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EXPERIMENTAL AND NUMERICAL ANALYSIS OF EROSION BY PARTICLE-LADEN IMPINGING JETS

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Abstract. *Erosion caused by solid particles is an important phenomenon in many industrial applications, since erosive damage can occur to key monitoring instruments and components, reducing their life cycle and increasing the risks of operation. In this work, numerical simulations and experimental tests of normally impinging erosive jets are carried out on AISI 304 stainless steel flat plates using SiC abrasive particles. The effects of Reynolds number (Re=20,300, 29,200 and 34,100), impact angle (30°, 45°, 60° and 90°) and particle size distribution (mean diameters of 50 and 100* μm*) on erosive wear are studied through numerical and experimental analysis. Photographs of eroded plates and the eroded profiles for different conditions are presented. For the numerical investigations, custom libraries are developed on OpenFOAM to compute both erosive damage and partially inelastic particle-wall collisions.*
The results clearly show that erosion wear is highly dependent on the kinetic energy of the particle at impact. The larger the size of the particle or the larger its velocity, the larger is the damage it causes. This work shows a comparison between the velocity profiles resulting from PIV measurements, measured eroded profiles, and numerical simulations to validation of erosion models for conditions off their original calibration ranges.

Keywords: *Erosion, Impinging jet, Particle Image Velocimetry*

1. INTRODUCTION

Particle-laden flows are a subject of great interest and importance in industry. In the oil and gas sector, solid particles carried by the flow often cause erosive damage in flow control and monitoring equipment. The prediction of wear or failure of those components is critical for operation management and to ensure adequate levels of reliability and safety.

A good review of early work on wear modelling can be found at Meng and Ludema (1995). The existing knowledge on the problem clearly highlights the complexity of the phenomenon and the absence of a general purpose model. Further works on this topic with a particular emphasis on well and pipeline applications are compiled in Parsi *et al.* (2014), where the details of different erosion models, including computer-based modelling and validation approaches, are discussed.

A few works (see, e.g., Elhimer *et al.* (2017)) show the limitations of the distinction between particles and tracers in Particle Image Velocimetry measurements is crucial to correctly identify the turbulent motions in the flow. The addition of tracers in the flow mitigates some of the limitations found by Lin *et al.* (2018), where PIV measurements were performed for different sand particle sizes, using these particles as tracers. The present work aims at quantifying the effects of Reynolds number, impact angle and particle diameter on erosive wear through numerical and experimental studies of a particle-laden jet impinging on a flat surface.

2. EXPERIMENTAL SETUP

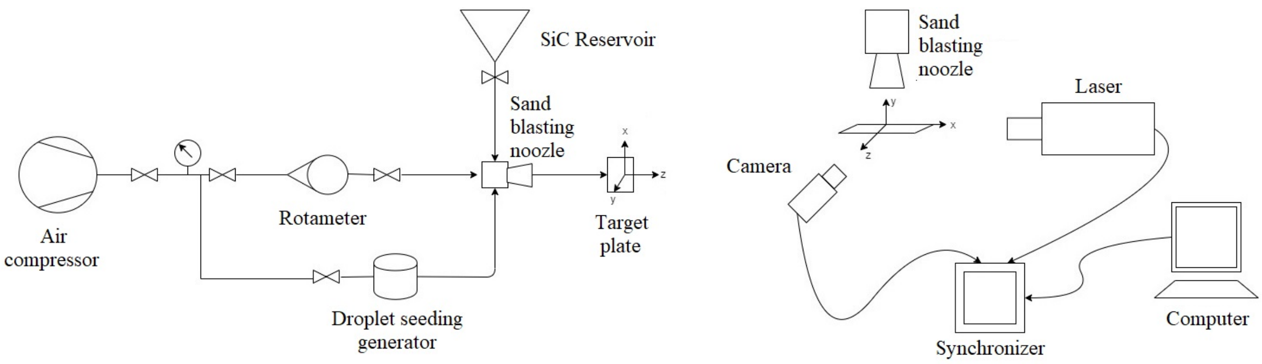

Figure 1. Experimental setup.

