SIMULATING TRANSPORT IN AND ENTRAINMENT FROM NONWOVEN FIBROUS, KNITTED, AND OPEN-CELL FOAM FILTERS

V. Golkarfard[1, 2, *], B.J. Mullins[2, 3], A.J.C. King[1, 2], S. Abishek[2, 3], G. Kasper[4], W. Heikamp[5]
[1] Department of Mechanical Engineering, Curtin University, Australia
[2] Fluid Dynamics Research Group, Curtin Institute of Computing, Curtin University, Australia
[3] Occupation and Environment, School of Public Health, Curtin University, Australia
[4] Institute for Mechanical Process Engineering and Mechanics, Karlsruhe Institute of Technology, Germany
[5] Raschig GmbH, Germany

ABSTRACT

The movement and re-entrainment of liquid droplets from three different filter media, namely fibrous, knitted, and open-cell foam was investigated numerically using computational fluid dynamics (CFD). A range of face velocities were considered which resulted in a range of oil transform rates and steady state saturation levels. It will be shown that liquid volume fraction in filters depends on velocity and time. The minimum velocity required for detachment of droplets was also identified.
The main purpose of this research is to investigate the behaviour of pre saturated oil-mist filters in different geometric configuration and also different air flow conditions. In this study, all the produced filter geometries have a packing density (solidity) of 2 % with fiber/element diameter of 9 µm and overall dimensions of: 2mm (z), 0.5 mm (x), and 0.5 mm (y).
In order to capture the gas-liquid interface, the Volume of Fluid (VOF) method will be applied. To perform the simulations, the open source computational fluid dynamics (CFD) toolbox, OpenFOAM is used.
To verify the accuracy of computations, the calculation of clean pressure drop is compared against well-established pressure approximation in the literature.
This work has examined the movement and re-entrainment of droplets in fibrous, knitted, and open-cell foam 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 in all three cases. Furthermore, it has been shown that knitted media produced largest re-entrainment and the fibrous media the least. 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 knitted media would be advantageous in many cases as they would readily settle under gravity.

KEYWORDS

Computation Fluid Dynamics, Nonwoven Filter Media, Fibrous Filter, Mist Filtration, Drop Re-entrainment, Oleophobic, Foam Filter

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ABSTRACT

The movement and re-entrainment of liquid droplets from three different filter media, namely fibrous, knitted, and open-cell foam was investigated numerically using computational fluid dynamics (CFD). The Volume of Fluid (VOF) method, which is available in the OpenFOAM software package was applied to resolve this problem. All study cases were selected to have equivalent properties such as packing density, fibre diameter, initial saturation, and initial pressure drop. A range of face velocities were considered which resulted in a range of oil transform rates and steady state saturation levels. It will be shown that liquid volume fraction in filters depends on velocity and time. The minimum velocity required for detachment of droplets was also identified.

