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Numerical Study of Droplet Motion inside Non-woven Fibrous Media

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ABSTRACT

The migration of liquid droplet from non-woven fibrous filter was investigated numerically using OpenFoam, an opensource CFD platform. Different droplet velocities were considered which resulted in various steady state saturation level and droplet drainage rate. In this work dependency of liquid volume fraction on velocity and time have been shown during filtration. A nonwoven fibre filter having packing density 3%, with fibre diameter of 9µm and filter dimension of: 2mm(z), 0.5mm(x) & 0.5mm(y) was used. It was accomplished in this study that increasing the velocity and time, liquid volume fraction in fibrous filter get reduced. Furthermore a threshold velocity threshold of 2m/s is necessary for the motion and detachment of droplets from fibre.

1. Introduction

The micro scale study of drop motion on fibers is significant to many industrial applications such as drop coalescence and drainage in fibrous filter media. Fibrous filters are generally characterized by their collection efficiency and pressure drop. During the past 50 years, there have been many studies dedicated to the development of mathematical theories for predicting collection efficiency and pressure drop of fibrous media. Removal of the liquid droplets from the exhaust streams of many chemical, automotive, aeronautics, textile and health and safety industries is of vital importance. These droplets can lead to clogging of the fibrous filters during the cleaning operation. It is significant to design a self-cleaning filter, whereby the liquid droplets collect on the filter and drain down onto some collecting device. This reduces the operational and cleaning cost of the filter. The underlying need for all these applications is estimation of the velocity of a drop along the fiber axis. Filters are divided into two main categories which named oleophilic and oleophobic. In oleophilic media, droplets collect and spread out over the fibre surface and a thin film will be formed. This film will be immediately broken up into an array of droplets due to Plateau-Rayleigh instability [1-3]. Most of the industrial filters are oleophilic which are relatively well described [4-7]. On the other hand, in the oleophobic case, captured liquid aerosol does not coat the fibre, and it remains as discrete droplet,

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unless it moves and contact other droplets which consequently resulted in coalescence or carried through filter by airflow forces. In the case of liquid aerosol filtration, some researchers have reported their experimental investigations of this process, the results revealed that during filter clogging there is a decrease in the medium's performance for particles smaller than 100 nm and an increase in efficiency for particles with a diameter >200 nm. Both effects are induced by the amount of liquid collected in the medium [8]. The influence of the operating conditions was carried out which highlighted the significant roles of filtration velocity, the nature of the filter, and the physico-chemical characteristics of the aerosol on filter efficiency and clogging [9]. In regard to numerical studies, simulations have been developed for single fibre systems, as well as more complicated multi-fibre systems, the most advanced of which approach whole filter simulation. The predominant method for filtration simulation is applying Finite Volume Method (FVM) of Computational Fluid Dynamics (CFD). These simulations include investigating the effect of fibre diameter on filter permeability [10], fibre orientation on filter performance [11]. Spielman and Goren [12] solved the flow through 3-D arrays of cylinders randomly oriented in all three directions by analytical techniques. Many researchers have studied air flow through filters as well as particle deposition to bring about the insight phenomenon of fibrous structure and capture mechanism on collection efficiency and pressure drop [13-15]. The motion of droplets on fibres is important in terms of the drainage behaviour of filters. Since it is very difficult to assess the microscopic drainage behaviour of filters at the whole filter level, a number of researchers have considered single fibres. The main goal of the research is to understand the filtration mechanisms at micro scale. Subsequently the research will investigate specific interaction mechanisms: re-entrainment, collision and coalescence.

To the best of the author’s knowledge, no published study has been dedicated to investigate the role of micro scale droplet motion in non-woven fibrous media and their effect on saturation and collection efficiency.

