre/wire loops in knitted filters can be described by the classical strophoid equation,

$$\mathbf{r} = \mathbf{c} \cdot \mathbf{cos}(\mathbf{2}\theta)\mathbf{sec}\theta. \qquad (1)$$

The knit loop is of course an incomplete strophoid loop where the tails do not intersect. This strophoid equation has been extended by previous authors (Jeddi and Dabiryan, 2008) to include all parameters required to define the knitted loop, including height and width of each loop, spacing between loops, radius of the curvature of the connecting 'thread' between loops, and width of the loop 'throat'.

This work aims to construct a program to reproduce knitted structures, given the above parameters. Geometric model outputs can then be coupled with a novel computational fluid dynamics (CFD) model for fibrous filtration (developed by the authors). This will then allow the relationship between the aforementioned structural properties and critical filter properties such as particle capture efficiency and pressure drop to be investigated.

2 METHODS

2.1 Geometry Generation

A knit of 10 rows of 10 strophoid loops, of a size typical for a knitted filter, was generated in MATLAB(MathWorks). The geometry was also layered to be 10 layers deep, in order to give a representative filter thickness. This geometry was then imported to Blender, where the wire centreline from matlab was rendered to an appropriate wire thickness (75 μm). The geometry was also compressed by 33% and 66%, in order to simulate the compression which may be used during manufacture (as a means of increasing packing density and rigidity of the filter).

Table 1 shows the geometries utilised in the CFD simulation.

Table 1. Test Mesh Properties

Mesh	Thickness (mm)	Packing Density (-)	Wire Diameter (μm)
Original (Uncompressed)	23	0.00462	75
33% Compressed	15	0.00618	75
66% Compressed	8	0.0109	75

2.2 Discrete Particle Tracking and CFD

The flow field, pressure drop and particle capture efficiency of the knitted filters were simulated using OpenFOAM. A customised discrete particle code was utilised.

The motion of each influent particle is individually tracked through the air phase until the particle passes through a domain boundary, which includes being captured by a fibre. Tracking is conducted in a Lagrangian frame of reference, with explicit integration of the particle velocity and position conducted at least once per timestep.

The forces acting on each particle are due to buoyancy, drag, and thermal diffusion (Brownian Motion). Buoyant forces are determined from

$$\mathbf{F}_b = \frac{\pi d_p^3}{6} \left(\rho_{\mathrm{p}} - \rho_{\mathrm{fluid}}\right) \mathbf{g} \tag{2}$$

where d_p is the particle diameter, ρ_{p} the density of the particles, and ρ_{fluid} is the density of the air phase.

Drag forces are calculated from

$$\mathbf{F}_d = \frac{18\mu}{\rho_{\mathrm{p}} d_p^2} \frac{C_D}{24} \mathrm{Re} \tag{3}$$

where $C_D = f(\mathrm{Re})$ is the particle drag coefficient, and Re is the particle Reynolds number based on the relative velocity between the particle and the fluid.

Thermal diffusion is negligible unless the particle diameter is less than approximately 1 μm. For these particles forces due to thermal diffusion were calculated from

$$\mathbf{F}_t = \mathbf{G}\sqrt{\frac{\pi S_0}{\Delta t}} \tag{4}$$

where $\mathbf{G}$ is a vector whose components are independent zero-mean, unit-variance Gaussian random numbers.

S_0 is given by

$$S_0 = 216 \frac{\nu \rho k_b T_{\mathrm{ref}}}{\pi^2 d_p^5 \rho_p^2 C_c} \tag{5}$$

where C_c is the Cunningham Correction factor, λ is the particle mean free path, given by

$$\lambda = 0.385 \sqrt{\frac{\rho_{\mathrm{oil}} d_p k_b T_{\mathrm{ref}}}{\mu^2 \pi^2}} \tag{6}$$

In the above, k_b is the Boltzmann constant and the reference temperature, T_{ref} was taken as 293.15 K.

2.3 Particle Tracking Algorithm

A reasonably robust particle tracking algorithm is implemented in OpenFOAM and a detailed description of the algorithm is presented in (Macpherson et al., 2009), however a brief overview is presented here.

For each particle, the following steps are undertaken.

1. Fluid and flow properties at the current cell location are determined by interpolation.
2. The particle forces are evaluated.
3. The particle trajectory is calculated, based on the fraction of time remaining for the current time step.
4. Intersection of the trajectory with any cell face is determined.
   (a) If the particle's trajectory intersects a boundary face, a flag is set indicating which boundary and no further movement is calculated for the particle.
   (b) If the particle's trajectory intersects an internal face, the particle is transferred to the neighbouring cell, the fraction of the trajectory completed is deducted from the remaining time, and the process is continued from step 1.
   (c) If the particle trajectory does not intersect a face, the particle's position is updated and the next particle is tracked from step 1.

