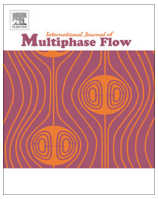
International Journal of Multiphase Flow 62 (2014) 152–160

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



On the deposition of particles in liquid metals onto vertical ceramic walls

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ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form 18 February 2014
Accepted 28 February 2014
Available online 13 March 2014

Keywords:
Non-metallic particle
Liquid metal
Ceramic wall
Turbulent flow
Deposition
Eulerian model

ABSTRACT

The deposition of non-metallic particles in liquid-metal flows is a serious industrial problem because the build-up of particles on ceramic walls clogs the flow path and interrupts the production, and this leads to large economic losses. This paper is an effort to extend the current state-of-the-art knowledge of particle deposition in air in order to predict particle deposition rates in liquid-metal flows using an improved Eulerian deposition model and considering Brownian and turbulent diffusion, turbophoresis and thermophoresis as transportation mechanisms. The model was used to predict the rate of deposition of particles in an air flow, and the predictions were compared to published measurements to demonstrate its performance. The model was then modified to take into account the differences in properties between air and liquid metals and thereafter applied to liquid-metal flows. Effects on the deposition rate of parameters such as steel flow rate, particle diameter, particle density, wall roughness and temperature gradient near the wall were investigated. It is shown that the steel flow rate has a very important influence on the rate of deposition of large particles, for which turbophoresis is the main deposition mechanism. For small particles, both wall roughness and thermophoresis have a significant influence on the particle deposition rate. Particle deposition rates under various conditions were successfully predicted.

1. Introduction

The deposition on a wall of particles dispersed in a turbulent flow is both of scientific interest and of engineering importance in a variety of fields, e.g. chemical engineering, mechanical engineering, physiology, physics and the urban environment. It is believed that the deposition of particles onto a surface occurs in two stages (Hussein et al., 2012). Firstly, advection and turbulent mixing transport the particles toward the surface, but this is not considered to be the controlling step of particle deposition in a fully developed turbulent flow. Thereafter, the particles are transported across a concentration boundary layer near a surface and are then deposited on the surface. An Eulerian scheme and a Lagrangian scheme are the two important available methods to describe the particle deposition. For a Lagrangian scheme, each particle is tracked by considering all the forces acting on it. This kind of tracking provides a great amount of information with respect to an individual particle's behavior, such as the particle velocity, location, and flying time before touching a wall. However, it is sometimes necessary to track a large number of particles in a turbulent flow to obtain sufficient statistical data. To track so many particles, a Lagrangian scheme is very time-consuming. In an Eulerian scheme, a specific type of particle is considered as a continuum, and this way of describing the deposition rate for a large number of particles is much less time-consuming than a stochastic Lagrangian scheme.

Numerous researches have investigated the particle deposition in air, both experimentally and using Eulerian models (Hussein et al., 2012; Guha, 1997; Wood, 1981; Sehmel, 1973; Liu and Agarwal, 1974; Sippola and Nazaroff, 2004; EI-Shobokshy, 1983; Liu and Ilori, 1974; Friedlander and Johnstone, 1957; Zhao and Wu, 2006a,b). The experimental data of Liu and Agarwal (1974) are considered to be particularly reliable, and they are widely used by many authors to verify their models. This provides a strong basis for the development of reliable models.

During the last decades, the modeling of particle deposition in air has made great progress. The early models used to investigate the particle deposition rate are called "stopping distance" models (Liu and Ilori, 1974; Friedlander and Johnstone, 1957), since they assume that particles first move to one "stopping distance" and thereafter make a "free flight" to the wall. However, it is difficult to give a physically satisfactory description of the free-flight

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.02.002
0301-9322/

velocity. Furthermore, an important particle deposition mechanism, turbophoresis, is not included in these "stopping distance" models.

Turbophoresis was probably firstly recognized by Caporaloni et al. (1975). It represents the interaction between the particle inertia and the inhomogeneity of a turbulent flow field. Lai and Nazaroff (2000) proposed an easy-to-use three-layer deposition model, but the lack of any turbophoresis mechanism in the model restricts its application to very fine particles, for which turbophoresis is unimportant due to their small inertia. As a good contribution to predict the particle deposition rate, Zhao and Wu (2006a) developed an improved model based on the model of Lai and Nazaroff (2000), in which they considered the influence of turbopheresis in order to make predictions for large particles. Furthermore, the influence of the wall roughness on the deposition rate was investigated (Zhao and Wu, 2006b). Piskunov (2009) went a step further to derive simple approximate formulae, based on the model of Zhao and Wu (2006a) and semi-empirical models of Sehmel and Hodgson (1978) and Kharchenko (1997), to calculate the deposition rate on both smooth and rough walls. All these models take only one parameter, the roughness height, into account when investigating the effect of roughness on deposition rate. An improvement was then made by Hussein et al. (2012), who put forward a new approach to determine the roughness by considering both the roughness height and the peak-to-peak element distance at a wall surface. It is now common knowledge that the dry deposition rate of particles onto a vertical surface, which shows a sigmoidal deposition curve with respect to dimensionless particle relaxation time τ_p^+, can be divided into three regimes (Hussein et al., 2012; Guha, 1997; Wood, 1981): (i) a turbulent particle diffusion regime ($\tau_p^+ < 0.1$) related to Brownian diffusion and eddy diffusion, (ii) an eddy diffusion-impaction regime ($\tau_p^+ = 0.1 - 10$) due to turbophoresis (Friedlander and Johnstone, 1957) and (iii) a particle-inertia-moderated regime ($\tau_p^+ > 10$) due to a low transport rate for large particles across the turbulent core.

