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An experimental procedure to estimate tube erosion rates in bubbling fluidised beds

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A B S T R A C T

We studied the erosion rate of a horizontal plaster tube in a cold-model bubbling fluidised bed of 510 μm glass beads at different fluidisation velocities and at ambient pressure and temperature. To this end, we developed a new experimental procedure based on the cyclic immersion of a cylindrical probe in a bed kept at incipient fluidisation ($U = 1.03\ U_{mf}$) and we compared the obtained results with those achieved during experiments with the same probe immersed at a fixed position inside the fluidised bed operated in bubbling regime. The new procedure was meant to simulate the impact of the bubbles wake with the probe, providing a simplified physical model for erosion in the bed. We also interpreted the experimental results in light of existing models to describe the overall erosion rate. The analysis of data indicated a clear correlation among surface erosion and bubble wake dynamics. Besides, the new procedure provided a way to address the angular profile of tube erosion caused by the exposure to the wake of a single rising bubble. Once multiplied by the product between bubble frequency and wake length, these data allow reconstructing the angular erosion rate profiles in the range of the fluidisation velocity investigated. This result finds confirmation in the analysis of the pertinent literature concerning the drag coefficients of a horizontal tube immersed in dense and dilute granular flows.

1. Introduction

Wear is generally understood as the progressive loss of material from the surface of a solid body caused by mechanical action, i.e., the contact and relative motion with a solid, liquid, or gas, or by chemical phenomena, i.e., corrosion or scaling [1]. In a gas fluidised bed wear is an ubiquitous phenomenon occurring for any immersed surface and for the same bed walls. The mechanical components of wear are mainly related to the erosion caused by the impacts with the fluidised particles. Since this motion is determined by the fluidisation regime, erosion can be either a side effect to take care of or a desired phenomenon that may be suitably tuned. The first case is, for example, the occurrence of failures in components of heat recovery tube banks [2–5] while examples of the second case are the mechanical treatments, as polishing or de-coating, used to treat the surface of workpieces [6].

Wear is related to three main variables, i.e., the gas properties, the structural and morphological properties of the eroded surface and of the eroding particles, and the dynamics of particle impact on the surface.

Gas properties affect erosion either due to corrosion, scaling and oxidation [7–10] phenomena or due to the effects of pressure and temperature on the fluidised bed fluid dynamics [5,11–14].

In terms of mechanical properties of the eroded surfaces, the most relevant parameters are usually the mechanical hardness in either the Vickers or the Shore scale, although surface roughness may substantially alter the dynamics of particle–surface impacts and the associated erosion mechanisms, as also suggested by Barletta [6] and Sooraj and Radhakrishnan [15]. These surface roughness effects become increasingly relevant for liquid suspensions with high solid concentrations [16–18]. In recent times, significant results were published concerning the behaviour of steels in fluidised beds. Among them, it is worth mentioning the works of Cachon-Nava et al. [19], and Wellman and Nicholls [20], and the series of papers presented by Huttunen-Saarivirta, Antonov and co-workers (e.g., [7,8,21,22]) and by researchers form the Chalmers University [9,11,23,24]. These authors investigated the simultaneous erosion and corrosion of different steels treated with specific coatings, at elevated temperatures and in the presence of different gases, providing a relevant set of data on the behaviour of such materials in realistic operating conditions.

Particle properties influence erosion in different ways. On the one hand, erosion is proportional to the kinetic energy dissipated during the impact of particles with the eroded surface, and is thus recognised as directly proportional to particles mass [2,4,15,25]; on the other hand, particle angularity and hardness play a key role in determining the effective damage caused by each particle impact (e.g., [1,2,15,26]).

The peculiarity of bubbling fluidised bed erosion relies on the specific dynamics of particle impacts with the eroded surfaces. To address this effect, the main physical modelling of fluidised bed erosion is based on

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the concept that erosion is the result of the repeated impacts of particles with the surface (e.g., [27]). Therefore, a reliable model should consider a description of the elemental erosion due to a single particle impact coupled with a proper estimation of the number of colliding particles, their velocity and their angle of impingement with the immersed surface. Although conceptually understandable, this description is quite challenging, since the information on particle–surface collisions can be hardly determined in practice. Besides, the same dynamics of single particle–surface impacts and the evaluation of those of them effectively influencing erosion rate is far from being predicted by available models (e.g., [6]). In fact, the kinematic conditions and the types of materials involved in the wear determine the types of wear, such as sliding wear, elastic rolling wear, impact wear, oscillation wear and shock wear [1]. For a surface immersed in fluidised beds, all these components are present since the particles both slide, roll or impact onto the surface, because of the bubble motions, and oscillate due to their fluctuating motions. A comprehensive study on the underpinning physics of fluidised bed erosion and of the proposed modelling approaches were reviewed in the past by Lyczkowski and Bouillard [2] whose work still represents the most relevant reference in the field.

It is clear that only computational fluid dynamics can make practicable such complex models. Numerical modelling on erosion rate are based on either Eulerian–Eulerian approach [23,28–31] or on a Large Eddy simulation–discrete element method (LES–DEM) one [24]. Eulerian–Eulerian models are either in 2D and 3D set-up, and considered the Monolayer kinetic Energy Dissipation (MED) model [2,32,33] to describe the erosive effects of the impacting particles. The LES–DEM models are more recent and usually refer to pseudo 3D set-ups, for which the bed thickness is of few millimetres. It is worth noticing that some of these studies were not aimed to modelling of erosion rate but rather to the use of erosion experimental data and associated model equations as a tool to validate the hydrodynamic modelling. Recently, Jafari et al. [34,35] implemented numerical simulations (using a four-way coupled Eulerian–Lagrangian approach) and specific modelling to describe the erosion of particles by solid–gas flow in a tube, starting from the Huang et al. [36] erosion model. The same numerical approach was successfully adopted by Lin et al. [37].