For step 4a boundaries are labeled as 'active' or 'inactive'. If a particle has collided with an 'inactive' boundary, it is marked as deleted. After all particles have moved, collisions between particles are determined and if desired any particles marked as deleted are removed. There are a number of additional parts to this algorithm that deal with parallelisation issues, particle rebound, and poor quality meshes, however the reader is referred to (Macpherson et al., 2009) for these details.

2.4 Single fibre efficiency and pressure drop calculation

The Single Fibre Efficiency (SFE) theory is a well known semi-empirical theory which describes particle capture in fibrous filters (Hinds, 1999). For filters with a highly uniform geometry of fibres which are perpendicular to the flow direction, the SFE theory can predict filter capture efficiency accurately. The CFD results have been compared to SFE theory, in order to quantify the deviation in the behaviour of knitted filters from that of conventional (nonwoven) filters.

Furthermore, the pressure drop results should also be compared to classical filter models. The most appropriate model for this purpose was deemed to be that of Davies (1973),

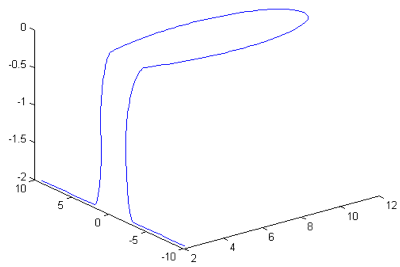
$$\mathbf{\Delta p} = \frac{\mathbf{u}\mu_{\mathbf{g}}\mathbf{z}}{\mathbf{d_f^2}}[\mathbf{64}\alpha^{\mathbf{1.5}}(\mathbf{1} + \mathbf{56}\alpha^{\mathbf{3}}), \tag{7}$$

where Δp is the pressure drop across the filter, *u* is the mean gas velocity at the face of the filter, μ_g is the gas viscosity, *z* is the filter thickness (in the flow direction), d_f is the fibre diameter and α the packing density of the filter.

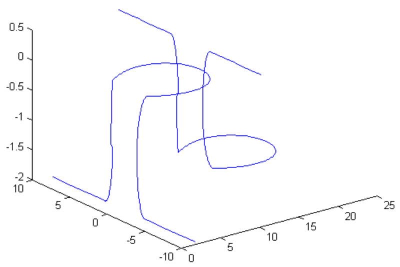
The Davies (1973) equation has been empirically derived to account for fibres which are not perpendicular to the flow field, and was therefore selected as the most appropriate equation for knitted filters.

3 Results and Discussion

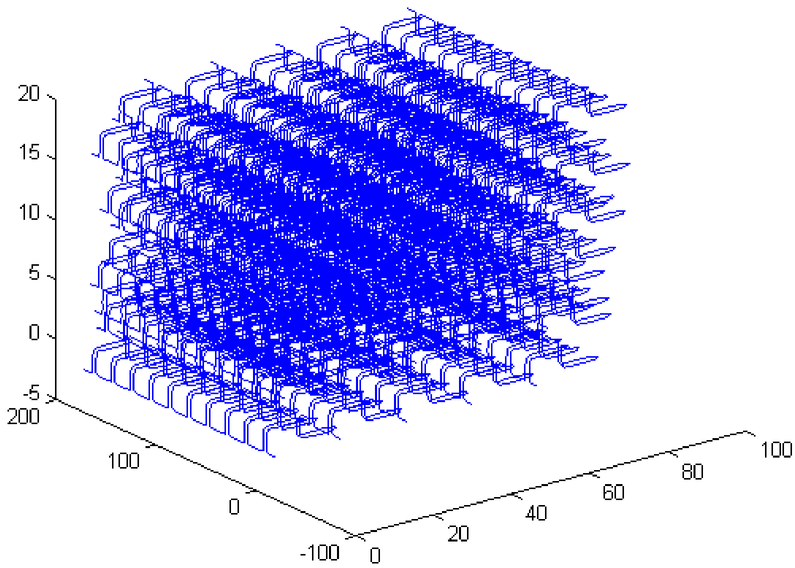
Figure 2 shows the output from the geometry generation program. (a) shows a single loop, (b) the method of connecting (or 'knitting') loops, and (c) the geometry used for later experiments (prior to rendering in Blender).



(a) Single Loop



(b) Connected Loops



(c) $10 \times 10 \times 10$ Mesh

Figure 2. Output from MATLAB geometry generation code.

As such filters generally operate at elevated velocities and are more suited to the collection of larger particles, the CFD simulations were run for each of the three geometries at a $u = 2.0ms^{-1}$ and for a particle size of 10 μm. SFE calculations were conducted for the full range of particle sizes, for the same conditions as the CFD simulation. Figure 3 shows the SFE results (curves) and the CFD results (single points at 10 μm particle size).