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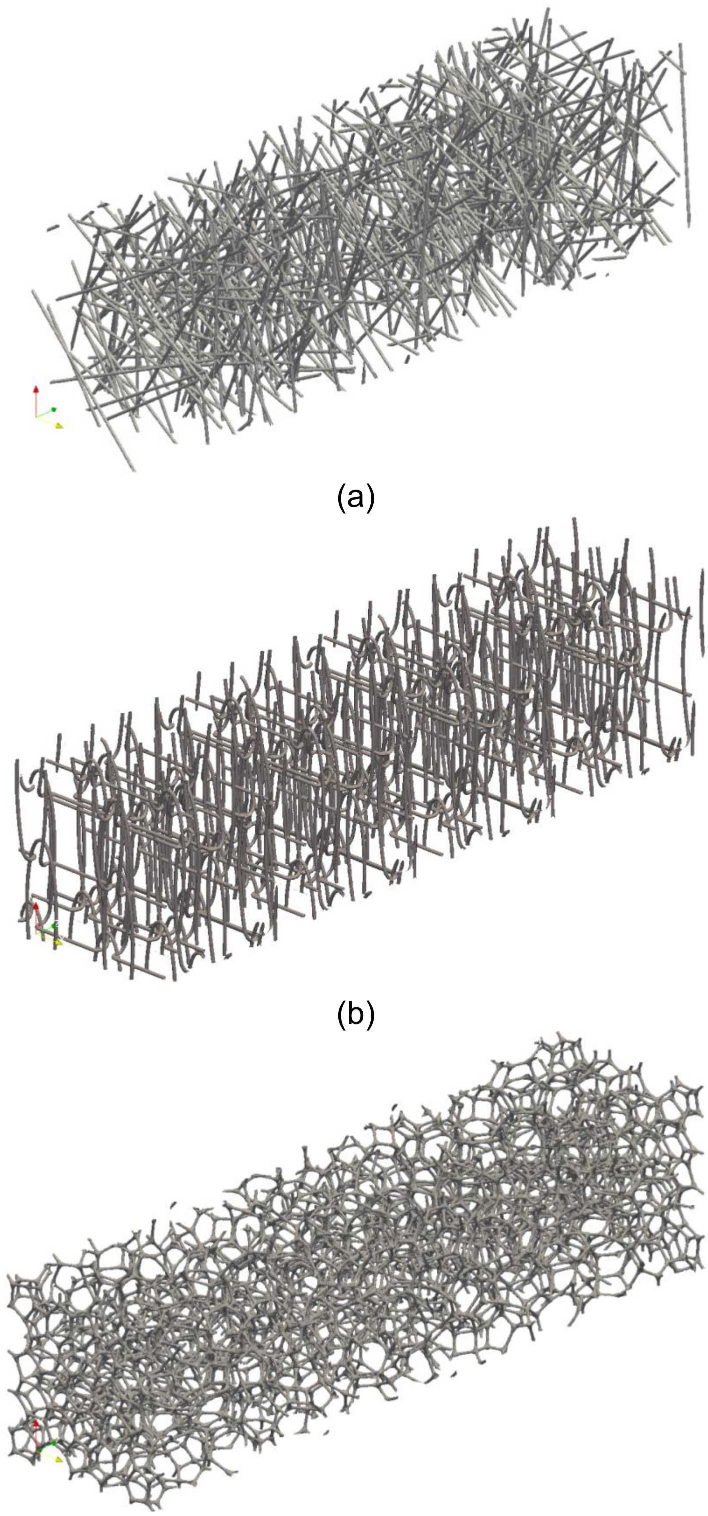
Introduction

During the past decades, due to increased needs of many advanced industries such as manufacturing, pharmaceutical, medical, Biology and electronics, filtration science and technology has been extensively studied (1-6). Furthermore, it is necessary for many branches of industry to purify a gas for different purposes by removing solid or liquid impurities from an exhausted gas, so many researches have been conducted numerically and experimentally in this field (7-9). In the case of liquid aerosols, such as oil-mists which are typically formed due to various industrial processes, their filtration dynamics differs from solid particle filtration (9). One of the most commonly used method for treating or removing liquids from gas is filters especially fibrous or nonwoven media (9) . Apart from the structure of filters which categorises them into fibrous, knitted, open-cell foam and so on, their wettability characteristics plays a key role in evaluation of filters' efficiency and performance. Filters are divided into two main category 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 (10-12). Most of the industrial filters are oleophilic which are relatively well described (13-16). On the other hand, in the oleophobic case, captured liquid aerosol do not coat the fibre, and it remains as discrete droplet, unless it moves and contact

other droplets which consequently resulted in coalescence or carried through filter by airflow forces. Since the coalesced oil, due to lower surface energy, will not fully wet the fibre, oleophobic filters may possess lower saturation level for equivalent media properties. Moreover, it is possible that collected liquid in this kind of media to be “blown off” or even re-entrain into the flow regime from the rear side of the filter. There have been relatively few works that have studied oleophobic filters (17-20) and the majority of works have only considered droplets on single fibres. Recently, Mullins and Mead-Hunter (21) have carried out a comprehensive study of true oleophilic and oleophobic media, examining pressure drop, drainage rate, saturation, and efficiency of these filters.
Like most of the engineering research, this filed can be separated into both experimental and numerical studies. In the case of liquid aerosol filtration, some researchers have reported their experimental investigations of this process (13, 22, 23). 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 (24), fibre orientation on filter performance (25). Spielman and Goren (26) 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 (24, 27-29). In 2013, Mead-Hunter et al. (4) have considered the capture and coalescence of liquid droplets in a filter. They used a combination of Lagrangian particle tracking and volume of fluid (VOF) method to simulate the filtering behaviour. A number of works have examined the movement of droplets on fibres. These typically have considered droplet motion along a fibre (30-32), though have also considered droplet detachment (8, 21). 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.
In this work, the behaviour of saturated oil-mist in three different oleophobic filter geometries (fibrous, knitted, and open-cell foam) and also different air flow velocities will be investigated numerically. The main goal of the research is to understand in detail and at small scales, the various filtration mechanisms. Subsequently the research will investigate specific interaction mechanisms: re-entrainment, re-suspension, collision and coalescence, and fluid behaviour after pre saturation in different filter media types.

