Wear 348-349 (2016) 126–137

Contents lists available at ScienceDirect

Wear

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

Effect of particle size on erosion characteristics

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ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
28 November 2015
Accepted 10 December 2015
Available online 19 December 2015

Keywords:
Erosion
Particle size
Erosion mechanism
Erosion profiles
Erosion rate

ABSTRACT

When entrained into a carrier flow, such as liquid or gas, sand particles are able to interact with material surfaces strongly, which may cause serious erosion damage. How particle size affects the erosion characteristics, such as erosion pattern, erosion rate, erosion mechanism and erosion profile remains largely unexplored. In this study, we perform both experiments and numerical simulations to study the effects of particle size on those factors. In the experimental setup, a wet erosion test-rig is used, in which the flow speed of a mixture of sand particles and water is set to be 30 m/s and the different average sand particle sizes of 50, 80, 150, 350, 450 and 700 µm are taken. The experimental results show that there is a transition in the erosion profile from a "W" shape to a "U" shape with increasing the sand particle size. The sample surface profiles obtained from the experiments are then used to create geometry models for our numerical simulations. The simulation results are in good agreement with experimental measurements in terms of erosion rate and erosion pattern. Importantly, the simulations show that the larger sand particles able to dig deeper into the sample surface than smaller particles, providing a cogent explanation for the observed transition. The present work highlights the important role of particle size in affecting the erosion pattern, erosion rate, erosion mechanism and eroded profile.

1. Introduction

Wet erosion test-rig (water–sand erosion test-rig) has been frequently used in laboratories to test erosion of the equipment components that work in a multiphase flow condition (solid particle – fluid flow) in many industry applications. In the setting, the jet flow of water and sand particles is either perpendicularly or obliquely directed towards the test sample surface, causing a high static pressure region on the test sample surface [1]. In this region, the incoming mixture of sand particles and water is pushed away to the outer from the centre of this region (the stagnation point), resulting in a dramatic changes in sand particle velocity and trajectory, as well as sand particle distribution as they hit on the test sample surface. The changes of these impact parameters may cause changes in erosion characteristics, such as erosion pattern, erosion rate, erosion mechanism, and erosion profile. In fact, the response of sand particles to the changes of carrier flow (water flow) was found to strongly depend on the sand particle size [2–5]. Although many studies have been performed to investigate the effects of particle size on erosion characteristics, a detailed and complete understanding on these effects is still lacking. Thus, it is both important and necessary to revisit this issue so as to design strategies to minimize or even completely avoid the effects of erosion damage to equipment components.

In general, an erosion process often involves two interdependent stages, that is, particle-fluid dynamic stage (prior impact stage) and impact stage (erosion stage) [1–5]. At the prior impact stage, sand particles exchange their momentum with carrier flow. This implies that sand particles need to respond to the change of carrier flow through momentum exchange. In reality, the sand particles with smaller sizes are found to be more responsive than larger particles due to their differences in inertia force and drag force, resulting in their differences in the particle distribution, particle trajectory, and particle velocity at the impact stage [2–5]. It was shown that particles with sizes (smaller than 200 µm) often failed to approach the specimen surface, while the particles with larger sizes (order of 1 mm) had little diversion from their original trajectories [3]. As discussed in the review paper by Humphrey [4], impact parameters, such as impact velocity, impact angle, number of impacts, which greatly influence the erosion characteristics, are strongly dependent on particle's ambient conditions [3,5]. However, we note that previous studies discussed little on the effects of particle size to erosion profile and rate [3,5] and particle motion on the erosion mechanism

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http://dx.doi.org/10.1016/j.wear.2015.12.003
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[4]. Thus, it is important to understand the particle-fluid dynamics and its effect on erosion behaviour.

At the erosion stage, the solid particles hit on the material surface at certain impact velocities and impact angles inherited from the prior impact stage. For this stage, the research focus has been mainly on how materials properties affect erosion behaviour [4]. However, a number of studies have also addressed several issues centred around the effects of particle size on erosion characteristics [2,3,5–12]. In general, these studies can be classified into four important categories: (1) erosion rate, (2) erosion pattern, (3) erosion mechanism, and (4) erosion profile. For example, Clark and co-workers [5–7] studied the particle size effects on the erosion rate in slurry erosion. They found that an increase in the particle size is able to result in an increase in the erosion, while particles with very small sizes cause vanishingly small erosion rates. It is noted that these previous studies attempted to explain the effects of particle sizes on erosion rate based on particle mass, particle kinetic energy, and number of impacts. Moreover, Misra and Finnie [9] explained the effect of the particle size on erosion in terms of material properties and surface properties, such as the surface layer work hardening and dislocation entanglement near the surface. For small particles, they abrade the surface by only influencing the hard (debris) layer and thus encounter much harder material than do larger particles, which will also deform the material below the debris layer and thus abrade more. After some critical particle size, the influence of the debris layer will become minor, and thus there will be no increase in wear rate for a further increase in particle size. Of particular interest is that these studied recognized an important fact that the nature of particle size effect on the erosion rate of a material can only be understood by quantitatively considering the effect of particle size on the slurry flow and particle impact conditions. Based on this understanding, many researchers [2,3,5–11] employed the mean size of the particles to establish the relationship between erosion rate and particle mean size. Their studies showed that they follow a power law (erosion rate=(particle size)^n) with n ranging from 0.3 to 2.0. This wide range of the value of n can be attributed to the differences in material properties, experimental conditions, and particle sizes. It is now know that the erosion rate may depend on many factors, such as (1) particle size, (2) the number of particles striking on the surface per unit time, (3) particle kinetic energy, i.e. mass and velocity, (4) particle impact angle, and (5) the interference between particles striking and rebounding from the surface. Hence, it is necessary to study the combination of these parameters to fully understand the influence of particle size on erosion rate.

