Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 1881~1885

Particle deposition in random fibrous porous materials: effect of acoustic fields, fibres distribution and porosity

Richardson Teixeira[1] and Antonio F. Miguel[1,2*]

[1]Geophysics Centre of Evora (CGE), Evora, portugal
[2]Department of Physics, University of Evora, Evora, portugal

(Manuscript Received May 7, 2007; Revised July 21, 2007; Accepted July 21, 2007)

Abstract

Porous filters are widely used to control air pollution and have different industrial applications since they constitute a reliable and low cost solution to separate particulate matter from an air stream.

In this study, the particle deposition within 3D porous filters subjected to low-frequency acoustic fields is studied following a numerical approach. Findings demonstrate that the application of acoustic waves enhances the deposition of particles, which in turn improves filter performance. It is shown that frequencies ranging from 200 to 1000 Hz (intensity 120 dB) increase particle deposition up to 2.5 times. Besides, the manner in which fibres are distributed in the porous material and the filter porosity affect considerably the number of particles deposited, for filters subjected to the same filtration velocity.

Keywords: Porous filter; Particle deposition; Acoustic field; Fibres distribution; Porosity

1. Introduction

Separation and removal of particles from a gas stream is a topic of relevance because of its impact in many natural and industrial systems [1-3].

There is evidence that deposition is enhanced by air humidity and the electrostatic charge of the filter media. Filters were found to be more efficient when operated at high humidity, except when dealing with hygroscopic particles at humidity above the deliquescent point [4]. The concept of electrostatically charging a filter media was applied since the first-half of the twentieth century. Ever since then, electrostatic filters have been used to enhance filter media efficiency [1, 5]. Recent experiments have indicated that acoustic waves may also influence the performance of fibrous filters [6]. Moreover, there is considerable experimental evidence that acoustic fields are effective in agglomerating aerosols through a process which produces rapid growth in particle size [7-9]. This can be explained by the fact that the propagation of high intensity acoustic waves through aerosols induces a particle motion, which results in collisions and leads to aerosol agglomeration.

This paper is devoted to the analysis of aerosol filtration under the influence of low-frequency acoustic fields in random fibrous filters. A numerical study was performed in order to learn about the effect of acoustic fields, the filter porosity and the influence of the manner in which fibres are distributed in the porous material on the particle deposition within the filter. The simulations were performed at Reynolds numbers lower than one that is the usual range in filtration processes [1-3].

*Corresponding author. Tel.: +351266745372, Fax.: +351266745394
E-mail address: afm@uevora.pt

2. Problem definition and numerical method

The simulations were conducted in three-dimensional filter models shown schematically in Fig. 1. These models consisted of filters composed by cylindrical fibres with porosities ranging from 0.5 to 0.95. For each of the porosities, four random fibrous structures were generated by using a similar procedure as that developed by Koponen et al. [10]. This is largely justified because in the production process fibres are arranged randomly [11].

Computational simulations of the flow of suspensions of particles in the geometries depicted in Fig. 1 were performed by using the commercial finite-volume-based program *Fluent* [12]. In this study, we consider that the flow of air (density 1.2 kg/m^3 and viscosity 15.1x10^{-6} m^2/s) through filters is laminar (Reynolds numbers of 0.05 and 0.1). This is within the usual range of operation of filters [1-3].

There are two important aspects of particle transport and deposition simulations: the motion of the particles in the fluid and the treatment of the interaction of the particles with the fibres.

The first aspect is dealt with the solution of a differential equation for the particle motion. It is considered that particles do not influence the airflow and that particles do not collide with other particles. This is only valid under the assumption that there is a very low concentration of aerosols in the flow and that the particles are small enough. In the presence of an acoustic field, we also consider that the secondary acoustic forces are negligible. Therefore, the motion of a particle is described by [13, 14]

$$\frac{du_p}{dt}=\frac{1}{\rho_p}\left[F_B-F_D\left(u-u_p\right)+F_a\right] \tag{1}$$

where u_p is the particle velocity, u is the fluid velocity, ρ_p is the particle density, $F_D(u-u_p)$ is the drag force

Fig. 1. Schematic representation of two of the four random porous materials used in this study.

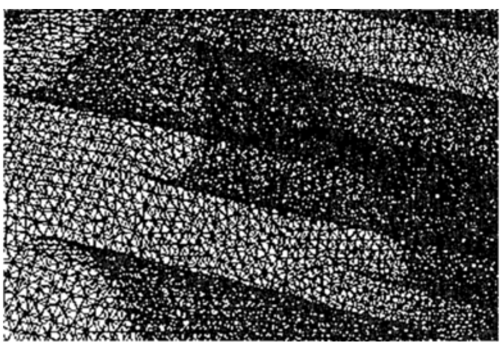

Fig. 2. Detail of the grid for the fibrous porous materials.