Overall, the absence of an acceleration term, when the turbophoretic velocity is calculated in the above models, makes the calculation of the deposition rate for large particles less accurate (Guha, 1997, 2008). In addition, these models are not completely physically satisfactory, since they are not based on a good physical framework. Therefore, it is not easy to extend these models to include other effects in a good physical manner. A valuable contribution was made by Guha (1997), who developed a theoretical model that not only provides a good physical framework, by solving the particle continuity equation and the particle momentum conservation equations to determine the particle deposition rate, but is also easily extended to consider other effects on the particle deposition rate. The predictions were shown to be in good agreement with the experimental data over a range of particle sizes (Guha, 1997). In Guha's model (1997), the particle eddy diffusivity is assumed to be equal to the turbulent viscosity of the fluid. This assumption is reasonable for situations in which the relative velocity between the particle and fluid is small, e.g. for relatively small particles. However, it may be irrational for relatively large particles with a large velocity relative to the fluid, especially in an air-particle flow with a large particle/fluid density ratio. A possible way to correct this is to add an additional term to the particle eddy diffusivity equation (Zhao and Wu, 2006a; Hinze, 1975).

Since Guha's model provides a good physical framework to predict the particle deposition rate in a turbulent air flow, it should be interesting and meaningful to extend the model to a liquid-metal-particle system in an attempt to understand several observed problems. For example, it can be used to predict particle deposition rates in a liquid steel flow or in a liquid aluminum flow. The deposition of non-metallic particles in some liquid metal flows is a serious industrial problem. The build-up of particles, such as Al_2O_3, CaS, TiN, rare earth metal oxides and some complex compounds like spinel, at the interface between the liquid steel and the ceramic wall often clogs the steel flow path. This interrupts the continuous casting process in steel production. One kilogram of typical low-carbon aluminum-killed steel contains 10^7–10^9 non-metallic particles (Kiessling, 1980). Particles in molten steel normally have a size of the micrometer level (Bi et al., 2012), and their volume fraction in liquid steel is very low. Due to that the particles and the ceramic nozzle wall materials are normally not wetted by liquid steel, particles tend to stick to a ceramic refractory wall driven by the decrease in interfacial energy when they come close to the wall (Levada et al., 2009; Shinozaki et al., 1994; Muki et al., 1999). A large amount of research, summarized by the present authors (Ni et al., 2013), has increased the understanding of the particle behavior in molten steel, but none of them presented enables the particle deposition rate to be predicted. Therefore, the model here presented, based on Guha's model (Guha, 1997, 2008) with a good physical framework and some proposed improvements, is expected to be a useful and time-saving tool to enable the particle deposition rate to be predicted in complex liquid-metal-particle systems.

The purpose of this paper is to present a method for calculating the rate of deposition of particles in liquid metals (taking liquid steel as an example while the model is not limited only to use in steel flow) onto ceramic walls. This modified Eulerian deposition model, which is based on Guha's model (Guha, 1997, 2008) and includes both the effect of wall roughness proposed by Hussein et al. (2012) and a corrected particle eddy diffusivity (Zhao and Wu, 2006a; Hinze, 1975), was first used to predict the particle deposition rate in an air flow and the results were compared to the experimental data. Due to differences in, e.g. the ratio of particle to fluid density, between a gas-particle and a steel-particle system, the deposition model was modified before it was used to predict the rate of deposition of some micro-particles in a molten steel flow onto ceramic walls. In order to get example values for the steel flow parameters, the steel flow field in a vertical pipe (outflow from a tundish, i.e. flow in a submerged entry nozzle) was first calculated using the commercial software PHOENICS (2008). The parameters obtained of the flow field were then put into the model to calculate the particle deposition rate. This paper also presents a parameter study in which the method was used to investigate the rates of deposition of different particles in a liquid steel flow for different flow situations and different boundary conditions.

2. Modeling of particle deposition

2.1. Description of the particle deposition model

The model was based on the following: (1) the volume fraction of the dispersed particles is very low, and the particles are spherical and do not interact with each other; (2) a one-way coupling is assumed; and (3) particles are assumed to deposit onto a wall after they touch the wall. The model arises from the basic conservation equations of a fluid-particle system in an Eulerian frame of reference. In a steady state, the equations of motion can be written as follows (Guha, 1997, 2008):

$$\nabla \cdot (\rho_p \boldsymbol{V}_p) = 0 \tag{1}$$

$$\rho_p (\boldsymbol{V}_p \cdot \nabla) \boldsymbol{V}_p = -\nabla p_p + \rho_p \boldsymbol{F} + \rho_p \boldsymbol{C} \tag{2}$$

where $\boldsymbol{V}_p$ represents the velocity vector of the particles, on which a random thermal velocity is superposed that gives rise to the partial pressure p_p, $\boldsymbol{G}$ is the total external force vector per unit mass (e.g. gravitational, electromagnetic) on the particles, ρ_p is the partial