2. Methodology

Stokes flow equations are numerically solved in the void space between the fibers using the open source CFD code [16]. The Stokes equations are given Eq. (1) to (4) as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial p}{\partial x}=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

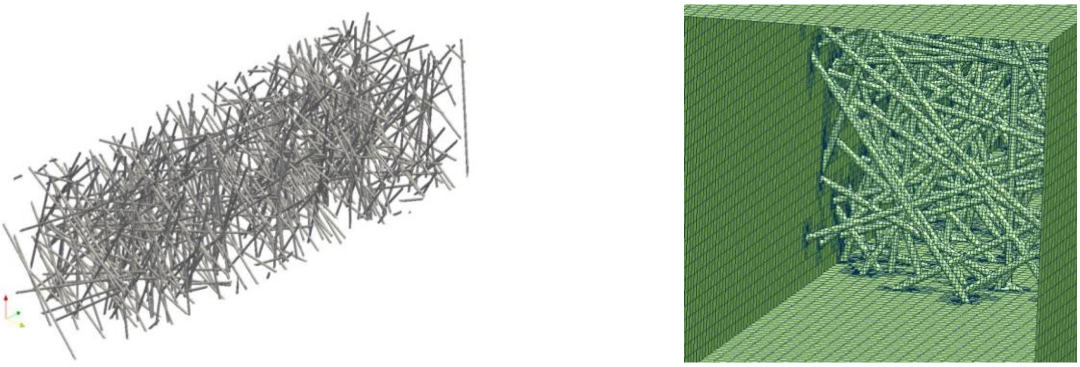
$$\frac{\partial p}{\partial y}=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\frac{\partial p}{\partial z}=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Our simulation strategy here is based on specifying an inlet face velocity of 0.1 m/s (resulting in a Reynolds number in the order of unity) to obtain the media’s pressure drop. For the air flow at the fiber surface, we assumed the no-slip boundary condition. We used a SIMPLE algorithm for pressure–velocity coupling along with a second order upwind scheme for the momentum equation discretization [17]. Our criterion for convergence was at least four-orders of magnitude reduction in the residuals for the continuity and momentum equations in the x-, y-, and z-directions [18]. In order to discretise the computational domain, snappyHexMesh utility is used (see Figure 1). For the purpose of grid independency, we considered eight different meshes and check their dependency on grid size with coarser mesh 64^3 and finer mesh of 130x130x120. The mesh was refined that means the grid spacing is progressively reduced until further decreases made no significant change in the predicted pressure drop for simulations (see Figure 2). The calculation of pressure drop is compared against well-established pressure approximation by Lloyd Spielman and Simon L. Goren [12]. In their work, the filter pressure drop used is the dimensionless pressure drop factor which is represented by:

$$\varphi = \frac{\Delta P a^2}{4\alpha\mu U Z} \tag{5}$$

Where ΔP is calculated pressure drop, filter radius, α is packing density (solidity) of the filter, μ is gas dynamic viscosity, U is flow velocity, and Z is filter length. It is clear from the Figure 3 that the experimental data matches very closely with simulation performed in OpenFOAM.



(a) (b)