Cases Studied

The main purpose of this research is to investigate the behaviour of pre saturated oil-mist filters in different geometric configuration and also different air flow conditions. Figure 1 represents the representative filter geometries.



(c)

Fig. 1. Filter geometries: (a) Fibrous, (b) Knitted, (c) Open-cell Foam

In this study, all the produced filter geometries have a packing density (solidity) of 2 % with fiber/element diameter of 9 µm and overall dimensions of: 2mm (z), 0.5 mm (x), and 0.5 mm (y). The computational domain is 4 mm in the z direction and 0.5 mm in both the x and y directions. The initial pressure drop through the filters are 106.2, 76.8, and 94.8 *pa* for fibrous, knitted, and foam, respectively which provide a basis to compare the performance of the three types of media.

The saturation of the filters is initialised 20% of the simulated filter volume with

DEHS. In regard to compare these three filter media, the initial distribution of DEHS droplets are similar in all study cases. Figure 2 shows the initial position of droplets for fibrous case in computational domain as a representative.

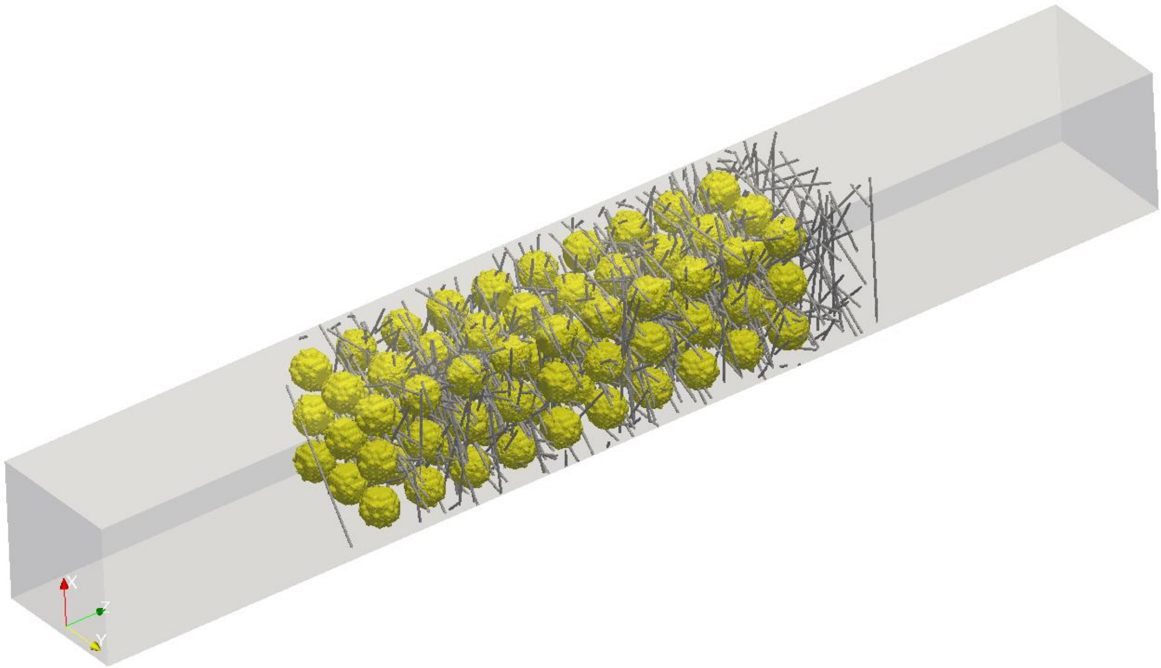


Fig. 2. Initial position of distributed droplets

For studying re-entrainment of droplets, five different velocities of 0.5, 1, 2, 3, and 5 m/s are prescribed at inlet boundary.