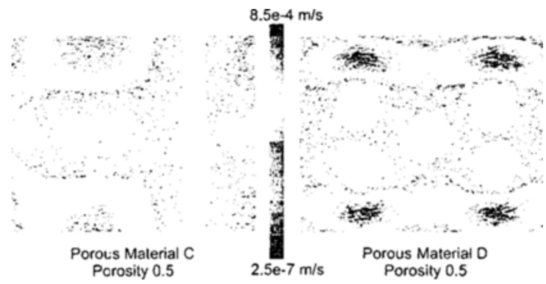

Fig. 3. Detail of the velocity contours of the air within fibrous porous materials C and D.

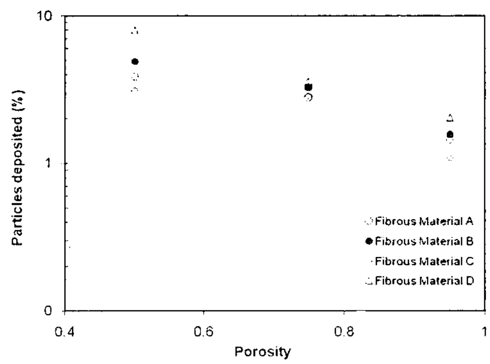

Fig. 4. Particles deposited within the porous material versus porosity in absence of acoustic fields (Re=0.05).

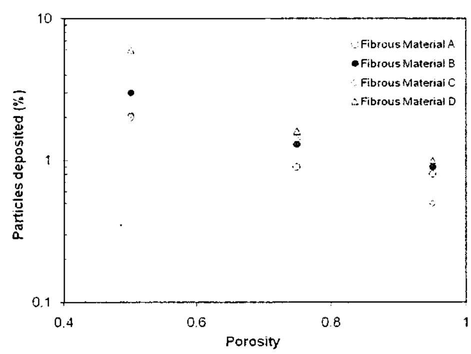

Fig. 5. Particles deposited within the porous material versus porosity in absence of acoustic fields (Re=0.1).

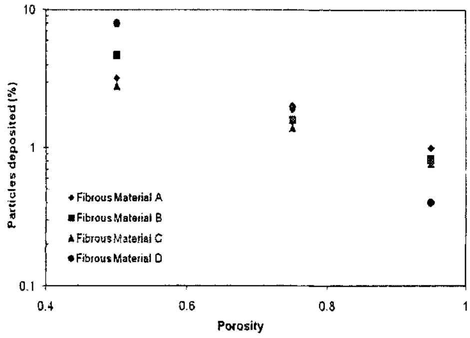

Fig. 6. Particles deposited within the porous material versus porosity in the presence of an acoustic field with intensity 120 dB and frequency 200 Hz (Re=0.1).

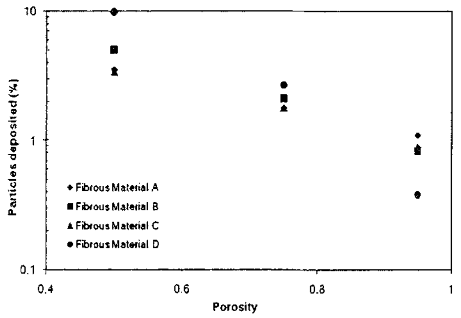

Fig. 7. Particles deposited within the porous material versus porosity in the presence of an acoustic field with intensity 120 dB and frequency 500 Hz (Re=0.1).

[13-15], F_B represents additional forces such as lift force due to shear, the force due to the pressure gradient in air and the Brownian force [2], and F_a is the acoustic force as defined as the gradient of the acoustic potential, described in detail by Barmatz and Collas [16] and by Song [17].

Based on Eq. (1), particle motion can be computed at each point in space, and these motions can be integrated to predict particle trajectories.

In this setup, particles touch a fibre and stick to it at first collision. However, there are more advanced models of inelastic collision and adhesion forces between fibres and particles [18].

Particles of specific size (density 2250 Kg/m^3, diameter 10 μm) are introduced in an uniform distribution at the inlet of geometries depicted in Fig. 1, and tracked through the geometries until they are trapped in the wall of the fibres or escape through the outlet of the filter. CFD simulations were performed with no acoustic forces (F_a=0) and in the presence of an acoustic field (intensity 120 dB, frequencies

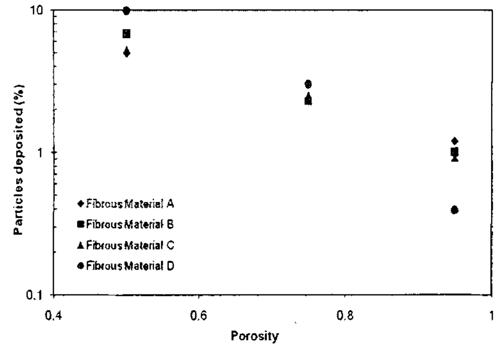

Fig. 8. Particles deposited within the porous material versus porosity in the presence of an acoustic field with intensity 120 dB and frequency 1000 Hz (Re=0.1).

