INTRODUCTION

The air quality has become a very important environmental factor that decides the quality of human health and well-being. Today the air has become extremely polluted due to presence of numerous contaminants. The size of contaminants present in the air varies from a few micrometers to a few millimeters. The fibrous filter media are known to capture finer to coarser particles effectively, but the higher filtration efficiency is often associated with the higher pressure drop. This ultimately leads to reduction in the quality of the filter media. The mixed fibrous filter media composed of finer and coarser fibres improve the filter quality by optimizing the filtration efficiency and the pressure drop. In this study, a series of virtual three-dimensional mixed fibrous filter media were generated on computer by varying the percentage of finer and coarser fibres in the media. A structure generator based on the three-dimensional voxel model was used. The Stokes flow was computed to determine the permeability and the pressure drop characteristics of the filter media. The Lagrangian formulation of particle transport was used to simulate the filtration efficiency of the filter media at the most penetrating particle size. It was observed that the mixed filter media made from a specific mixing composition of finer and coarser fibres showed the highest quality factor.

Key Words: Air filtration, Mixed fibrous media, Simulation, Quality factor, Lagrangian formulation

ABSTRACT

The quality of human health and well-being can be improved by providing more healthy, comfortable and productive environment. Air quality is one of the prime concerns among many environmental factors as the air is highly polluted today due to presence of numerous contaminants. The size of contaminants present in the air varies from a few micrometers to a few millimeters. The fibrous filter media are known to capture finer to coarser particles effectively, but the higher filtration efficiency is often associated with the higher pressure drop. This ultimately leads to reduction in the quality of the filter media. The mixed fibrous filter media composed of finer and coarser fibres improve the filter quality by optimizing the filtration efficiency and the pressure drop. In this study, a series of virtual three-dimensional mixed fibrous filter media were generated on computer by varying the percentage of finer and coarser fibres in the media. A structure generator based on the three-dimensional voxel model was used. The Stokes flow was computed to determine the permeability and the pressure drop characteristics of the filter media. The Lagrangian formulation of particle transport was used to simulate the filtration efficiency of the filter media at the most penetrating particle size. It was observed that the mixed filter media made from a specific mixing composition of finer and coarser fibres showed the highest quality factor.

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INTRODUCTION

The air quality has become a very important environmental factor that decides the quality of human health and well-being. Today the air has become extremely polluted due to presence of numerous contaminants (particles). However, there are rising demands for purifying the environment and providing a more healthy, comfortable and productive climate in public areas, commercial buildings, vehicles and manufacturing facilities. It is observed that the air surrounding the human beings contains numerous particles of size varying from as small as 0.0001 micrometer to as high as 10000 micrometer. These particles can be separated from the polluted air stream with the help of air filtration techniques. There are many air filtration techniques available today such as oil bath, spray, cyclone, venturi scrubber, fibrous filtration, membrane filtration, to name a few. Of them, the use of fibrous filters in air filtration is growing exponentially due to their easy availability, complex pore geometry and low cost of manufacturing. These filters are produced by using the nonwoven technology. The products are quite diverse and range from HVAC filters to cabin air filters to HEPA filters, ULPA filters, swimming pool and spa filters, face masks, respirators, and blood filters.