The erosion pattern is often represented by the wear scar (or affected area), where the solid particles hit on the material surface. The size of wear scar depends on several system parameters such as particle size, liquid properties, fluid flow conditions, etc. As discussed in [2,3], bigger particles experience a lesser diversion from their original trajectories as they hit on the sample surface. This implies that smaller particles may spread out on a larger area as they approach the sample surface. The above analysis implies that the erosion pattern should be strongly dependent on the particle trajectories. Thus, to protect for the equipment surface caused by erosion damage, it is necessary to understand the effect of particle size on the erosion patterns.

In studying the effect of particle size on erosion mechanism, Finnie et al. [9] revealed four erosion mechanisms, which are cutting, sliding, ploughing and chipping. They also observed that a small increase in ploughing was observed with decreasing particle size, and sufficiently large particles, which can penetrate the surface layer, could cause a plastic deformation that led to a more softening of the surface than small particles. In general, they suggested that the erosion mechanism does not change significantly with particle size as compared to the weight loss curve as a function of impinging angle for different sizes of particles. Moreover, Desale et al. [11] studied the effects of particle size on erosion mechanism by performing the experiments of sand-water slurry erosion with sand particle size ranging from 37.5–655 μm. They found that two distinct mechanisms for the mean particle size above and below 200 μm for the range of parameters. The deformation wear was found as the impact angle was about 90 degrees, while the platelets mechanism was found at low impact angles. In addition, they also found that there was no significant difference in erosion mechanism of different particle sizes at the impact angle of 90 degree. For a low impact angle, they found that the number and size of crater decreased as the particle size decreased. The threshold kinetic energy for different operating conditions was determined and its relation with the change in erosion mechanism was discussed. Abouel-Kasem et al. [8] performed experiments for sand particle size ranging from 112.7 μm to 516 μm and observed that the erosion mechanism was via indentation and material extrusion when particle size was below 200 μm, while the erosion mechanism was via ploughing as particle size was greater than 200 μm.

In slurry erosion, the eroded profile is another important factor in the study of erosion characteristics. Observation of an eroded profile can point out the erosion rate at certain location, from which, we can determine the lifetime of the equipment in service. The “W” shape is often observed in eroded profile [1] in wet erosion test-rig (water–sand), while the “U” shape is obtained in dry erosion test-rig (air–sand) [12,13]. In fact, the eroded profile strongly depends on erosion rate at certain location in the eroded area, which is related to the particle trajectory, particle contribution and velocity. The maximal eroded wear location in wet erosion test-rig may be closer to or away from the nozzle axis, depending on the particle size and fluid flow conditions. Therefore, increasing particle size may change the eroded profile from a “W” shape to a “U” shape, and vice versa. Hence, understanding the influence of the combination of particle size and fluid flow conditions on the eroded surface profile is important to predict the lifetime of equipment in services, as well as in surface material processing.

Currently, it is still a great challenge to track individual particles in slurry flow experimentally. In order to study the pre-impact stage, instead, numerical methods have been frequently used to track individual particles in a system with a huge number of particles. However, we still need experiments to capture erosion characteristics at the erosion stage, which cannot be easily obtained by a numerical method. These experimentally obtained erosion characteristics, together with the results obtained in the prior impact stage allow us to study the effect of particle size on erosion characteristics in great details. Thus, in this study, we use a combination of experiment and numerical simulation to study the effect of particle size on erosion characteristics. In the following, Section 2 introduces the experimental setup and measurement; Section 3 describes the geometry model, numerical methods, as well as model validations; Section 4 presents the results and discussion on erosion rate, eroded profile, erosion pattern and erosion mechanism; and finally Section 5 concludes the paper.

2. Experimental setup and measurements

In this study, experiments have been performed by using different particle sizes to provide the evident for study the effects of particle size on erosion characteristics, such as the surface profiles, erosion pattern and depth of the wear scar, the average erosion rate, and the surface morphology. All experiments were carried out for 10 minutes of exposure time. Experiments were also