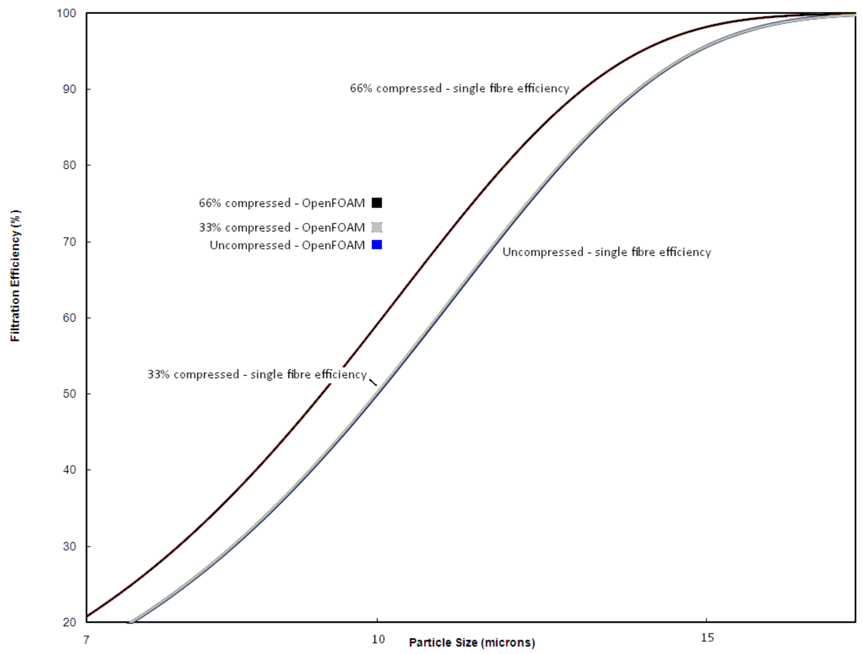


Figure 3. Single fibre efficiency curves, and modelled results for 10 μm particle size

The SFE curves for the uncompressed and 33% compressed filters are almost overlaid. The SFE results and CFD results follow the same general trend, however there is evidently a significant discrepancy between the values. Table 2 shows the results for particle capture efficiency (Eff.) from the SFE and CFD simulation, as well as Δp results from the CFD simulation and the Davies (1973) equation, together with the discrepancy between the two sets of results.

Table 2. Test Mesh Results

Mesh	Eff. CFD (%)	Eff. SFE (%)	Discrepancy %	Δp CFD (Pa)	Δp Davies (Pa)	Discrepancy %
Orig	69.6	49.9	39	6.11	2.97	51
33%	71.9	50.1	44	6.18	3.00	51
66%	75.1	59.2	27	6.22	3.75	40

For the Original/uncompressed and 33% comressed geometries, the differences are relatively consistent, at 40% for efficiency and 51% for pressure drop. However the 66% shows a decreased discrepancy, however the reason for this is unclear at this stage and a more extensive study is required.

It should be noted, that as the filters under investigation in this work were knitted from metal wires, therefore the filters are typically highly rigid. However, one of the key drawbacks of knitted filters mentioned by Anand and Lawnton (1991), was the ability of the loops in knitted textile filters to move and/or distort. Therefore, for less rigid knitted filters, it may be necessary to include fluid-structure interactions in the CFD simulation.

3.1 Conclusions and Recommendations

This paper presented a new code for generating geometries of knitted filters, which, when coupled with appropriate meshing software and CFD solvers, allows flow fields, pressure drop and capture efficiency in knitted filters to be simulated.

A preliminary study showed that a significant and relatively systematic discrepancy exists between the pressure drop and particle capture efficiency of knitted filters versus a conventional filter of the same properties (packing density, fibre diameter and thickness) at the same filtration/fluid conditions.

More research into knitted filters is therefore needed, such that simple models (similar to those which exist for conventional/nonwoven filters) may be developed.

ACKNOWLEDGMENTS

The authors would like to thank Rhodius GmbH for assistance.

REFERENCES

Anand, S. and P. Lawnton (1991). The development of knitted structures for filtration. *JOURNAL OF THE TEXTILE INSTITUTE 82*, 297–308.

Davies, C. (1973). *Air Filtration*. London: NISBN: 0-471-19410-7, Academic Press.

Hinds, W. (1999). *Aerosol Technology*. California: NISBN: 0-471-19410-7, Wiley-Interscience.

Jeddi, A. and H. Dabiryan (2008). Ideal stitch model for interlock-knitted fabric. *JOURNAL OF THE TEXTILE INSTITUTE 99*, 369–374.

Macpherson, G. B., N. Nordin, and H. G. Weller (2009). Particle tracking in unstructured, arbitrary polyhedral meshes for use in cfd and molecular dynamics. *Communications in Numerical Methods in Engineering 25*(3), 263–273.