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Approaches for Predicting Collection Efficiency of Fibrous Filters

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ABSTRACT

This paper describes different approaches for predicting collection efficiency of nonwoven fibrous filters. Traditionally, the flow field has been obtained by analytically solving the Navier-Stokes equations inside over-simplified geometries with the fibers placed in regular arrays perpendicular to the flow direction. Our approach, on the other hand, is to exploit a numerical method based on the finite-volume technique to solve the flow inside 3-D virtual webs generated based on the properties of real filters. Our results showed a good qualitative agreement with previous works.

Keywords: Permeability; Cell model; CFD; Filtration; Nonwoven.

INTRODUCTION

During the past several years, there have been many pioneering studies (Davies, 1973; Brown, 1998; Hinds, 1999), which have helped developing the filtration science and technology to its current level. This is because the rising awareness of environmental agencies and the general public for a clean environment together with demands of many advanced industries have urged the filtration industry to investigate on ways to prove the indoor-air-quality.

Fibrous filters, such as nonwoven media, are widely used to remove submicron particles owning to its low cost and easy implement. It is quite important to evaluate the filters' performance of based on various particle and filter properties, which is generally characterized by collection efficiency and other parameters. In next section, we first introduce the traditional analytical method to predict the collection efficiency. Section 3 introduces our algorithm for generating nonwovens and then investigates on their nano-particle collection efficiency. In section 4, we compare our study with the well-known available 2-D model mentioned in section 2.

Analytical Models: Cell Model

It is difficult to analytically analysis the flow field around a fiber in the real fibrous filter. In order to predict collection efficiency of fibrous filter, influence of a single fiber has been extensively investigated.

Several results from calculation of efficiency of this smallest element in the fibrous filter have been obtained based on different flow models. Potential flow and

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Lamb flow are two of those early models describing the flow around a cylindrical fiber (Davies, 1973), however because there is no neighboring fiber influence, they cannot present the realistic flow. The neighboring fiber interference was first adequately taken into account by Kuwabara (1959) and Happel (1959). Both theories differ from the earlier isolated fiber models, since they consider the fiber in a finite space instead of an infinite space (shown in Figure 1). For this reason, the effects of other fibers at the outlet could be taken into account (Brown, 1993).

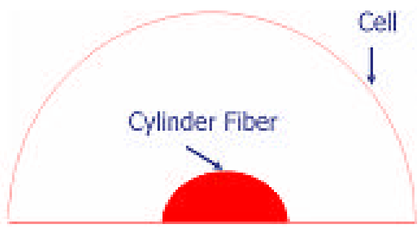


Figure 1: Cell Model considers a fiber in a finite space

It has been known that the flow fields near the surface of the cylinders without considering the slipping effect could be expressed in polar coordinates the equations by (Stechkina and Fuch, 1965; Happel, 1959; Kuwabara, 1959):

$$U_r = (1 - \frac{1}{r^2} - 2\ln r)\cos q \qquad (1)$$

$$U_q = (1 - \frac{1}{r^2} + 2\ln r)\sin q \qquad (2)$$

in which r is the dimensionless distance and U_r and U_q are the components of the dimensionless flow velocity U_0 which could be represented by

$$U_0 = \frac{U}{2K} \qquad (3)$$

where U is the flow velocity and K is the hydrodynamic factor , which could be varied by different models. K in Cell model is Kuwabara hydrodynamic factor Ku, which could be represented by

$$Ku = -\frac{\ln a}{2} - \frac{3}{4} + a - \frac{a^2}{4}$$ (Kuwabara, 1959; Rao and Faghri, 1988).

Collection efficiency of a fibrous filter E could be obtained by the single fiber efficiency h by the following equation (Lee and Liu, 1982 ;Hinds, 1999):

$$E = 1 - \exp(\frac{-4a\,h\,t}{p\,D_f}) \qquad (4)$$

in which a is the Solid volume fraction, h is the air viscosity, t is the thickness of the filter, and D_f is the fiber diameter.

Among all the mechanisms which will influence collection efficiency, interception, Brownian diffusion and inertial impaction are three of the most importance for pure aerosol filtration (Davies, 1973). Based on the studies done by Hinds (1999) and Lee et al (1982), the arithmetic sum of efficiencies for these mechanisms could be considered as an approximation of efficiency for the single fiber.

$$h = h_R + h_D + h_I \qquad (5)$$

in which h_R, h_D and h_I are the single fiber efficiency due to the interception, diffusion and inertial impaction, respectively.

In the most penetrating particle size region (around 300 nm), work of Stechkina et al. (1969) has shown diffusion and interception are dominant filtration mechanism. Particularly, interception is dominant when D_p is comparable to D_f while Brownian motion is the most important mechanism when $D_f >> D_p$.

