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Reconsideration of the hydrodynamic behavior of fluidized beds operated under reduced pressure

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ABSTRACT

Fluidized beds operated at sub-atmospheric pressure can be employed for granulation and drying of thermo-sensitive materials in the food and pharmaceutical industries. However, the hydrodynamics of vacuum fluidized beds has not been extensively investigated. Some authors argue that at low pressures, the slip flow of gas is the major factor influencing the hydrodynamic behavior. The influence of change in gas properties on the hydrodynamics due to reduction in pressure has not been clearly distinguished. In this contribution, the individual effects of gas properties and slip flow on the hydrodynamic behavior, particularly on the minimum fluidization velocity, of vacuum fluidized beds are quantified. This has been achieved by expanding the classical minimum fluidization velocity correlation, valid under atmospheric pressure, to include the slip flow term. The results obtained describe a critical Knudsen number which indicates when the slip term begins to significantly influence the flow behavior. The derived correlation is compared with correlations reported in literature as well as validated with experimental data.

1. Introduction

Fluidized bed granulation and drying processes are increasingly used for the production and treatment of granular solid materials as they offer high heat and mass transfer rates. In the production of bioactive materials in the pharmaceutical or food industry, the problem of deactivation is often encountered. While the deactivation can be lowered by reducing the drying temperature, this can also lead to a low process throughput due to the reduced drying potential of the gas medium. Other low temperature methods such as freeze-drying can be used, but they are costly and time consuming for bulk production as compared to high temperature drying processes. An alternate approach is to operate the fluidized bed at moderate vacuum conditions. Thus the gas will continue to be used as a heat carrier and a considerable reduction in the product temperature and equipment cost can be achieved. Vacuum fluid-bed dryers show a reduction of the vaporization temperature and shortening of drying time [1].

There are relatively few studies of fluidized beds operated under reduced pressure. Wraith and Harris [2] considered the application of vacuum fluidized beds in metallurgy for metal extraction. They observed large velocity gradients which resulted in an intermediate fluidization regime characterized by a fluidization front for deep beds. Tatemoto et al. [3] studied the drying characteristics of heat-sensitive material immersed in a fluidized bed of inert particles under reduced pressure. They observed that a high drying rate can be achieved even at a relatively low mass velocity of the drying gas, when the chamber pressure is low.

The hydrodynamic characteristics of fluidized beds operated at elevated temperatures and pressures, such as minimum fluidization velocity, bed voidage and elutriation, have been rigorously analyzed [4]. In fluidized beds operated under elevated pressures (101–1600 kPa), the minimum fluidization velocity depends on particle size. It is unaffected by pressure for fine Geldart A powders and decreases with increase in pressure for coarse materials. The dependence of minimum fluidization velocity on pressure is due to the effect of pressure on the physical properties of gas, namely, the density and viscosity [5].

In comparison, the hydrodynamics of fluidized beds operated under low pressure has not been extensively studied. Some authors report that the minimum fluidization velocity derived for atmospheric pressure conditions cannot be used to predict the velocity at reduced pressure. The proposed argument is that at low pressure, the hydrodynamic flow regime is no longer laminar but is better described by assuming slip flow [6,7]. They derived correlations for predicting the minimum fluidization velocity which takes into account the slip flow regime. The correlation from Llop et al. [6] has been developed for high as well as sub-atmospheric pressures. Kozanoglu et al. [8,9] have also proposed new equations by modifying the constants used in the Llop correlation. These correlations account for the slip flow via the dimensionless Knudsen number (Kn), which is the ratio of the mean free path of the gas molecules to the characteristic length. However, there are three key aspects in this argument that are not discussed by any of the authors: (1) the proposed correlation is not compared for the limiting

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case of $Kn \rightarrow 0$ to existing correlations derived for atmospheric conditions; (2) the range of validity of the slip flow regime is not analyzed and (3) as in the case of fluidized beds operated under elevated pressure, the influence of gas properties on minimum fluidization has not been quantified for low pressure conditions.

This analysis is essential because if, indeed, the slip term dictates the flow behavior at sub-atmospheric pressures, then not only the minimum fluidization velocity correlation will have to be modified, but other hydrodynamic parameters such as elutriation velocity, bed expansion, and bubble formation will also have to be remodeled. The non-continuum effects due to slip flow on the drag force experienced by the fluidized particles will also have to be accounted for. In the case of particles suspended in air, the drag force is calculated using Stokes' law, which is derived from equations of continuum mechanics. But as the particle diameter approaches the same order of magnitude as the mean free path of air molecules, non-continuum effects are accounted for in the Stokes' law by introducing a slip correction factor. The slip correction factor is generally applied for particle diameters less than 10 μm as in the case of pollutant particles suspended in air [10].

Along with the hydrodynamics, the slip flow will also affect the heat and mass transfer characteristics. Hence the Nusselt and Sherwood number correlations would also have to be modified. In the field of micro-reactors, where the characteristic dimension of the channel is of the order 50–200 μm, the slip flow regime and rarefaction effects are taken into account. The heat and mass transfer characteristics are different from macro-reactors as rarefaction effects also cause jumps (discontinuities) in temperature and concentration at the walls of the reactors [11]. In the case of fluidized beds operated under reduced pressure, Kozanoglu et al. [12] have developed a correlation for Sherwood number in terms of Reynolds and Knudsen number. But here as well the range of applicability of the slip effect has not been discussed in terms of the particle diameter and operating pressures.

