

Thesis Title: Numerical and Experimental Investigation of the Particle Filtration Behaviour of a Single Fibre and Fibrous Air Filters

Student: Utsav Bhardwaj (2020QIZ8865)

Abstract

To mitigate the adverse effects of airborne particulate matter, nonwoven fibrous air filter media are increasingly used, particularly in regions with poor air quality where rapid clogging of filtration systems is common. Optimizing filter performance remains a complex challenge due to multifaceted interactions between air, particles, and filter media. This research investigates the behavior of airborne inertia-dominated particles in fibrous filter media, focusing on the influence of various filter-based parameters and operating conditions on particle deposition morphology, dust holding capacity, and filtration performance. The filtration performance parameters include particle capture efficiency, pressure drop, and quality factor. The filter-based governing parameters considered are the through-plane fibre orientation, segmental aspect ratio of fibres, fibre material, fibre diameter distribution, fibre volume fraction, and filter thickness. On the other hand, the operating conditions considered are the face velocity, particle size distribution, and dust feed rate. The study employs both computational and experimental methods, combining the two/three-dimensional numerical simulations of particle capture by a single fiber-segment with the full-scale filtration experiments on filter media in order to understand the filtration phenomena at an elementary as well as a realistic scale. The lattice Boltzmann method (LBM), coupled with Lagrangian approach for two-dimensional simulations and discrete element method (DEM) for three-dimensional simulations, has been employed for numerical modeling and simulations.

For inertia-dominated particles, it has been found that an optimum through-plane orientation, as well as an optimum segmental aspect ratio, exists for fibres at which the quality factor is highest. The optimum through-plane fibre orientation lies around 20° - 25° for low segmental aspect ratios of a fibre whereas 35° for higher ones tested in the present study, and it is independent of the Stokes number. For the presented set of parameters, the optimum segmental aspect ratio of a fibre is found as “2”. The interplay between particle diameter and face velocity is such that despite the Stokes number and fibre-based Reynolds number remaining constant, different pairs of particle diameter and face velocity can exist, yielding substantially different particle deposition morphologies and filtration performance parameters during the initial stages of filtration. At a given Stokes number and fibre-based Reynolds number, large particles injected at a low face velocity can be captured with a better overall filtration performance compared to the small particles injected at a high face velocity, where these two combinations are equivalent in terms of inertia-dominated particle capture. A low dust feed rate is found to facilitate depth filtration alone to a great extent of the dust loading of filter media, whereas a higher dust feed rate leads to an earlier transition (partial) to surface filtration. The surface coverage of dust cake increases with rise in dust feed rate and face velocity, but it decreases with rise in fibre diameter. The dust holding capacity (*DHC*) of filter media decreases until fibre diameter is increased to a certain extent, which is attributed to the associated reduction in

the specific surface area of fibres. However, *DHC* increases with further increase in fibre diameter, which is attributed to the dominant influence of the associated increase in mean pore size.

An optimum face velocity for particle capture is found to exist, at which the cumulative particle capture efficiency is maximum. The optimum face velocity has been found to decrease with rise in particle diameter, but it increases with rise in fibre diameter and dust feed rate. The optimum face velocity is also conjectured to increase with enhancement in particle-fibre adhesion forces, filter thickness, and fibre volume fraction. When any operating condition varies during the filtration process, the cumulative filtration performance parameters are found to depend on the sequence in which the concerned operating condition varies. For example, if dust concentration in a given space changes due to nearby activities (such as smoke generation, windstorm, rainfall, or operation of another air filter), or if an air filter is relocated to a room of different size or to an environment with lower/higher pollution level, the filtration flow rate would need to be adjusted, which in turn alters the face velocity. In such a case, the cumulative particle capture efficiency, coverage of dust cake, and pressure drop are higher if a higher face velocity follows a lower one, compared to the respective quantities obtained when the same lower face velocity follows the higher one.

This research provides valuable insights for optimizing filter design and operation, contributing to improved filtration performance, energy efficiency, and extended service life in a wide range of applications.

Keywords

air pollution, particles, nonwoven fibrous air filters, air filtration, particle deposition morphology, particle capture efficiency, pressure drop, quality factor, depth filtration, and dust cake