The interception of a homogenous spherical particle by a cylindrical fiber could be defined as a particle is intercepted by a fiber when the distance from the center of the particle mass to the fiber surface is equal or less than the radius of the particle (Hinds, 1999). In the Kuwabara flow, the expression of the single fiber efficiency due to the interception is (Lee and Liu, 1982).

$$h_R = \frac{1+R}{2Ku}[2\ln(1+R) - 1 + a + (\frac{1}{1+R})^2(1-\frac{a}{2}) - \frac{a}{2}(1+R)^2] \quad (6)$$

In which R is the fiber radius, and a is the solid volume fraction which equals to the ratio of fiber volume and filter volume.

There exist several approximation forms of Equation 6 (Stechkina and Fuch, 1966; Lee and Liu, 1982.), yet small discrepancies from those approximation forms to the original expression cannot be avoided. The most widely accepted approximation of the single fiber efficiency due to the interception maybe is the simplified form obtained by Lee and Liu (1982).

$$h_R = \frac{1-a}{Ku}\frac{R^2}{1+R} \quad (7)$$

It is obvious to obtain from the above equation that h_R will be high while R is big, and low when R is small.

For aerosol filtration, particle may derivate from its original streamline when passing through a fibrous filter media. The derivation is caused by the combination of particle inertia and diffusion due to Brownian motion. Derivation of Brownian motion governs the particle trajectory when the particle is extremely small compared to the fiber size (Hinds 1999).

Steckina and Fuchs (1966) are the first to use cell model to deal with the efficiency caused by Brownian motion. They tried to get the particle trajectory due to the Brownian motion by solving convective diffusion of inertial-less particles towards a cylindrical fiber in the dimensionless coordinates (Stehina and Fuch, 1965). h_d could be calculated by the following equation:

$$h_d = \frac{d^3(1+R)}{2Ku}\int_0^p (\frac{\partial n}{\partial r_{=1+R}})dq \quad (8)$$

The single-fiber efficiency for this mechanism (h_d) achieved by the method mentioned above, could be presented as follows:

$$h_d = 2.9Ku^{-1/3}Pe^{-2/3} + 0.624Pe^{-1} \quad (9)$$

By using the method of boundary layer theory, Lee and Liu (1982) shows another prediction of diffusion h_d by using Kuwabara cell model

$$h_d = 2.6(\frac{1-a}{Ku})^{1/3}Pe^{-2/3}. \quad (10)$$

In which Pe is the Peclet Number. Lee and Liu claimed with the inclusion of the factor $1-a$ in the theoretical expression, the results could be applied over a wider range of the condition, especially for the case when a is high.

Inertial impaction is another derivative deposit mechanism. It could be defined as (Hinds, 1999) as "a particle, because of its inertia, is unable to adjust quickly enough to the abruptly changing streamlines near the fiber and crosses those streamlines to hit the fiber". The single fiber efficiency for impaction is given by (Lee and Liu, 1982; Hinds 1999) as,

$$h_I = \frac{(Stk)J}{2Ku^2} \quad (11)$$

where $J = (29.6 - 28a^{0.62})R^2 - 27.5R^{2.8}$ for $R < 0.4$ and Stk is the Stokes number, defined as the ratio of particle stopping distance to fiber diameter.

It is obvious to see that collection efficiency of a fibrous filter is a function of a number of parameters of flow, particle and filter and could be easily calculated based on the equations by using cell model. However, a precise prediction of the collection efficiency requires the particle trajectory based on the flow to be solved for each fiber in the filtration medium, and to characterize the efficiency for single fiber by using the average result; In the cell model the fibers inside the filter are treated the same way, even though there exist big difference among fibers (Brown, 1998).

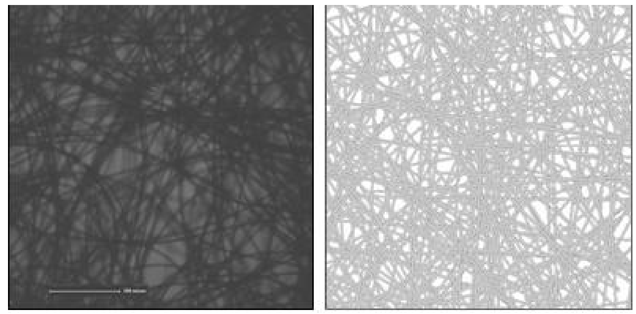
Numerical Models: 3-D Virtual Web Model

As we could see from section 2, most of the previous studies have been limited to systems consisting of rows of fibers perpendicular to the flow direction in a two-dimensional geometry. To our knowledge, there have been few attempts in realistically simulating the filter's disordered structure in a three-dimensional geometry (Wang et. al 2006). Moreover, the role of the filter structure and its relationship with performance of the media has not been fully established. This is because of the difficulties involved not only in generating 3-D structures similar to a nonwoven media, but in calculating the particle collection efficiency when the geometry is too complex as well. The current study is the first step to predict the collection efficiency based on 3-D virtual webs (Wang et. al 2006).