The following correlation proposed by Richardson for the minimum fluidization Reynolds number, Re_{mf}, is widely used:

$$Re_{mf}\left(d_p, \rho_p, P\right) = -25.7 + \sqrt{25.7^2 + 0.0365 Ar}. \tag{1}$$

This correlation was based on data obtained only at atmospheric pressure conditions [13] and expresses the minimum fluidization Reynolds number as a function of the Archimedes number.

The Archimedes number is a function of the particle diameter (d_p) and density (ρ_p), gas density (ρ_p) and kinematic viscosity (v_g). Of these, gas density and kinematic viscosity vary with pressure. As the pressure is reduced, the change of gas properties is reflected in Re_{mf}. However, for a fixed particle diameter the operating pressure (P) at which the change in gas properties can no longer accurately predict the Re_{mf} is the critical pressure below which the non-continuum effects also become significant. This critical point analysis can be done in terms of the dimensionless Knudsen number, which distinguishes between these two effects. The critical point analysis is essential because only after the identification of this critical value it is possible to conclude whether slip flow is the main phenomenon responsible for the change in Re_{mf} at a particular particle diameter and operating pressure. In layering granulation or drying processes, where the typical particle size is above 200 μm, it is essential to evaluate if slip flow affects the motion of particles in this size range.

In this study, a new correlation is developed for the minimum fluidization Reynolds number applicable at atmospheric as well as sub-atmospheric operating pressures in the fluidized bed. The correlation is compared to the classical Richardson equation (derived for atmospheric conditions) as well as to correlations reported in literature which account for the reduced pressure. The aim of this study is to quantify the individual effect of change in gas properties with pressure and that of slip flow on the minimum fluidization Reynolds number. A critical Knudsen number is identified which distinguishes between these effects. The need to apply a slip flow correction in the minimum fluidization Reynolds number is reevaluated and the conditions of pressure and particle diameter at which slip flow becomes relevant are identified. In other words, the range of validity of the classical correlation for minimum fluidization Reynolds number is determined for operating pressure smaller than atmospheric pressure.

This paper is organized as follows: The theory of rarefied gas flow in the fields of microfluidics and porous media is discussed in Section 2. A new correlation for the minimum fluidization Reynolds number which accounts for the slip flow is derived in Section 3. The critical Knudsen number which distinguishes between the influence of change in gas properties and slip flow is determined in Section 4. In the same section, the results are compared to correlations from literature as well as to experimental data. Pressure dependency is further elaborated in Sections 4 and 5, before coming to the conclusion.

2. Theory of rarefied flow

The slip flow regime in hydrodynamics becomes relevant when the characteristic geometric dimension is comparable to the mean free path of the gas molecules or for gas flows at low pressures. In the field of microfluidics, gas flow through the devices is usually in the slip and transition flow regimes [14]. In micro- and nanodevices, the gas exhibits non-continuum dynamics and the traditional Euler or Navier–Stokes equations fail in predicting the flow [15]. In porous media such as tight sands, with micro- or nanoscale pores, the gaseous flow through them also falls into slip or transition regimes [16].

The range of hydrodynamic regimes for rarefied gas flow is expressed in terms of the dimensionless Knudsen number (Kn). This is the ratio of the mean free path of gas molecules to the characteristic dimension:

$$Kn = \frac{\lambda}{d_p}, \tag{2a}$$

where the modified mean free path λ can be obtained according to [17] from:

$$\lambda = 2\frac{2-\gamma}{\gamma}\sqrt{\frac{2\pi RT}{M}}\frac{k_g}{P\left(2c_{p,g} - R/M\right)}, \tag{2b}$$

and the accommodation coefficient γ can be calculated by means of the correlation:

$$log\left(\frac{1}{\gamma} - 1\right) = 0.6 - \frac{(1000K/T) + 1}{C}. \tag{2c}$$

In these equations, k_g is the thermal conductivity of the gas, T is the absolute temperature and C depends on the molar mass of the gas. For air, $C = 2.8$.

As there is a strong analogy between low-pressure flows and microflows, the following classification of the flow regimes as a function of Kn is generally used [18,14]:

- $Kn < 0.01$: continuum flow regime. This is modeled using compressible Navier–Stokes equations and no-slip boundary conditions. However, some authors report that non-equilibrium effects already begin at lower Knudsen numbers ($Kn > 10^{-3}$) [19].
- $0.01 < Kn < 0.1$: slip flow regime. The Navier–Stokes equations are still applicable, but only with slip velocity and temperature jump boundary conditions.
- $0.1 < Kn < 10$: transition flow regime. Rarefaction effects dominate and continuum Navier–Stokes equations are invalid.
- $Kn > 10$: molecular flow regime. Intermolecular collisions are negligible as compared to collisions between molecules and surface.

Slip models (of first and second order) are used to improve the predictions of continuum methods for the slip and marginally transitional