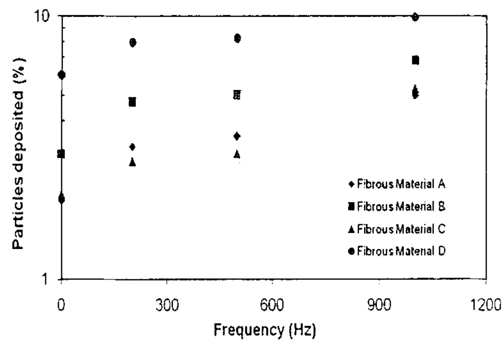

Fig. 9. Particles deposited within the porous material (porosity 0.50, Re=0.1) versus frequency of the acoustic field (intensity 120 dB).

ranging from 200 to 1000 Hz).

3. CFD solution

Computational simulations of the flow in the geometry depicted in Fig. 1 were performed by using non-slip boundary conditions set along the geometry. The developed velocity profile is prescribed at the inlet while outflow boundary conditions are set at the exit.

The accuracy of our numerical simulations was validated with respect to refinement and spatial resolution of the CFD grid based on the methodology proposed by Roache [19] and Sidi [20]. Grids with 10300 – 570000 quadrilateral cells and 21000 - 104000 nodes are found to be appropriate for the present study (Fig. 2). Solutions were obtained for laminar flow (Reynolds numbers of 0.05 and 0.1) and convergence took about 700 iterations.

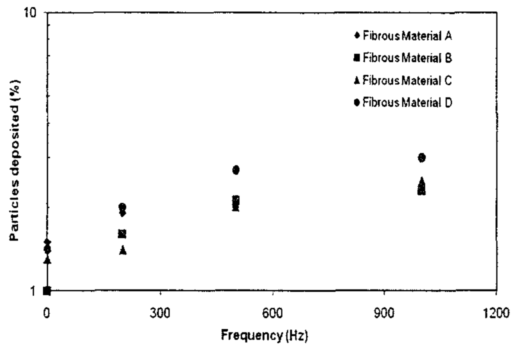

Fig. 10. Particles deposited within the porous material (porosity 0.75, Re=0.1) versus frequency of the acoustic field (intensity 120 dB).

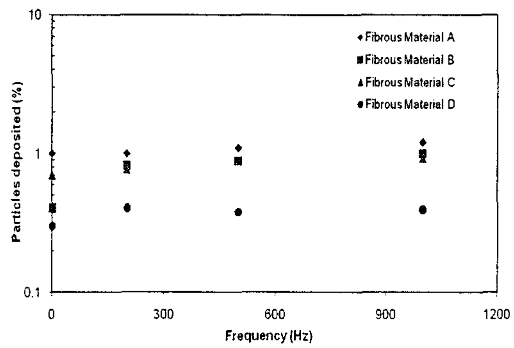

Fig. 11. Particles deposited within the porous material (porosity 0.95, Re=0.1) versus frequency of the acoustic field (intensity 120 dB).

4. Results and discussion

CFD simulations were performed both in the absence and in the presence of an acoustic field.

First, a numerical study was performed in order to determine the influence of the fibres' distribution on the air velocity field inside the fibrous materials without acoustic fields. The results of our simulations have been compared for filters with the same porosity and subjected to similar inlet conditions. The velocity field within filters with different fibres distribution (porosity 0.5) is represented in Fig. 3 as a contour map. This figure shows that although the inlet velocity and the filter porosity are the same, the velocity contours inside the filter are different. These differences may influence the deposition of particles and were also studied. The results of this study are presented in Figs. 4 and 5 for an initially unloaded filter (clean filter). For the particle size under study (10 μm), the plots show that the way how the fibres are arranged inside the material has an important effect on the deposition of particles. This is because the distribution of fibres in the filter affects the deposition mechanisms such as the inertial impaction and the direct interception [1, 25]. In addition, the deposition of particles decreases with the porosity and the Reynolds number, which is in agreement with [1-3].

To evaluate the effects of acoustic fields on particle deposition, a CFD simulation was also performed for fields with an intensity of 120 dB and frequencies ranging from 200 to 1000 Hz. The effect of the presence of an acoustic field on the particle deposition in filters with different random fibre distributions and porosities is depicted in Figs. 6-8 for an initially unloaded filter (clean filter). These results lead us to conclude that particle deposition is still strongly dependent on the porosity and the fibre distribution inside the porous material. This dependence is similar to that obtained in the absence of acoustic fields (Figs. 4 and 5).