Methodology

In order to capture the gas-liquid interface, the Volume of Fluid (VOF) method will be applied (33, 34). The VOF method is based on the definition of an indicator function which indicates whether the cell is occupied by one fluid or another or a mix of both. In the conventional volume of fluid (VOF) method, the transport equation for an indicator function, representing the volume fraction of one phase (the oil in the case of coalescing filters), is solved simultaneously with the continuity and momentum equations. The governing equations are fully detailed in (33, 34).
To perform the simulations, the open source computational fluid dynamics (CFD) toolbox, OpenFOAM (35), is applied. This software is based on finite volume method, and the solver used was a three-dimensional unsteady solver which utilised the Multidimensional Universal Limiter with Explicit Solutions (MULES) algorithm to handle the transport equation and the Pressure Implicit with Splitting of Operators (PISO) algorithm for the coupled pressure-velocity fields (36).
In order to discretise the computational domain, snappyHexMesh utility is used. 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. Figure 3 indicates the produced mesh for fibrous case as a representative.

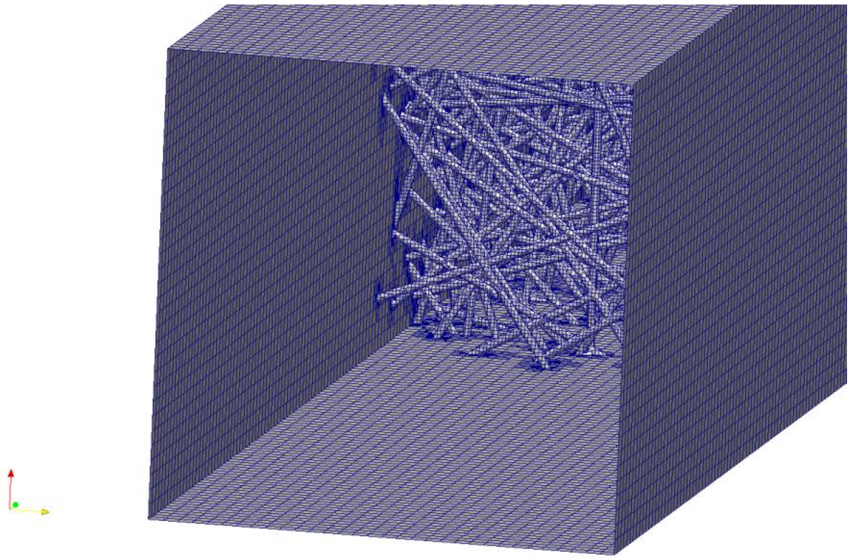


Fig. 3. Mesh generated by snappyHexMesh utility for fibrous filter

In VOF-based methods, since the convergence and stability are strictly depend on the equation for volume fraction, both time step control and bounded discretisation schemes for divergence terms are employed to overcome these difficulties.
In the case of boundary conditions, which play an important role in CFD calculations, it should be stated that boundary conditions that are required to be exerted on the filter surfaces are velocity and contact angle conditions. The no-slip condition is considered for the surface of the filters. Furthermore, effect of contact line velocity on the contact-angle that is not taken into account, and the contact angle which is prescribed at the filter surface was considered as a static one without any changes equal to 120 degrees.
Also, Gravitational forces were not considered in simulations, as it has been proven insignificant for droplets with diameter less than 100μm.

Validation

To verify the accuracy of computations, the calculation of clean pressure drop is compared against well-established pressure approximation by Lloyd Spielman and Simon L. Goren (26). In their work, the filter pressure drop used is the dimensionless pressure drop factor which is represented by:

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

Where ΔP is calculated pressure drop, *a* is filter radius, α is packing density (solidity) of the filter, μ is gas dynamic viscosity, U is flow velocity, and Z is filter length. The clean pressure drop for all three filters are calculated and compared against (26), and is presented by figure 4.