Fig. 1. (a) Filter geometry and (b) mesh generated by OpenFOAM software

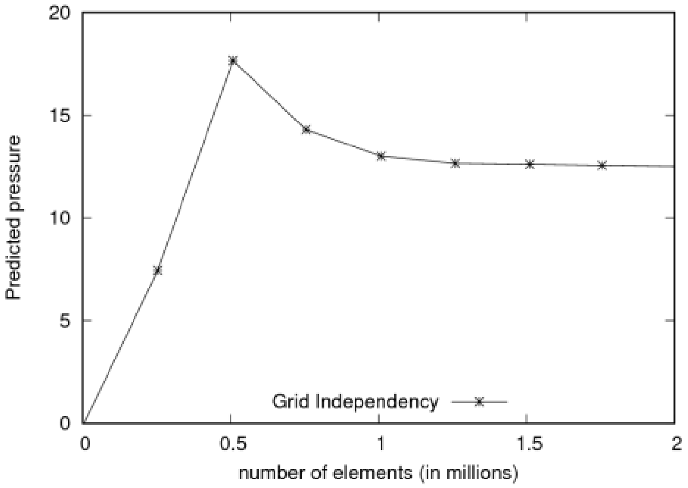


Fig. 2. Grid independency test

It is important to ensure that the size of simulation domain is sufficiently large such that the pressure drop values are not dependent on domain size. There are three basic mechanisms that lead to the capture of an aerosol particle in a neutral filter medium: interception, inertial impaction, and Brownian diffusion. Brownian diffusion is important only for small particles. Interception is important when the size of the particles and fibers is comparable, and inertial impaction becomes considerable only when the particle's momentum is not negligible, either because of its large mass or velocity. The total particle collection efficiency of a filter is the result of a combination of all the above mechanisms. As the particle size 9µm, we used a Lagrangian modeling approach, in which each individual particle is tracked throughout the solution domain Eq. (6) to (8). In the Lagrangian method, the force balance on a given particle is integrated to obtain the particle's position in time. The dominant force acting on a particle is the air drag force. For $R_p = \frac{\rho V d_p}{\mu} < 1$, Li and Ahmadi [19]

$$\frac{du_p}{dt} = \frac{18\mu}{d_p^2 \rho_p C_c}\left(u - u_p\right) \tag{6}$$

$$\frac{dv_p}{dt} = \frac{18\mu}{d_p^2 \rho_p C_c}\left(v - v_p\right) \tag{7}$$

$$\frac{dw_p}{dt} = \frac{18\mu}{d_p^2 \rho_p C_c}\left(w - w_p\right) \tag{8}$$

Boundary conditions to be exerted on the filter surfaces are velocity and contact angle conditions. The no-slip condition for the filters surface and static angle of 125 degree between filter surface and droplet is used.

3. Results

In this section numerical results for the movement and detachment of oil droplets through non-woven filter media are presented. The physical properties used for fluids are given in Table 1.

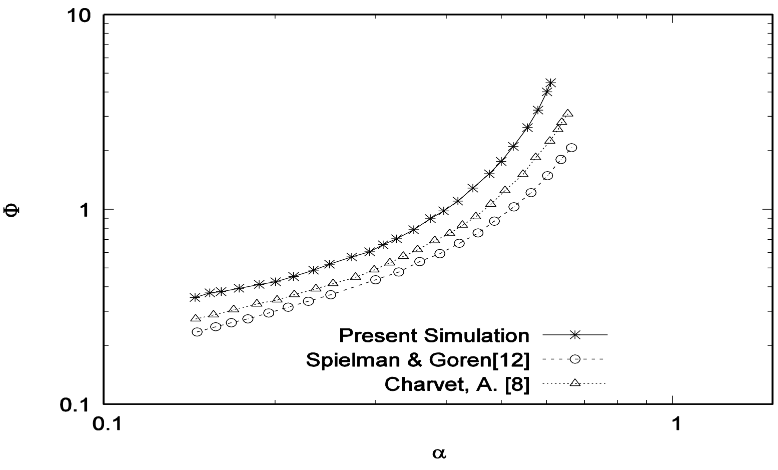


Fig. 3. Predicted pressure drop against the packing density comparison with previous results

Table 1
Physical Properties of Fluids

Fluid	Density (Kg/m^3)	Dynamic viscosity (Pa-s)	Surface tension (N/m)
Oil	890	0.023	0,0324
Air	1.23	1.47x 10^{-5}	-

Figure 4, shows simulated values for saturation (S) in the non-woven filter versus dimensionless time. The volume fraction φ is calculated by $\phi = \frac{V_l}{V_{void}}$. Where V_l, is the volume of liquid phase (oil) in the filter domain and V_{void} is the summation of the liquid phase volume and gas volume (volume inside the filter not occupied by fibres).