The experimental apparatus was particularly designed to allow changes in the flow rate through a 8.3 mm diameter sand blasting nozzle. Initially, the nozzle was aligned in the normal direction of a AISI 304 stainless steel flat plate 7896 kg/m^3 density, 193 MPa elastic modulus, 123 $Brinell$ Hardness), as shown in Fig. 1. The nozzle-to-wall distance was 12.7 mm. The test section is supplied with dry air, through an air compressor that keeps a 5 bar pressure in the line. A Rosemount^{TM} manometer calibrated between 0 and 20 bar and a calibrated Conaut^{TM} rotameter with a 1.85 m^3/h nominal flow rate Q, were used to read the pressure and the air flow rate respectively. Due to the presence of changes in the air specific volume, a thermodynamic adjustment in the air flow rate was considered. Two different carbon silicate particle sizes (150 and 320 meshes) were used to feed the suction of the sand blasting nozzle. The particle mass flow rate was 0.3 g/s. To evidence the particles breakup in the process, the size distributions before and after the experiment for mesh 150 are shown in Fig. 2a.

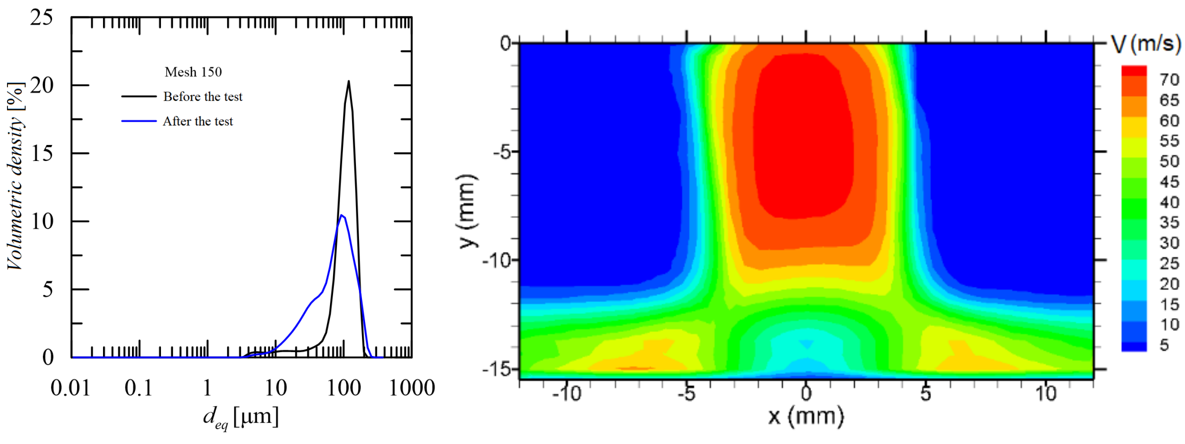

Figure 2. (a)(Left) Particle size distribution for Mesh 150. (b)(Right) Velocity field obtained from PIV measurements for Re = 29,200 and impact angle of 90°.

Measurements through Particle Image Velocimetry offer details of the continuous phase. The PIV system was composed by a Litron Nd-Yag laser of 135 mJ and 15 Hz repetition rate. The lasers are combined into a 1 mm laser sheet that illuminates an axial plane. A CCD camera with 1920x1200 px resolution records up to 4170 pairs of images. In this experiment, a high-volume liquid droplet seeding generator was used to atomize glycerin particles, with a 2 μm mean diameter, to be used as tracers. The continuous phase velocity fields for the impinging jet were analyzed for three different Reynolds numbers (20,300, 29,200 and 34,100). Fig. 2b shows the velocity field for Re = 29,200. A comparison with a single-phase air flow is made to validate the simulations mentioned in the next section.

Fig. 3a shows a photograph of an eroded plates for different impact angles. The eroded profiles were measured with a Form Talysurf Intra Profilometer from Taylor Hobson, the results are in Fig. 3b.