The fibrous filters are sheets or webs made up of natural or/and manmade fibres which are bonded by mechanical or thermal or chemical means or combination thereof. On the one hand, they are soft, porous, and voluminous, but, on the other hand, they offer sufficient resistance to mechanical deformation. The random arrangement of fibres in the three dimensional space of the fibrous
filters makes the structure of the pores present inside more complex, resulting in higher probability of capturing of particles. But, at the same time, this provides higher resistance to the air passing through the fibrous filters, causing an increase in pressure drop. By using appropriate fibres and suitable manufacturing process, the structure of the filters can be designed such a way that the dust is loaded in the interior portion of the filters, rather than the dust is deposited only on the surface of the filters. This provides a low pressure drop across the filter, resulting in low running cost.\(^4\) The fibrous filter media are known to capture the airborne particles of different sizes due to Brownian diffusion, direct interception, inertial impaction, gravity settling, and particle sieving mechanisms. But, there are particles of around 0.3 micron diameter where the aforesaid mechanisms fail and the particles are found to be mostly penetrating through the filter media.\(^5\) These particles are known as most penetrating particles. To enhance the filtration performance of the fibrous filter media in the region of most penetrating particle size is recognized as a great challenge for research. The filtration performance of the fibrous filter media is characterized by filtration efficiency and air permeability characteristics. The filtration efficiency refers to the ability of filter media to prevent particles going from the upstream region to the downstream region and the air permeability refers to the ability of filter media to allow the air to pass through the thickness direction of the media. Often the filtration efficiency in conjunction with pressure drop of the filter media is expressed by a term called quality factor.\(^6\) It is known that the higher is the quality factor the higher is the filtration performance of the media. The fibres are the building block of the fibrous filter media. The fibres vary in their physical properties such as length, cross-sectional shape, and cross-sectional size. In most of the cases the fibres with circular cross-section are preferred to non-circular cross-section as the circular fibres are easy to manufacture and process. The size of the fibres is one of the most important factor that determine the filtration performance of the fibrous filter media. Numerous analytical, numerical and empirical studies have been conducted on the filtration performance of fibrous filter media comprising of either fine fibres or coarse fibres.\(^7\)\(^-\)\(^9\) Such fibrous filter media are known as single-component fibrous filter media. However, a great portion of fibrous filter media available today is made from a mixing of fine and coarse fibres.\(^10\)\(^,\)\(^11\)\(^,\)\(^13\) Such fibrous filter media are known as mixed fibre filter media. Till date a few research work has been done on the permeability, pressure drop and filtration characteristics of mixed fibre filter media. But, there is no research article available on the filtration performance of mixed fibre filter media at the most penetrating particle size. The present research work is directed to study the permeability and filtration behaviours of mixed fibre filter media in terms of the quality factor at the most penetrating particle size.

**AIMS AND OBJECTIVES**

The overall objective of this study is to investigate the air filtration behaviour of the mixed fibre filter media at the most penetrating particle size. The specific objectives of this study are to examine the air permeability, particle filtration, and quality factor of the mixed fibre filter media.

**MATERIAL AND METHODS**

In this work, a series of three-dimensional virtual fibrous filter media were generated on computer. This was done by using a structure generator that worked on the principle of three-dimensional voxel model. The polypropylene fibres of different finenesses were taken in different mass proportions as the building block of the virtual fibre filter media. The individual layers made from fibres were stacked one over another to achieve desired weight and thickness of the filter media. The solid volume fraction of all the filter media was kept at 0.05. The resulting three-dimensional structure of a virtual mixed fibre filter medium is displayed in Fig. 1. The Reynolds number of the three-dimensional virtual fibrous filter media was calculated and it was found to be less than unity. Therefore, the Stokes flow was found to prevail in these filter media. The Stokes flow was computed with periodic boundary condition across the filter media to determine the velocity of the air.
The permeability of the media were calculated by using Darcy’s law as stated below

\[ \frac{Q}{A} = k \frac{\Delta P}{\eta Z} \]  

(4)

where, \( Q \) is the volumetric flow rate; \( A \) is the cross-sectional area of the medium, \( \eta \) is the dynamic viscosity of air, \( \Delta P \) is the pressure drop over a thickness \( Z \) of the medium and \( k \) is the permeability of the medium. The air filtration simulations were carried out by Lagrangian formulation of particle transport that include Brownian motion, friction with the air, and inertia of particles due to mass. It was thought that the particles may collide with the fibres and stick due to adhesion or bounce off if they have enough energy or they may also be sieved by being stuck between three or more fibres. By iterating this procedure the filtration performance of the virtual filter media was evaluated. The filtration performance of the media is expressed as follows

\[ E = \frac{N_{\text{IN}} - N_{\text{OUT}}}{N_{\text{IN}}} \]  