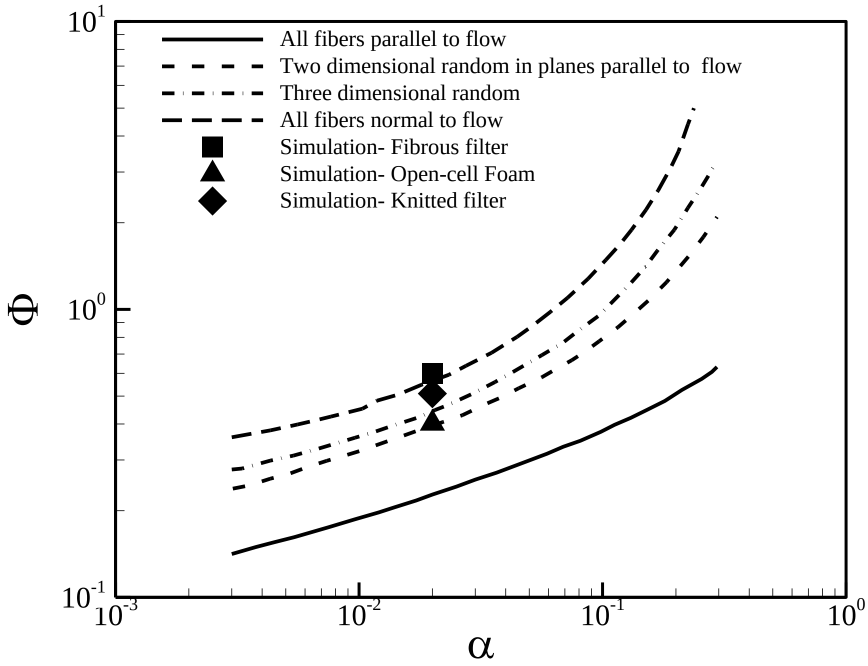


Fig. 4. Comparison of predicted clean pressure drop with (26)

As can be seen from this figure, a good agreement exists between the simulations and (26). Even though the latter considered fibrous media only, and it is the main reason that the numerical results of fibrous media pressure drop adheres to the proposed equation perfectly. Since the created geometry for fibrous media is randomly distributed fibres in a plane and normal to flow direction, the predicted pressure drop for the fibrous case agrees well with the case in which the fibres are all normal to flow direction.

Results and discussion

In this section, the numerical results for the movement and detachment of DEHS droplets through and from different filter media are presented. Simulations were conducted on nonwoven fibrous, knitted, and open-cell foam media at different inlet velocities: 0.5, 1, 2, 3, and 5 m/s. The physical properties used for fluids are given in Table 1.

Table 1. Physical properties of fluids.

Fluid	Density, ρ ($^{kg}/_{m^3}$)	Dynamic viscosity, μ ($Pa\ s$)	Surface tension, σ ($^{N}/_{m}$)
DEHS	914	0.025	0.0324
Air	1.1845	1.557×10^{-5}	-

Figure 5 shows simulated values for saturation (S) in the filter domain versus dimensionless time. The volume fraction is calculated by:

$$S = \frac{V_l}{V_{void}} \tag{6}$$

Where V_l , is the volume of liquid phase (DEHS) 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).

