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Rayleigh type streaming effect on magnetohydrodynamic characteristics of fluidized bed particles

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ABSTRACT

We developed and implemented a theory, involving the propagation of a wave in a magnetic field for boundary layer analysis of flow structures. Our investigation revealed that the position of nodes in a standing wave is a function of the applied magnetic field. Hence, an approximate solution to the acoustical wave problem near a rigid wall was derived using the perturbation theory. Our results revealed that the velocity of the steady flow outside the boundary layer was independent of viscosity but was dependents on magnetic field. The practical implication of the derived result has been presented by discussing one illustration: a case in which an external standing wave is imposed in the transverse direction with respect to the main flow. The flow may be described using the three non-dimensional parameters. Streamline behavior was plotted for the volumetric flow rate analysis of the problem.

1. Introduction

Fluidized beds are used in the processing industry as an efficient contacting method to promote heat/mass transfer between a fluid and a solid. The main characteristics of the instabilities [17], Table 1 take the form of rising and growing voidage fluctuations whose propagations characteristics are related to the particle size.

The application of an external magnetic field and a sound wave to a ferromagnetic particle bed considerably alters its fluidization behavior. The application of a magnetic field to beds of ferromagnetic particles induces cohesive forces between the particles and imposes anisotropy in their arrangement along the field lines [1]. The influence of an external field depends on both the intensity and orientation of the magnetic field [2]. The magnetic effect can be used either to promote stirring or generate stabilization. Magnetic fluidized beds consisting of magnetically susceptible particles are considered one of the technologies developed for eliminating the drawbacks of fluidized beds. Imposing a magnetic field on a bed of magnetized particles suppresses or delays bubbling of these particles. This technique is commonly used in various applications, including the combustion of solid fossil fuels [3], methane-carbon dioxide catalytic reforming [4], and in separation processes, such as magnetic-nonmagnetic dust-filtration, ion exchange, adsorption [5], copper cementation [6–7], yeast filtration [8], particle separation based on density and magnetic properties [9–10], gas separation [5], and ethanol fermentation [11].

An acoustic standing wave in a fluid adjacent to a vibrating solid wall results in acoustic streaming and the chronological account of the available literature on this phenomenon begin with analysis in a uniform duct by Lord Rayleigh [12]. This work was continued by Schlichting [13] and many other researchers. A stream passing through a magnetic field generates a current which produces a body force on the fluid. Dynamic processing through fluidization implies the presence of some inter-particular forces [14], caused by the small dimensions of the particles. For compensating these inter-particular forces, the use of a magnetic field in the presence of acoustic streaming was investigated. Determining the most crucial parameters of Rayleigh – streaming - modeled granulated fluidized media in the presence of a magnetic field, with major emphasis on the adsorption process, is necessary. Acoustic streaming basically consists of the generation of a rotational fluid flow around solid objects in the presence of an acoustic field. The oscillations of a solid, otherwise at rest in a viscous fluid also causes acoustic streaming. A large number of theoretical and empirical works have demonstrated that acoustic streaming notably enhances the transfer of heat and mass between a fluid and solid. However, acoustic streaming effects are reported in a large variety of processes performed under different conditions, ranging from large - sized industrial - scale reactors to the micron – sized scale of the lab – on – a - chip application. A few examples are observed in combustion and other pyrometallurgy reactions, CO2 capture; liquid drops evaporation and regeneration, and liquid and powder mixing. Acoustic streaming effects are also observed in biological mechanisms in the streaming motions generated by cochlear traveling waves in the ear. These effects can play a part in the process of transduction by inner hair cells.

Bubble motion describing fluidized bed were the main focus of attraction from 60s. Many ideal models were solved mathematically to demonstrate the acoustic streaming phenomena. Davidson and Harrison [24] studied mainly the bubble motion system instability and

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Table 1
Magnetically stabilized bed advantages.
(Adapted from Rosensweig [18].)

	Fluidized bed	Stabilized bed	Fixed bed
Small particle size with low pressure drop	Yes	Yes	–
Yields high contacting efficiency	–	Yes	Yes
Avoids solids entrainment	–	Yes	Yes
Prevents solids back mixing and fluid bypassing	Yes	Yes	–
Continuous solids throughput if desired	Yes	–	–
Good heat transfer	Yes	–	–

mass transfer. Chararie and Grace [27] have compared the mathematical results for model of catalytic decomposition of ozone in a fluidized bed with the experimental results. Tarelho [26] studied numerically the control of gaseous emissions during coal combustion in a fluidized bed. Pain CC et.al [25] have investigated fluidized bed dynamics in 2-D geometries, numerically. Savage [23] investigated numerically and theoretically the vibration induced flow and mixing of dry granular materials. Jinnshah et al. [20] have studied a standing wave thermoacoustic refrigerator made of readily available materials. Ajay et al. [19] have studied the mapping of acoustic streaming in sonochemical reactors theoretically and experimentally. Garnavi et al. [21] have studied mathematically a continuous fluidized bed dryer. The simulation results show an improvement to the prediction of other models that considers uniform size bubbles. Wang et al. [22] have studied mathematical model of heat and mass transfer of fluidized- bed drying of porous material. Vainshtein et al. [16] have proved that acoustic streaming results in marked enhancement of heat transfer between parallel plates.