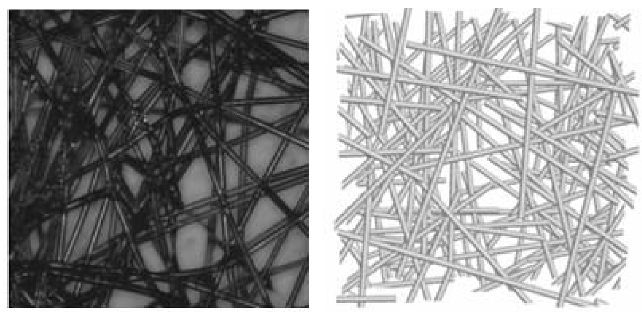
Our virtual models of these fiber-webs are basically similar with the real nonwoven media. For simplicity, we assumed that fibers lie horizontally in the plane of the web and do not bend at the crossovers. One of the most important features of our structure simulation is that it allows the orientation distribution of the fibers to be taken into consideration (as opposed to the cell model which is based on a regular 2-D fiber distribution) (Pourdeyhimi et. al 1996a; Pourdeyhimi et al. 1996b; Pourdeyhimi et al. 1997).

To generate a 3-D web, first a new fiber is generated at an altitude greater than the current thickness of the web. The fiber is then lowered until it reaches the fiber-webs. For more details reader are refereed to our previous publication by Wang et al (2006). The difference existing between the long-fiber web model (such as Electrospinning, Meltblowing, and Spun-bonding) and short-fiber web model (such as Air-laying, Carding and Wet-laying) is that we used the so-called *μ*-randomness for generating continuous filaments and *I*-randomness for short fibers (Pourdeyhimi et. al 1996a; Pourdeyhimi et al. 1996b; Pourdeyhimi et al. 1997).

A steady state laminar incompressible model has been adopted to describe the flow regime inside our virtual geometry. The finite volume method implemented in Fluent code is exploited to solve the flow field.



(a)



(b)

Figure 2: Nonwoven webs and their virtual model: a) a typical long fiber web; b) a typical short fiber web.

The governing equations including continuity, conservation of linear momentum, and energy could be written in vectorial form as:

$$\frac{Dr}{Dt} + r\nabla \cdot V = 0 \qquad (12)$$

$$r\frac{DV}{Dt} = -\nabla p - h\nabla \times (\nabla \times V) + 4/3h\nabla(\nabla \cdot V) \qquad (13)$$

$$rc_p \frac{DT}{Dt} = -\frac{Dp}{Dt} + \Phi + k\nabla^2 T \qquad (14)$$

In above-mentioned equations, r, k, and c_p represent air density, thermal conductivity, and the specific heat of air, respectively.

Symmetry boundary condition has been used for the sides of the computational box, even though there is no plane of symmetry in a disordered fibrous structure. This boundary condition is considered for the simulations because there lacks of information regarding the flow velocity and/or pressure inside of the structure prior to the simulations.

We assumed a no-slip boundary condition for the air flow on the fiber surfaces. This is because for the air thermal condition and the fiber diameter considered in this study, the continuum flow prevails, i.e., $Kn_f = 2l / d_f << 1$, where Kn_f is the Knudsen number of fiber, and l is the mean free path of the air molecules (64.5 nm at STP).

Once the particle-free flow field is obtained, the airborne particulates, modeled by rigid spheres of uniform density $r_p = 1000 kg/m^3$, are introduced into the flow domain. Particle trajectories are then tracked via the Lagrangian method and their positions are monitored. Figure 3 shows a typical trajectory of one particle inside flow domain.

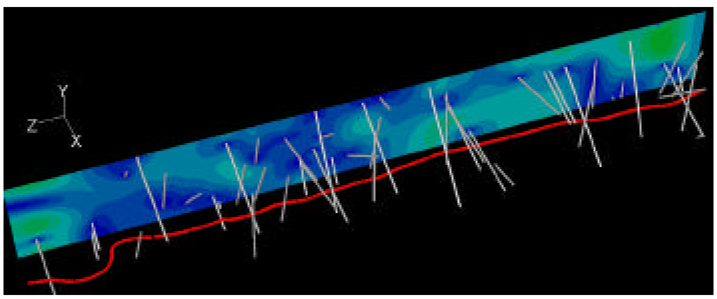


Figure 3: Particle trajectory of 3-D virtual webs.