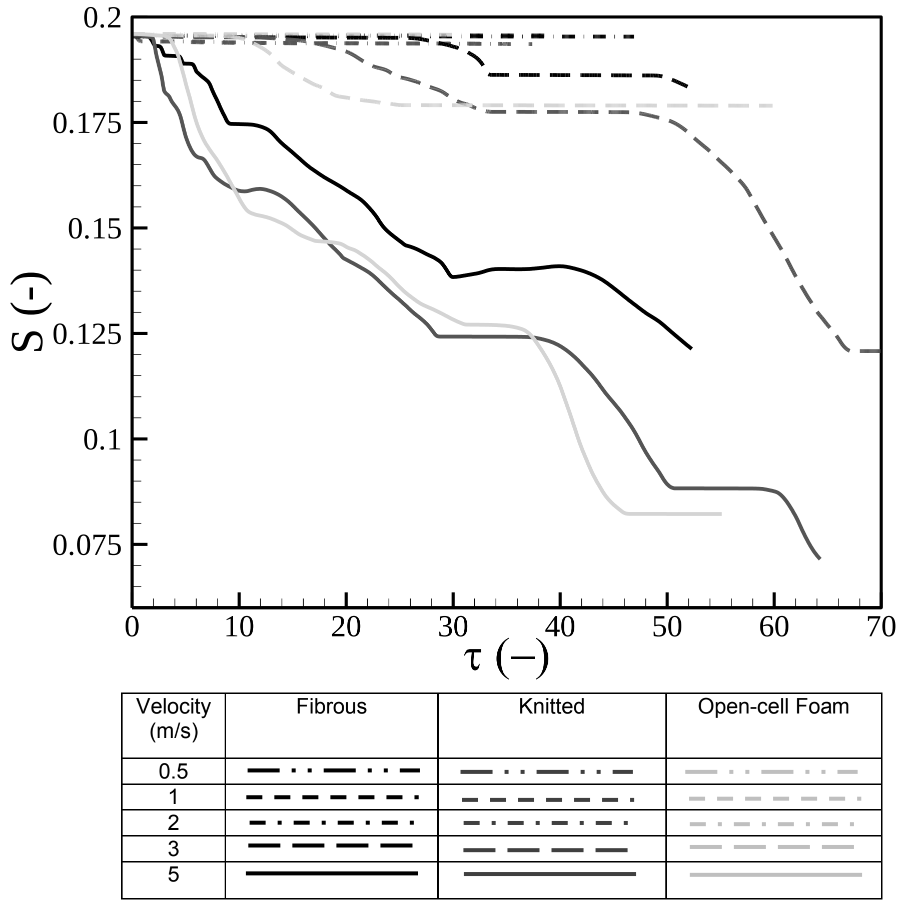


Fig. 5. Change in saturation with time

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It is clear from figure 5 that re-entrainment is significantly more pronounced in the knitted case as the liquid saturation decreases the fastest. Figure 6a-d presents comparative images of oil detachment from the different filters for the 5 m/s case at dimensionless time equal to 10, 20, 30, and 50.