The simulation of experimental tests at either high temperatures for real combustors are still beyond the capacity of the current numerical modelling due to the concurrent presence of corrosion, oxidation and scaling phenomena, which cannot be properly addressed.

In terms of experimental studies, pertinent literature on surfaces' erosion in bubbling fluidised beds mostly refers to experimental tests on single tubes or tube banks, usually performed by measuring the loss of material and/or the radius size reduction at a given angular position, thus establishing a surface erosion profile [2–4,38]. Since an effective measure of mass consumption and size reduction usually requires a very long time – generally from several tens to hundreds of hours – only time-average values of erosion rates can be experimented.

Experiments on the erosion rates were mainly carried out by varying particle size, d_p, excess gas velocity, $U–U_{mf}$, pressure, temperature, height from the distributor and sometimes, tube orientation.

Tests by Nieh et al. [3] on the average mass losses of tubes in fluidised beds showed that the eroded mass doubles when passing from a vertical to a horizontal cylinder. The same authors also pointed out that erosion rates were negligible for packed bed conditions, while being a linear function of the excess gas velocity for the fluidised bed. In addition, erosion rate was higher for tubes positioned at a higher distance from the distributor.

The studies of Wiman and co-workers [4,5] on the angular profiles of erosion of specific elements of tube banks showed that the gas pressure usually increased the erosion rate, although a non-monotonic trend can be observed for tube banks with lower pitch. The erosion rate increased with the excess gas velocity in agreement with Nieh et al. [3] and was slightly higher passing from finer ($d_p = 450$ μm) to coarse (700 μm) particles. Wiman and co-workers [4,5] also argued that higher temperatures should lead to an increase of the pressure levels at which the maximum erosion occurs.

Dellenback and Johansen [25] investigated the erosion rate of a plaster probe in a bubbling fluidised bed of glass beads with mean diameters of 425, 500 and 600 μm and with excess gas velocities $U–U_{mf}$ of up to 0.5 m/s. The authors noted that the mass erosion rate followed an almost linear trend with the excess gas velocity. Differently, the authors correlated the local erosion rate to both the relative gas velocity and to the angular profile of a parameter called "attenuation pressure", which was measured during the experiments. The attenuation pressure is a dimensionless measure of the difference between superficial tube pressure and hydrodynamic pressure in the bulk of the bed at the same height from the distributor of the eroded surface. It represents a measurement of the pressure profile generated by each rising bubble. Dellenback and Johansen [25] proved that the attenuation pressure in bubbling fluidised bed is a function of the angular tube position, but is scarcely dependent on the particle diameters and of the gas velocity up to 2.5 U_{mf}.

Experimental results were also interpreted with empirical or semi-empirical or mechanistic models [2,26,27,33,39–42] reconstructing the overall erosion rate starting from a fluid dynamic analysis of bubbling fluidised beds. In these studies, the role of bubble wake in determining the erosion rate was clearly remarked. The most representative of these models are presented later and used to interpret our experimental results.

In order to decouple the complex hydrodynamic of fluidised beds from the superficial behaviour of eroded materials, several wear testing rigs were proposed, for example that of Huttunen-Saarivirta, Antonov and co-workers (e.g., [7,8,21,22,43]) and that of MacAdam and Stringer in Berkley (e.g., [44–48]). These works proved the occurrence of a qualitative consistency between erosion rate profiles experimented in fluidised beds and in the wear testing rigs. Therefore, information on behaviour of surfaces subjected to erosion can be reliably gathered from experiments with the controlled fluid dynamic set-up of the wear testing rigs proposed.

However, one current limit in the application of wear testing rigs results is the absence of a reliable method to estimate the angular surface erosion profile as a function of the fluidisation velocities. The same limit occurs for experiments in real fluidised beds, for which it is hard to predict the evolution of surface erosion profiles at velocities different from those experimented.

To this end, this paper presents the results on a new wear testing rig aimed to simulate fluidised bed erosion mechanisms by controlling the motion of an eroded surface in a bed at incipient fluidisation. This procedure (thereinafter named MP as the acronym of a Moving Probe test) is meant to mimic the dynamics of surface impact with the rising bubble wake and drift phases and was conceptually similar to that proposed by MacAdam and Stringer in Berkley (e.g., [44–48]). Experimental tests were carried out in a 510 μm glass bead bubbling fluidised bed at velocities up to twice the minimum fluidisation. A cold model fluidised bed was used at atmospheric pressure and temperature, since, in these conditions, the largest amount of experimental and modelling studies to describe hydrodynamics and transport phenomena were developed in the past. This allows removing additional uncertainties due to the effects of pressure and temperature on fluidisation dynamics.

The erosion rate data in the wear testing rig and in the fluidised bed were correlated to address quantitative consistency between them. This correlation allows shedding light on the mechanisms of fluidised bed erosion in the investigated conditions and provides a method to predict erosion rates at fluidisation velocity different from the experimented conditions.

2. Materials and methods

The experimental rig used in this study consisted of a cylindrical erosion probe immersed horizontally in a fluidisation column. The Plexiglas® column had a circular section (I.D. of 150 mm, O.D. of 160 mm) and a total height of 2 m. The column was made by two flanged