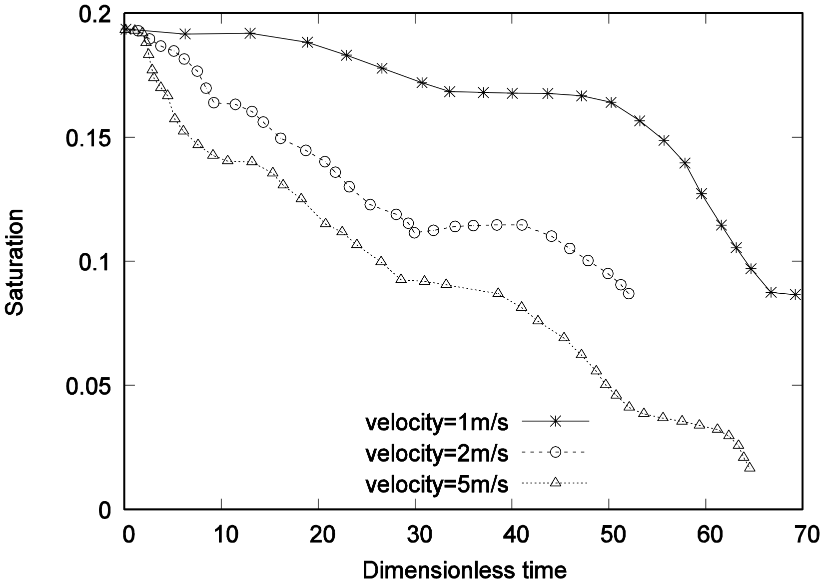


Fig. 4. Development in saturation with time

It is clear from Figure 4, that re-entrainment for the non-woven filter is quite good as the liquid saturation decreases very fast with increase in velocity and time interval. Initially the saturation is around 0.2, for velocity 1m/s the droplets did not get enough momentum to travel through the non-woven filter therefore a slight decrement in saturation is observed with time. As we increase the velocity it was observed that droplet now gain some momentum and moves toward outlet by lowering the saturation level. When we increase velocity to 5m/s saturation drops suddenly to 0.015 and clears the filter. Figure 5 presents images of oil droplet detachment from the non-woven filters at higher velocity at different time interval.

Dimensionless time 10

Dimensionless time 20

Dimensionless time 30

Dimensionless time 50

Fig. 5. Oil drop detachment from the non-woven filters at veloity 5m/s

In general, we can see from the results that the non-woven media provides larger re-entrained droplets and has higher re-entrainment rates at specified speed. This may have advantages in some applications, as it will ensure pressure drop remains lower, and the large re-entrained drops wills settle out rapidly after the filter. The main reason for this may likely be due to the filter structural morphology [20]. As it can be seen from Figure 5, the non-woven filter allow collected droplets to create larger droplets by coalescing which results in displacement of their mass centre away from centre of fibre. This increased parameter would decrease the force required to move a droplet. Another important concept which can be gained from figure is that although liquid volume fraction reduces by increasing in time, for cases with lower velocity (0.5, 1, and 2 m/s) this volume fraction remains constant which means that droplets do not re-entrain to the flow regime. For better examination of this phenomenon, Figure 6 indicates the variation of saturation versus velocity.

