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Transport analysis and model for the performance of an ultrasonically enhanced filtration process

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Abstract

This paper presents an analysis of a filtration technique that uses ultrasound to aid the collection of small particles (tens of microns in diameter) from suspension. In this method, particles are retained within a porous mesh that is subjected to a resonant ultrasonic field, even though the pore size of the mesh is two orders of magnitude greater than the particle diameter. The role of acoustic forces in driving the retention phenomena has previously been studied on a micro-scale, which included modeling and experimental verification of particle motion and trapping near a single element of the mesh. Here, we build on this work to develop an overall transport model to predict macroscopic performance criteria such as breakthrough times and the dynamics of the filtration performance. Results from this model compare favorably to experimental studies of the filtration phenomena; simulation results scale appropriately with experimental results in which inlet feed concentration and flow rate are varied.

Keywords: Filtration; Mathematical modeling; Particle; Porous media; Separations; Ultrasonic processing

1. Introduction

A process for the filtration of small suspended particles using a high-porosity polyester mesh situated in a resonant ultrasonic field has been reported recently (Gupta and Feke, 1997, 1998; Wang et al., 2004). A schematic of this filtration concept is depicted in Fig. 1. Shown is a rectangular chamber in which the polymer mesh is sandwiched between a piezoelectric transducer and a glass reflector. As suspension flows through the mesh when the sound field is active, small particles are entrapped even though the pores of the mesh are approximately two orders of magnitude larger than the particle diameter. Upon deactivation of the acoustic field, the particles are released from the mesh.

The basis for the particle entrapment arises from complex interactions between the mesh, the acoustic and hydrodynamic flow fields, and the particles themselves. The acoustic field, scattered from the mesh elements, results in acoustic forces that attract particles toward the collector. The relevant transport phenomena active on the length scale of the particles been modeled and experimentally verified. This microscale analysis focuses on the motion of individual particles in the vicinity of one collection element comprising the mesh (Grossner et al., 2003, 2005). While this single-collector model is an excellent tool to understand the underlying fundamental phenomena active in the acoustic filtration process, it alone is not sufficient to predict the macroscopic performance of such a filter system. Here, we seek to develop a model that combines information from the single-collector studies and properties of the overall filtration system that leads to predictions of important process characteristics such as particle breakthrough times and the general retention performance of the acoustic separator.

An approach taken by investigators of high gradient magnetic separation (HGMS) provides the starting point for this analysis (Gerber and Birss, 1983). In HGMS, a steel mesh (similar to steel wool) is magnetized to collect small

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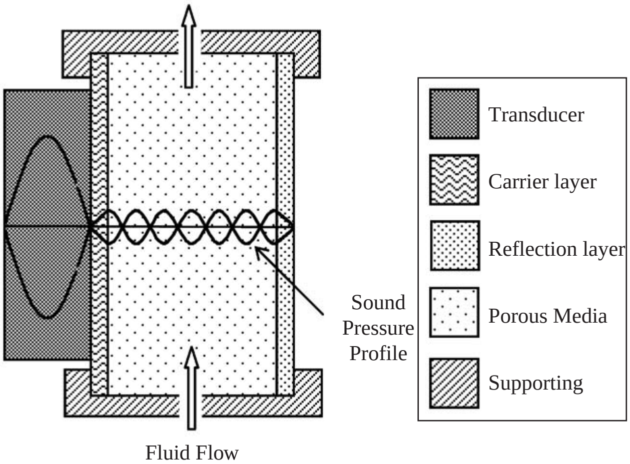

Fig. 1. A schematic of the acoustic filtration process.

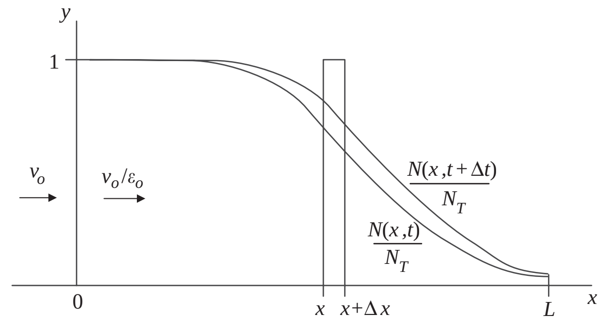

Fig. 2. Schematic depicting the coordinate system used for the model. The suspension flows (superficial velocity v_0) into the mesh (porosity ε_0) at $x = 0$ and exits at $x = L$; N_T is the concentration of captured particles at saturation. The temporal variable is t.

magnetically susceptible particles from a suspension. This process has been examined microscopically (Gerber and Birss, 1983) in a similar manner as the acoustic separation process in this research. Once a capture radius has been defined for a single collector (akin to the "capture window" discussed in a previous paper (Grossner et al., 2003)), a multi-collector model is assembled to form a model of the entire separator (Gerber and Watmough, 1982).

In this paper, we extend this approach to derive a performance model for the acoustic filtration process. Numerical simulations of the model provide predictions of the spatial and temporal evolution of the concentration of particles captured within the mesh. These model results are further compared to the results of experiments in which macroscopic performance parameters, such as particle breakthrough times, are reported.

2. Derivation of the transport model

2.1. Coordinate system and important parameters

The overall operation and performance of the filtration device is modeled on the basis of a conservation relation for the suspended particles. Consistent with the configuration within the experimental trials, the model assumes dependence on only one spatial variable. A schematic with coordinate system definitions are presented in Fig. 2. The chamber has length L in the flow direction and a cross-sectional area of S. The independent variable in the flow direction is x. Due to the presence of the mesh, the convective flow is taken to be a one-dimensional plug flow with superficial velocity v_0.

Two variables are used to describe the spatial and temporal distribution particles within the chamber. First, $C(x, t)$ is used to denote the concentration of particles in free suspension (not trapped within the mesh), and has units of the number of particles per volume of fluid. The variable $N(x, t)$ denotes the particle retention density, or number of trapped particles per unit volume of the mesh, and N_T is used to indicate the saturation value of N inside a particular mesh. With the concentration of the entering suspension fed to the mesh $C(0, t)$ specified as a boundary condition and the initial loading of the mesh $N(x, 0)$ specified as an initial condition, the model intends to predict how C and N change with position and time during operation of the filtration process.

2.2. Particle conservation model

A material balance for a differential section of the mesh is used as the basis for a model relating C and N to position and time. Since the particles are presumed to be relatively large (tens of microns), diffusion is neglected. We also assume that the mesh has a uniform porosity ε_0 throughout. As particles become trapped, the free volume within the mesh decreases. However, in the experimental trials, ε_0 is high (typically 95 vol%) and solids loading within the mesh is typically below 10 vol%. Thus, we use the single parameter ε_0 to approximate the mesh porosity throughout the course of the particle collection process. A material balance on particles with the mesh is then

$$\frac{\partial}{\partial t}(N + \varepsilon_0 C) + v_0 \frac{\partial C}{\partial x} = 0. \tag{1}$$

To close this model, an expression relating the conversion of free to trapped particles (the functional relationship between N and C) must be developed. Our previous microscale analysis of the efficiency of individual collectors to capture suspended particles provides the basis for this relationship. Here, we extend the results of the single-collector analysis to apply to the multiple collectors present within the actual mesh.

The ability of an individual collection element to capture particles can be quantified in terms of a capture window (Grossner et al., 2003). This is the area, upstream from the collectors, defined such that particles that flow through this window eventually become associated with the collector element. Particles that do not flow though the upstream capture window will flow around the collector. The single-collector