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Discrete simulation of fluid dynamics

Finite-difference lattice Boltzmann simulation on acoustics-induced particle deposition

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ABSTRACT

Particle manipulation by acoustics has been investigated for many years. By a proper design, particle deposition can be induced by the same principle. The use of acoustics can potentially be developed into an energy-efficient technique for particle removal or filtration system as the pressure drop due to acoustic effects is low and the flow velocity is not necessary to be high. Two nonlinear acoustic effects, acoustic streaming and acoustic radiation pressure, are important. Acoustic streaming introduces vortices and stagnation points on the surface of an air duct and removes the particles by deposition. Acoustic radiation pressure causes particles to form agglomerates and enhances inertial impaction and/or gravitational sedimentation. The objective of this paper is to develop a numerical model to investigate the particle deposition induced by acoustic effects. A three-step approach is adopted and lattice Boltzamnn technique is employed as the numerical method. This is because the lattice Boltzmann equation is hyperbolic and can be solved locally, explicitly, and efficiently on parallel computers. In the first step, the acoustic field and its mean square fluctuation values are calculated. Due to the advantage of the lattice Boltzmann technique, a simple, stable and fast lattice Boltzmann method is proposed and verified. The result of the first step is input into the second step to solve for acoustic streaming. Another finite difference lattice Boltzmann method, which has been validated by a number of flows and benchmark cases in the literature, is used. The third step consists in tracking the particle's motion by a Lagrangian approach where the acoustic radiation pressure is considered. The influence of the acoustics effects on particle deposition is explained. The numerical result matches with an experiment. The model is a useful tool for optimizing the design and helps to further develop the technique.

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1. Introduction

In most of the filtration and aerosol removal systems, particles are removed from the main air stream by deposition. For example, separators such as cyclones use external centripetal forces to displace particles from the main air stream, which are collected by deposition due to inertial impaction. In a filter, fibers introduce sudden changes in the airflow velocity and the particles are deposited onto them by interception and impaction. In these systems, either a high airflow velocity

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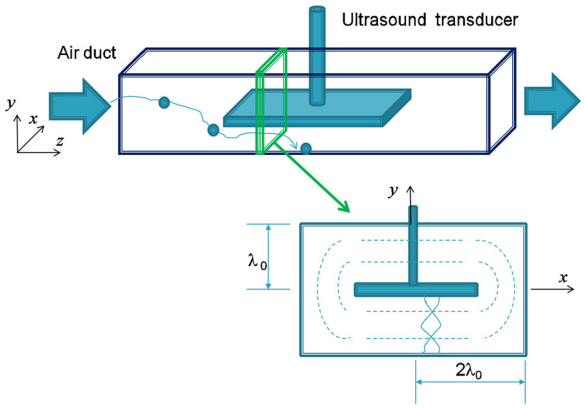

Fig. 1. (Color online.) Schematic diagram of the proposed filtration system.

is used or a high-pressure drop is required to be overcome, resulting in high energy consumption [1–3]. Recently, by using nonlinear acoustic effects, an innovative aerosol removal technique without high-pressure drop or high airflow velocity has been proposed, which has the potential to be developed into an energy efficient aerosol removal technique [4].

In the experiment carried out in [4], an ultrasonic transducer that generated an acoustic field was installed in an air duct. Particles were deposited and removed from the air stream by deposition onto the wall of the channel when passing through the air duct. By defining the removal efficiency as the number of particles removed with and without acoustic effects, the experiment shows that the removal efficiency increases by 20–30% by turning on the ultrasound transducer. Two nonlinear acoustic effects—acoustic streaming and acoustic radiation pressure—were studied and were accountable for the enhancement of the deposition. Acoustic streaming [5,6] causes vortices and enhances inertial impaction. Acoustic radiation pressure enhances deposition and sedimentation by encouraging particles to agglomerate and grow in size [7–9]. Although the experimental results give evidences to support the contributions of the two nonlinear effects, details of the flow and the particle dynamics are complicated in the acoustic field and cannot be revealed due to the limited precision of the existing experimental techniques. It is desirable to develop a mathematical model to further study the physics behind. A successful model also helps to optimize the design, so that an energy-efficient filtration technique can be developed.

Lattice Boltzmann method (LBM) has been developed into an alternative and a promising numerical scheme for the modeling of fluid physics and simulating fluid flows [10–12]. The equation is hyperbolic and can be solved locally, explicitly, and efficiently on parallel computers. Many versions of LBM have been developed for being applied to different kinds of flows with varying degrees of success. Recently, the finite-difference lattice Boltzmann method (FDLBM) proposed and developed by Fu et al. [13] provides a convenient algorithm for setting the boundary condition. Also, it eliminates the inherent compressibility effect of the conventional LBM [14]. The method is capable of simulating a number of flows including microchannel flow [13], stochastic flow [15], thermal incompressible flows [16], blood flow with complex boundary [17], natural convection with magnetic field effect [18], double diffusive mixed convection [19] and non-Newtonian flows [17–19].

The objective of this paper is to develop a numerical model to investigate particle deposition induced by acoustic effects in a duct flow. Since the study involves particle dynamics and two acoustic effects that are nonlinear and second order, a three-step approach is employed. Firstly, the acoustic field is found by solving the linear wave equations. A new LBM for the wave equations is proposed and verified. By using the mean square values of the acoustic field, acoustic streaming is determined in step two. The numerical method employed in this second step is the FDLBM by [13]. The ability of the FDLBM in applying to acoustic streaming is also demonstrated. After obtaining the flow pattern, the trajectory of a large number of particles are traced by a Lagrangian approach in step three. The acoustic radiation pressure is incorporated into the force balance equation of the particle dynamics.

2. Methodology

The schematic diagram of the proposed filtration system is shown in Fig. 1. It is essentially an air duct installed with an ultrasound transducer. The frequency of the ultrasound is 30 kHz and the wavelength (λ_0) is 0.011 m. The height (y-direction) of the duct is $2\lambda_0$ and the width (x-direction) of the duct is $4\lambda_0$. In this setting, standing waves with two pressure nodes between the transducer and the channel wall together with complicated sound field at the edge of the transducer are generated. Due to the acoustic effects, the particles entering the duct are encouraged to deposit onto the walls of the channel. The region affected by the ultrasound is assumed to be long, so that it is adequate to carry out a 2-dimensional simulation in x–y plane. The duration of particles in the region is the length (z-direction) of the transducer (20 cm) divided by the air flow velocity (0.2 m/s) and it is about 1 s.

Since the two acoustic effects are second-order effects, the simulation is divided into three steps. Firstly, the linear wave equations are solved to find the mean square fluctuations of the sound field. By using the mean square values of the sound

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