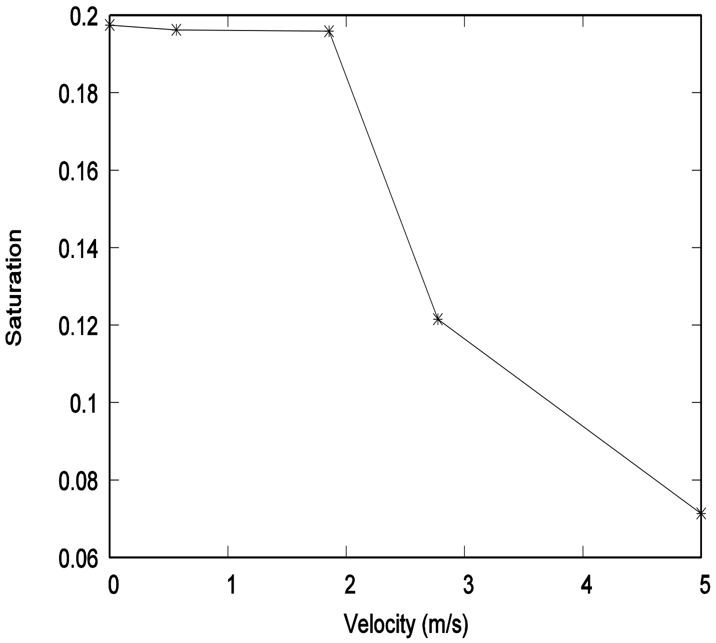


Fig. 6. Saturation dependency on velocity

As it is highlighted in the Figure 6, detachment point can be anticipated at velocity around 2.1 m/s for the filter media. From this, it can be found why there is no re-entrainment in cases with lower velocity which can be concluded from the fact that these lower velocities do not provide sufficient force to carry droplets out of filters. The separation is calculated based on the number of collected droplets. In steady-state of operation the collected liquid is drained and large droplets are released. However, the coalesced droplets which detach from the fibers are relatively large and easy to separate; therefore, they are considered as separated from continuous liquid (see Figure 7).

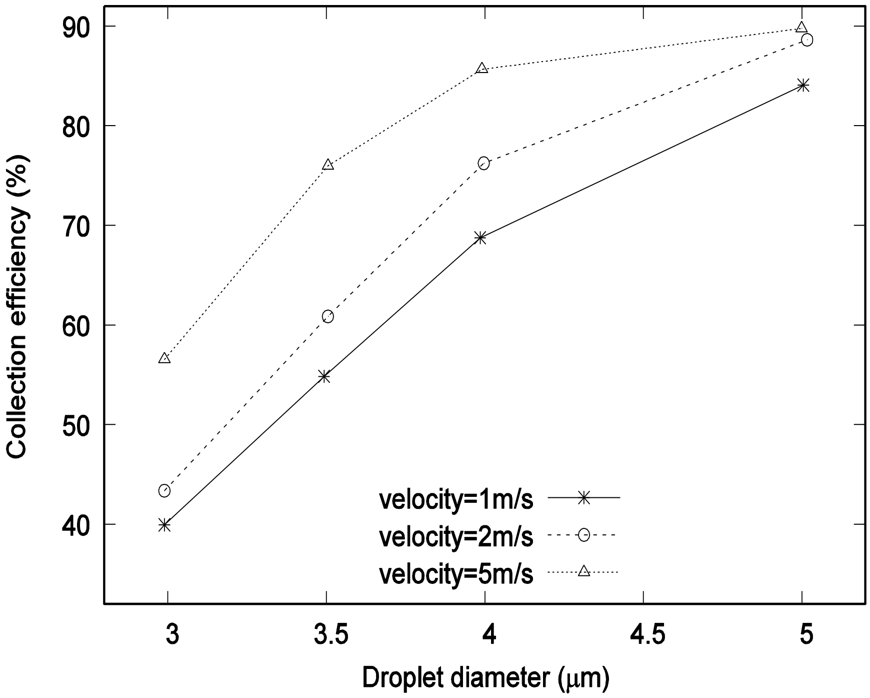


Fig. 7. Collection efficiency as a function droplet diameter. Fibre diameter is 9μm, and packing density is 3%

The effect of inertial mechanism of deposition is observed for small droplets [21], even below 3.5 μm, when comparing efficiency curves for 1, 2 and 5 m/s. When the droplets are in the range between 3.5 and 10 μm the effect of inertia becomes significant even for 1 m/s and the product of collection and coalescence efficiency becomes highest, and separation performance the best. So the collection efficiency for all velocities is nearly converge for larger droplet diameter and reached a steady state.

4. Conclusions

This work has examined the movement and re-entrainment of droplets in non-woven fibrous media with a range of different face velocities. It was found that by increasing in velocity and time, liquid volume fraction in the filters reduced though re-entrainment once a threshold of 2 m/s is achieved. Furthermore, it has been shown that non-woven media produced largest re-entrainment at higher velocity. It is worth mentioning that other factors such as saturation, initial droplet position, temperature may play an important role in re-entrainment form filter which are not investigated in this study. It is important to note however that these results would need to be validated in real media. The large drops entrained from non-woven fibrous media after coalescence would be advantageous in many cases as they would readily settle under gravity.

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