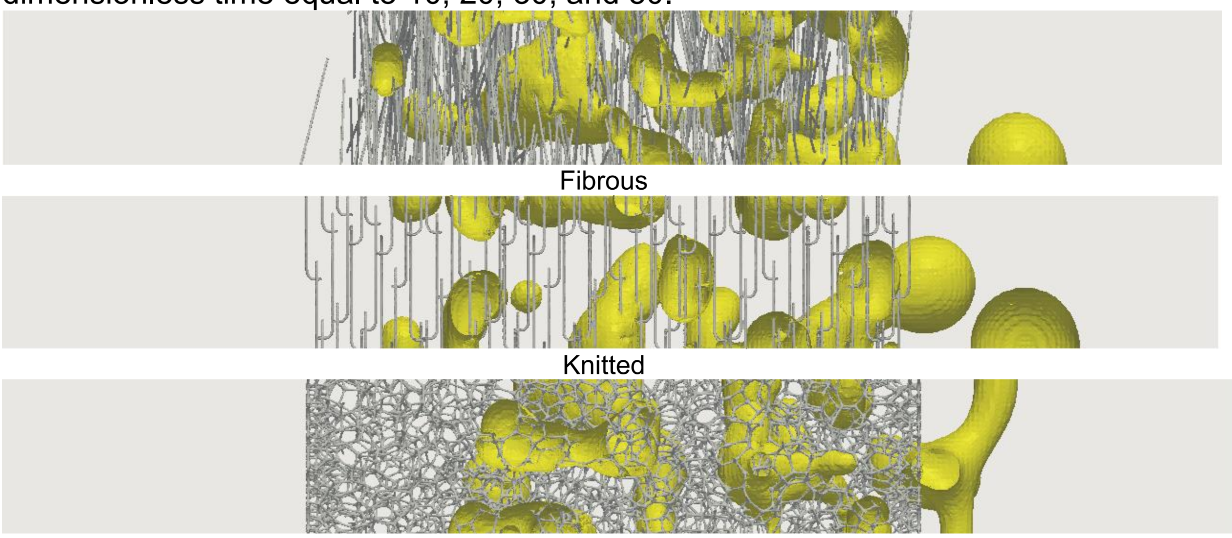

Fig. 6a. Comparison of oil detachment at dimensionless time 10

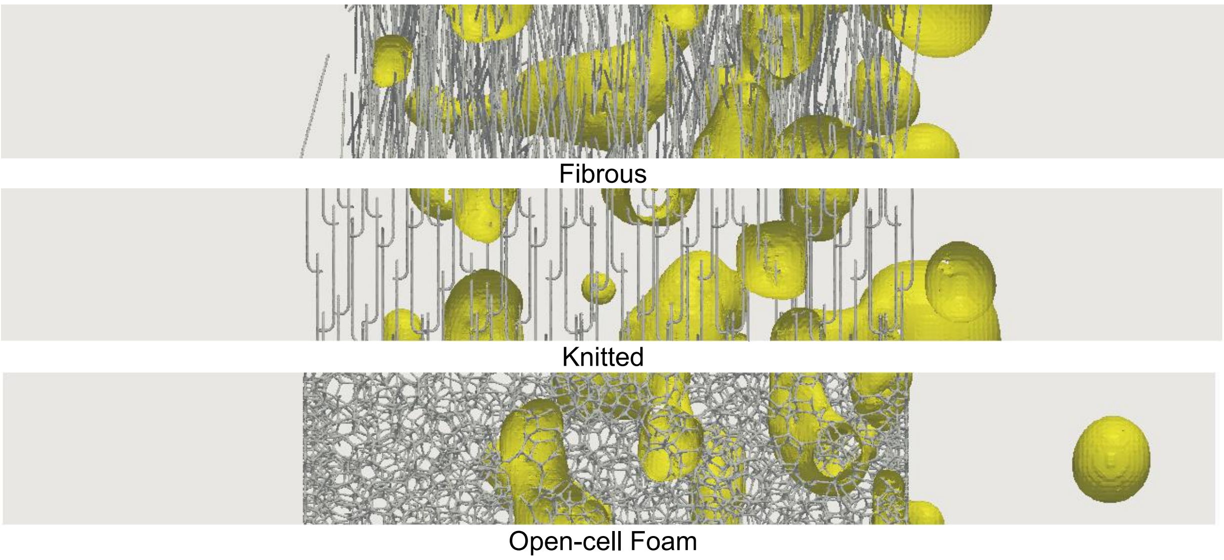

Fig. 6b. Comparison of oil detachment at dimensionless time 20

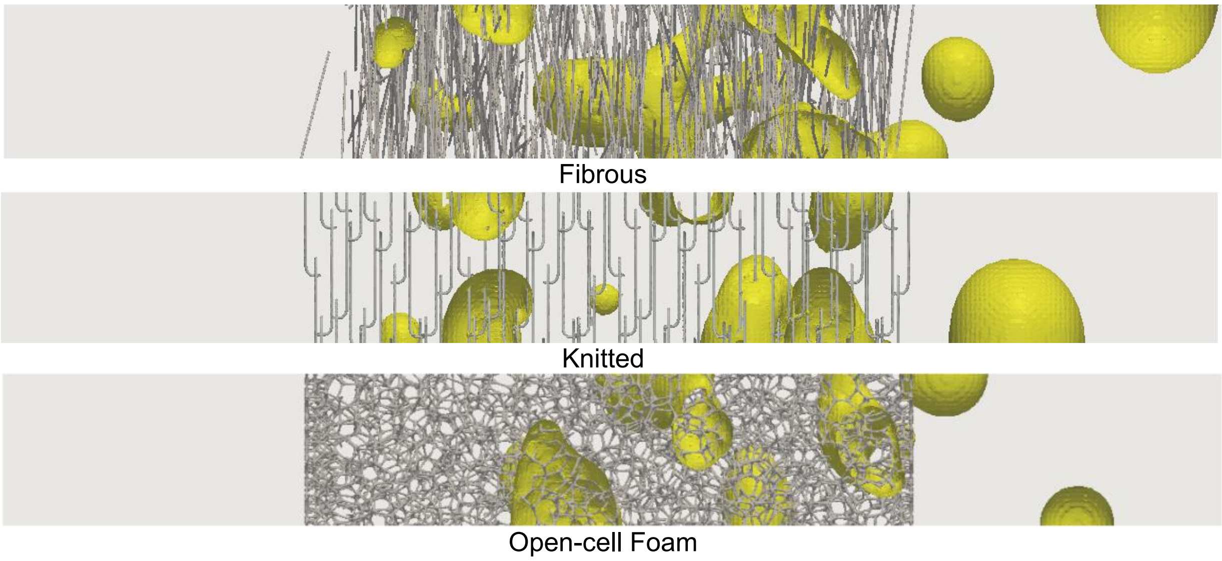

Fig. 6c. Comparison of oil detachment at dimensionless time 30

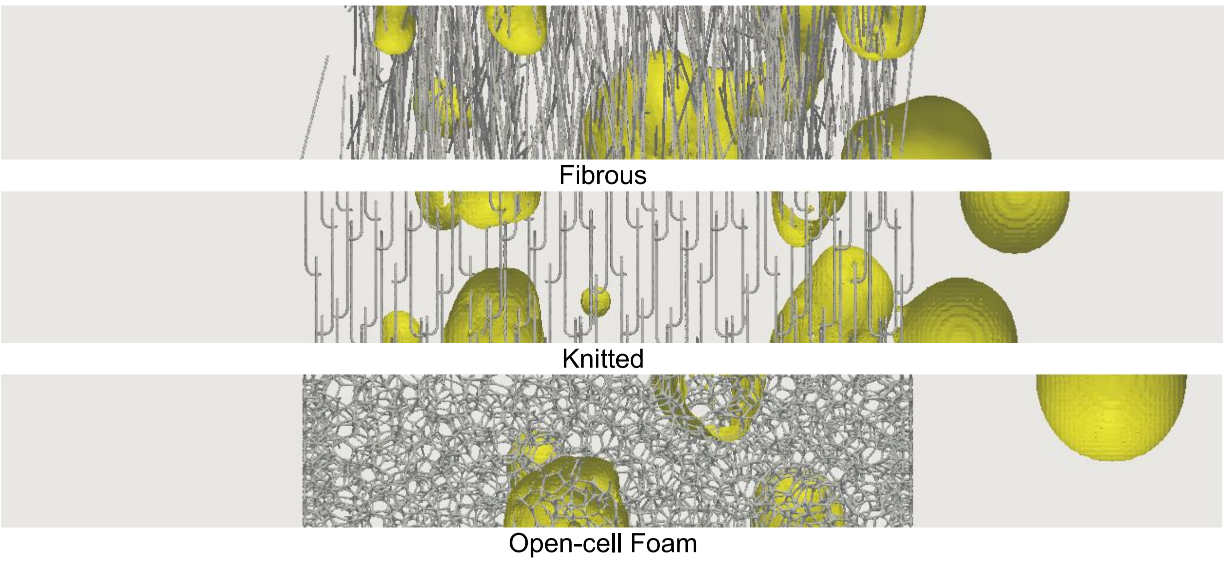

Fig. 6d. Comparison of oil detachment at dimension lesstime 50

In general, we can see from the results that the knitted media provides larger re-entrained droplets and has higher re-entrainment rates. 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 difference in these three filters. As it can be seen from figure 6a-d, the knitted filter can 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 (37).
Another important concept which can be gained from figure 5 is that although liquid volume fraction reduces by increasing in time, for cases with lower velocity (o.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 7 indicates the variation of saturation versus velocity. In this figure, the calculated numerical data are demonstrated by symbols while the lines show spline fits to these data.