Efficiency of a fibrous filter is determined by the number of particles can remove from an aerosol flow:

$$E = \frac{N_{in} - N_{out}}{N_{in}} \qquad (15)$$

where N_{in} and N_{out} are the number of entering and exiting particles, respectively.

Results and Discussion

Figure 4 shows the result of the simulation based on one of the above mentioned 3-D virtual web with different operating flow velocity and particle size. It is obvious that the collection efficiency is higher for the nano particle under with the low velocity. This is because for the nano particle, the dominant collection efficiency is Brownian Diffusion. For low velocity, the particle will have more residence time inside the filter and higher opportunity to be captured by the fiber.

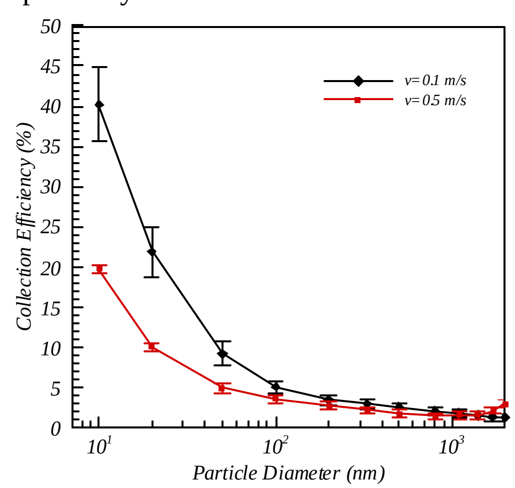


Figure 4: Collection efficiency is higher for the nano-particle at low velocity

Figure 5 shows the average collection efficiency of our virtual filter versus particle diameter along with the predictions of the Kuwabara's cell model. Monodisperse aerosols having a particle size ranging of 100 nm to 400 nm have been introduced to the simulation domain and tracked inside the structure. The inlet face velocity of was considered to be 0.1 m/s. It can be seen that the filter collection efficiency decreases by increasing the particle size in the range of 100 nm to 400 nm. The collection efficiency predicted by our simulations follows a trend very similar to that of the Kuwabara's cell model. However, there seems to be a slight difference between the two predictions.

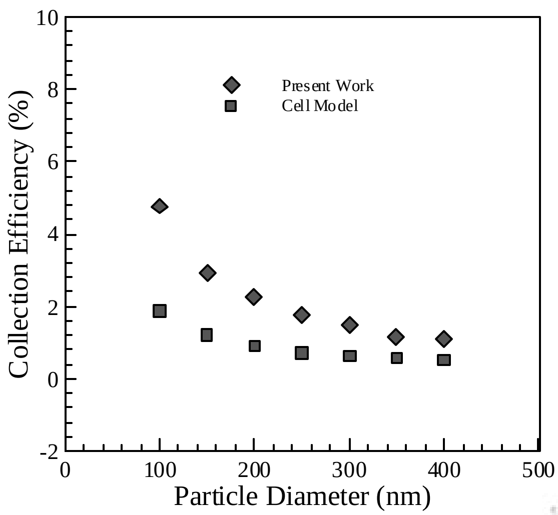


Figure 5: A comparison between collection efficiencies from CFD and cell model.

Conclusions

In this work, we simulated the filtration process of nanoparticle via different categories of nonwoven media. The numerical simulations presented here are obtained via solving the Navier-Stokes equations inside virtual 3-D filter media constructed in accordance with the real features of the nonwoven filters. We demonstrated that the collection efficiencies are higher for smaller face velocities. Our simulated collection efficiencies were compared with the predictions of the Kuwabara's cell model and similar trend has been found.

Acknowledgement

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APPENDIX

Notation:

c_p Specific heat of air

D_f Fiber diameter

D_p Particle diameter

E Collection efficiency

J Parameter related with inertial impaction,where

$J = (29.6 - 28a^{0.62})R^2 - 27.5R^{2.8}$ for

$R < 0.4$

k Thermal conductivity

K Hydrodynamic factor in Cell model

Kn_f Knudsen number of fiber

Ku Hydrodynamic factor in Kuwabara Cell model, where

$$Ku = -\frac{\ln a}{2} - \frac{3}{4} + a - \frac{a^2}{4}$$

N_{in} Number of entering particles of the filters

N_{out} Number of exiting particles of the filters

Pe Peclet number

R Fiber radius

Stk Stokes number (the ratio of particle stopping distance to fiber diameter).

t Thickness of the filter

U Flow velocity

a Solid volume fraction

h Single fiber efficiency

h_R Single fiber efficiency due to the interception

h_D Single fiber efficiency due to the diffusion

h_I Single fiber efficiency due to the inertial impaction

l The mean free path of the air molecules (64.5 nm at STP)

m Air viscosity

r Air density

r_p Particle density

? Viscous dissipation