(5)

where, \( E \) is the filtration efficiency, \( N_{\text{IN}} \) is the number of particles in the upstream and \( N_{\text{OUT}} \) is the number of particles in the downstream. Then the quality factor of the filter media was calculated as follows

\[ QF = \frac{- \ln(1 - E)}{\Delta P} \]  

(6)

where, \( QF \) is the quality factor, \( E \) is the filtration efficiency and \( \Delta P \) is the pressure drop across the thickness of the media.

RESULTS AND DISCUSSION

The air permeability characteristics of the virtual three-dimensional mixed fibrous filter media are plotted against the mass blend percentage of the finer fibres in the media in Fig. 3. It can be seen that the higher percentages of finer fibres led to lower permeability of the mixed fibre filter media. As the mass blend percentage of finer fibres in the media was increased, the total surface area occupied by the fibres in the media was also increased. The higher surface area occupied by the finer fibres in the media resulted in the higher resistance offered by the media against the flow of air. This resistance is known as drag.
resistance. Due to drag resistance the air permeability of the media was decreased with the increase of finer fibre percentage in the media. The mixed fibre filter media with higher percentage of finer fibres would need to overcome more drag resistance in order to maintain a constant flow velocity across the media. This ultimately led to increase in pressure drop across the media as shown in Fig. 4. Note that the pressure drop was the only driving force to maintain the flow of air across the media.

**Fig. 3**: Plot of air permeability of mixed fibre filter media

**Fig. 4**: Plot of pressure drop of mixed fibre filter media
The filtration behaviour of the two fibrous filter media made up of finer fibres (20 micrometer fibre diameter) and coarser fibres (50 micrometer fibre diameter) is displayed in Fig. 5. It can be observed that both the filter media were almost equally efficient to capture particle larger than 13 micrometer diameter. But the fibrous filter media composed of finer fibres were found to be more efficient in capturing smaller particles that the fibrous filter media composed of coarser fibres. This might be ascribed to the higher surface area of the finer fibres.

Fig. 5 : Plot of filtration efficiency of filter media made up of finer and coarser fibres

Fig. 6 shows the filtration efficiency of the mixed fibre filter media against the mass blend percentage of finer fibres in the media at the most penetrating particle size (0.3 micron). It is observed that the mixed fibre filter media having higher percentage of finer fibres showed more efficiency to capture the most penetrating particles. A similar observation would be made from the filtration behaviour of the fibrous filter media consisting of finer fibres as shown in Fig. 5.

Fig. 6 : Plot of filtration efficiency of mixed fibre filter media at most penetrating particle
Fig. 7 plots the quality factor of the mixed fibre filter media against the mass blend percentage of finer fibres in the media. It can be observed that as the mass blend percentage of the finer fibres was increased in the mixed fibre filter media, the quality factor was initially increasing, followed by a decrease in the quality factor. The mixed fibre filter media consisting of around 82% of finer fibres and 18% coarser fibres showed the highest quality factor among the all filter media studied in this work.

CONCLUSION

The fibrous filter media composed of finer fibres were found to be more efficient in capturing smaller particles than the fibrous filter media composed of coarser fibres, but the former filter media exhibits higher pressure drop than the latter filter media. The mixed fibre filter media were preferred to the filter media made from either fine fibres or coarse fibres to achieve low running cost and acceptable filtration efficiency. A mixed fibre filter medium composed of around 82% of finer fibres and 18% coarser fibres showed the highest quality factor among the all filter media studied in this work.

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REFERENCES


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The birds and bees and the flowers and trees are for everyone to see, but not to seize.

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**SAVE THE ENVIRONMENT**

- Good environment is good health
- Air pollution causes health hazards
- Recycle every drop of water