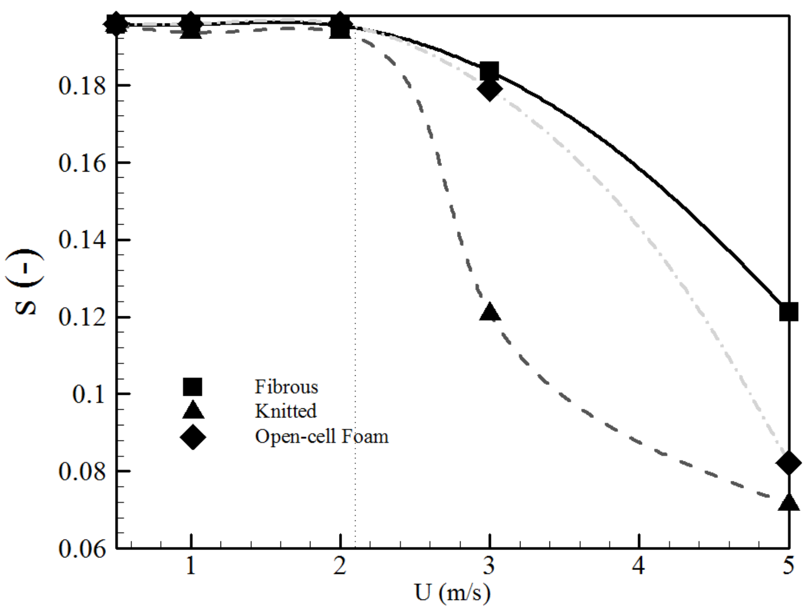

Fig. 7. Filter saturation versus velocity

As it is highlighted in this figure, detachment point can be anticipated at velocity around 2.1 m/s for all 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. Most interesting, however, is the onset of re-entrainment occurs at approximate 2 m/s in all three cases. A further point of interest is the knit and foam results converge at 5 m/s.

Conclusion

This work has examined the movement and re-entrainment of droplets in fibrous, knitted, and open-cell foam 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 in all three cases. Furthermore, it has been shown that knitted media produced largest re-entrainment and the fibrous media the least. 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 knitted media would be advantageous in many cases as they would readily settle under gravity.

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