The abovementioned survey indicates that in most of cited literature, the formation of acoustic streaming in magnetized fluidized bed is not modeled mathematically in most of studies given in literature. The aim of this manuscript is to analyze the behavior of magnetized fluidized beds under the influence of sound waves, which may produce an intense streaming motion of the fluid near the solid boundary, which is *acoustic streaming*. A main feature of sound - assisted fluidized beds is that acoustic streaming on a solid surface is superposed to fluidized gas flow which gives rise to a wide range of possible phenomena depending on the intensity and frequency of sound, properties of particle and gas, velocity of fluidizing gas and size scale. Section 2 of the present manuscript provides a mathematical formulation for the problem of Rayleigh - type acoustic streaming through a fluidized bed. On the basis of our formulation, the main characteristics of acoustic streaming to be expected of particles of the sizes typically used in fluidized beds are derived mathematically in Section 2.1. Section 2.2 pertains to quantifying the attenuation of sound intensity in fluidized beds, which may be results diverse mechanisms, critically dependent on experimental parameters such as sound frequency and particle size. Provided the particles are unmovable by the sound wave, in Section 2.3, the enhancement of mass transfer induced by acoustic streaming are evaluated by means of introduced dimensionless numbers. Section 4 focuses on the conclusions.

2. Formulation of the problem

In this section we mainly focused on the mathematical formulation of the flow induced in the fluidized bed because of magnetic interaction and the oscillatory motion of an acoustic wave with a small amplitude, on the lines of Landau and Lifschitz [17]. The velocity of the wave is small because the oscillations are small; thus in the equation of motion, the quadratic terms have been neglected. On steady solution, we superpose a small perturbation (due to oscillation) and can re-write the variables pressure and density in the following form:

$$p = p_0 + p', \rho = \rho_0 + \rho', \tag{1}$$

where the entities p_0, ρ_0 is related to the fluid at rest and p', ρ' is related to the medium perturbed because of the acoustics wave (negligible perturbation caused by magnetic disturbances) and thus are smaller than those formed in the absence of sound waves. Because of these perturbed quantities, the equation of continuity was reduced as follows:

$$\frac{\partial \rho'}{\partial t} + \rho_0 \; div \overrightarrow{v} = 0. \tag{2}$$

In physical sciences – and – electrical engineering, dispersion relations describe the effects of – dispersion – in a medium on the properties of a wave traveling within that medium. In the considered problem, the dispersion relation was derived by considering that the magnetic field does not create any flow. Murawski [15] derive model equations describing the coupling between Alfven and magnetosonic wave which are driven by the former and provided the dispersion relation for a small amplitude sound wave in the presence of a magnetic field as follows:

$$\left\{\omega^2 - k^2 {V_A}^2 Cos^2\theta\right\}\left\{\omega^4 - k^2\omega^2\left\{{V_A}^2 + {V_s}^2\right\} + k^4 {V_A}^2 {V_s}^2 Cos^2\theta\right\} = 0. \tag{3}$$

Eq. (3) indicates that there are three possibility of wave that can propagate through magnetohydrodynamic plasma. The first root is

$$\omega = kV_A Cos\,\theta, \tag{4}$$

So, Alfven wave cannot propagate in a direction perpendicular to the magnetic field (in the direction of wave vector k).Hence, associated with this root there will be the zero perturbation pressure. The remaining two roots of dispersion relation are as follows:

$$\left(\frac{\omega}{\kappa}\right)^2 = \frac{1}{2}\left[{c_s}^2 + {V_A}^2 \pm \left\{\left({c_s}^2 + {V_A}^2\right)^2 - \left(2c_s V_A Cos\theta\right)^2\right\}^{1/2}\right] \tag{5}$$

where V_A is Alfven wave speed and c_s is sound wave speed. The positive sign corresponds to the fast wave. Its velocity becomes faster of either V_A or c_s for $\theta = 0$.

A wave will be magnetic in nature if $c_s \ll V_A$ [15]. Hence, for a magnetic wave, the dispersion relation in Eq. (5) will take the following form:

$$\frac{\omega}{\kappa} \approx V_A. \tag{6}$$

Thus, the fast mode is essentially a sound wave in the upper chromospheres and corona. Moreover, that wave will be acoustical in nature if $c_s \gg V_A$ [15]. Hence, for an acoustic wave, the dispersion relation Eq. (5) will take the following form:

$$\frac{\omega}{\kappa} \approx c_s. \tag{7}$$

Thus, the fast mode is essentially a sound wave in the convection zone, photosphere and lower chromosphere. Moreover, this nature of the wave is crucial for obtaining a smooth flow in magnetohydrodynamic channels. Magnetism introduces the additional speed to standing acoustic wave. In presence of magnetic field some of the kinetic energy of a mechanical disturbance is converted to electrical and magnetic energy. This energy is both dissipated as joule heating and stored in electric and magnetic fields. The energy which is stored can change back into mechanical energy. This alteration between mechanical and electromagnetic energy provide the mechanism for a disturbances to propogate along the field of lines as an Alfven waves.

In an ideal fluid, a sound wave is adiabatic, so we assumed that the pressure variation was related to a small change in density and defined