The influence of the frequency of the acoustic field on particle deposition is presented in Figs. 9-11. These plots show that the particles' deposition within the fibrous filters is strongly dependent on the acoustic frequency. For all the porosities studied, there is a marked increase of aerosol deposition with frequency. The curves flatten out above well-defined frequencies, which are characteristic of each of the porosities tested. For fibrous filters with high porosity the curves flatten out at lower frequencies (i.e., for a porosity of 0.50 the curve flattens out for frequencies close to 1000 Hz but for a porosity 0.95 the curve flattens out for frequencies close to 200 Hz). This is a result of high practical relevance.

5. Conclusion

The CFD modelling approach is a very useful tool for studying particle deposition in filters. In this paper, we studied how suspended particles flowing through a random porous filter respond to an acoustic field. Among other results, this study indicates that the capture of particles is not only strongly dependent on the frequencies employed (frequencies of 200 to 1000 Hz for an intensity 120 dB were tested) but also on the filter porosity and the fibre distribution inside the porous material. These results provide useful insight into the operation of acoustic filtration devices.

Acknowledgement

This work is a part of the project supported by the Foundation for the Science and Technology (FCT) (project POCTI/EME/59909/2004).

References

[1] K. R. Spurny (Ed.), *Advances in Aerosol Filtration*, Lewis Publishers, Chelsea, (1998).

[2] A. Bejan, I. Dincer, S. Lorente, A. F. Miguel, A. H. Reis, *Porous and Complex Flow Structures in Modern Technologies*, Springer-Verlag, New York, (2004).

[3] A. F. Miguel, A. H. Reis, Transport and deposition of fine mode particles in porous filters, *Journal of Porous Media.* 8 (2006) 731-744.

[4] A. F. Miguel, Effect of air humidity on the evolution of permeability and performance of a fibrous filter during loading with hygroscopic and non-hygroscopic particles, *J. Aerosol Science.* 34 (2003) 783-799.

[5] A. F. Miguel, Porous media and filtration. In: "*Emerging Technologies and Techniques in Porous Media*", D. B. Ingham, E. Mamut, I. Pop (editors), Kluwer Academic Publishers, (2004) 419-431.

[6] L. Moldavsky, M. Fichman, C. Gutfinger, Enhancing the performance of fibrous filters by means of acoustic waves, *J. Aerosol Science.* 37 (2006) 528-539.

[7] D. T. Shaw, K. W. Tu, Acoustic particle agglomeration due to hydrodynamic interaction between monodisperse aerosols, *J. Aerosol Science.* 10 (1979) 317-328.

[8] E. Riera, J. A. Gallego, Ultrasonic agglomeration of micron aerosols under standing wave condition, *J. Sound Vib.* 110 (1986) 413-427.

[9] G. Funcke, A. Frohn, Investigation of the influence of different parameters on the acoustic agglomeration process using a numerical simulation, *J. Aerosol Science.* 26 (1995) 147-148.

[10] A. Koponen, D. Kandhai, E. Hellné, M. Alava, A. Hoekstra, M. Kataja, K. Niskanen, P. Sloot, J. Timonen, Permeability of threedimensional random fiber web, *Phys. Rev. Lett.* 80 (1998) 716-719.

[11] N. P. Vaugham, R. C. Brown Observations of the microscopic strcture of fibrous filters, *Filtration and Separation.* 33 (1996) 741-748.

[12] FLUENT 6 User's Guide, Fluent Inc. (2003).

[13] M. Aydin, G. Balik, A. F. Miguel, A. H. Reis, Some features of flow and particle transport in porous structures, *J. Mechanical Engineering.* 51 (2005) 495-500.

[14] A. F. Miguel, A. M. Silva, Particle deposition onto a flat plate with various slopes, *Journal of Aerosol Science.* 34 (2003) 667-668.

[15] M. Aydin, A. F. Miguel, A. H. Reis, Numerical particle transport in partitioned room, *WSEAS Transactions on Fluid Mechanics.* 4 (2006) 327-331.

[16] M. Barmatz, P. Collas, Acoustic radiation potential on a sphere in plane, cylindrical, and spherical standing wave fields, *J. Acoustical Society of America.* 77 (1985) 928-945.

[17] L. Song, Modeling of Acoustic Agglomeration of Aerosol Particles, Ph. D. thesis, The Pennsylvania State University, (1990).

[18] A. Bejan, S. Lorente, A. F. Miguel, A. H. Reis, Along with Constructal Theory, UNIL/FGSE Workshop series n° 1 (Hernandez & Cosinschi, editors), Lausanne University Press, Lausanne, (2006).

[19] P. J. Roache, Verification and Validation in Computational Science and Engineering, Hermosa Publishers, Albuquerque, (1998).

[20] A. Sidi, Practical Extrapolation Methods: Theory and Applications, Cambridge Monographs on Applied and Computational Mathematics, Cambridge, (2002).