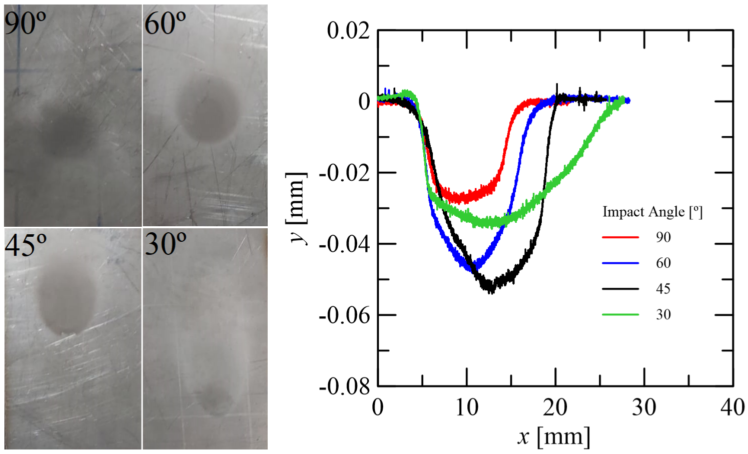

Figure 3. (a)(Left) Photographs of eroded coupons for different impact angles. (b)(Right) Eroded profiles comparison for Re = 29,200 and Mesh 150.

3. NUMERICAL RESULTS

Numerical simulations for the present work were performed through the open source OpenFOAM finite-volume computational fluid dynamics package. The computational mesh was generated using the `blockMesh` utility. Near wall cells were specially calculated to make sure that the resolved y^+ value was compatible with the employed turbulence model while still at the same time avoiding keeping the cell sizes smaller than the particle size, which, otherwise, would cause instabilities in the Lagrangian simulation. The continuous phase was modelled as dry air with kinematic viscosity $\nu = 1.544 \times 10^{-5}\ m^2/s$; the turbulence model was the Shear Stress Transport as implemented in OpenFOAM. The continuous flow field was solved using the SIMPLE algorithm through the use of the `simpleFoam` application for flow rate conditions.

Once the flow field was calculated, a one-way coupled cloud of particles was added to the flow through the use of the `icoUncoupledKinematicParcelFoam` application. The particles had the same size distribution for Meshes 150 and 320 as in the experiment, with typical properties for carbon silicate (SiC) abrasive particles: density of $\rho_p = 3200 kg/m^3$ and $\varphi = 0.8$ for non-spherical drag modelling as given by Haider and Levenspiel (1989). Some authors, including Brennen (2005), claim that for low volumetric ratios, one-way coupling is sufficient to model the particle dynamics, and, unless results differ significantly from the experimentally measured flow fields, this hypothesis should be considered. A custom library was implemented to consider the energy transfer from the particles to the wall as dependent on the impact angle (Grant and Tabakoff (1975)). A second custom library was implemented to enable the use of run-time selectable erosive and wear models.

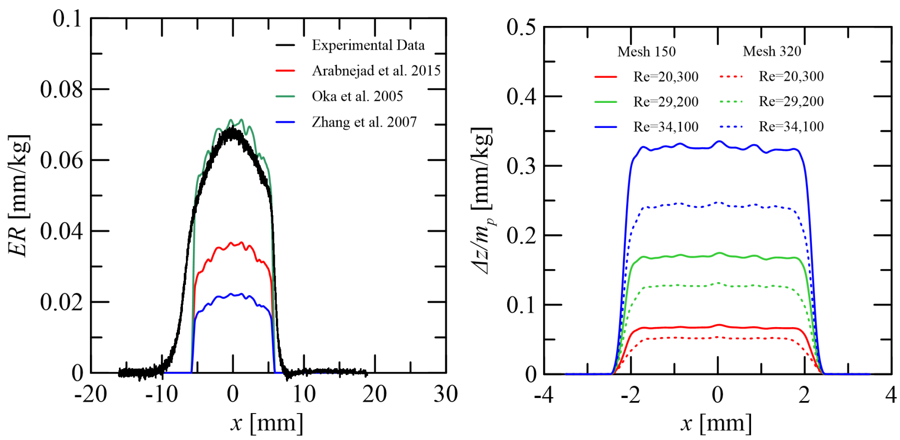

Figure 4. (a)(Left) Erosion rate for Re = 29,200 , 45° impact angle and 150 Mesh. (b)(Right) Thickness removed along the centreline per kilogram of particles introduced for 90° impact angle.

The numerical results Re = 29,200 and 45° are presented in Fig. 4a, where the experimental eroded profile is compared with the results plotted according to the wear models developed by Oka and Yoshida (2005), Arabnejad *et al.* (2015) and Zhang *et al.* (2007). The experimental results show a wider profile and a smoother transition between the flat surface and the eroded region when compared with simulations. In general, the model developed by Oka and Yoshida (2005) presents closer profiles to the experimental ones. The magnitude of the damaged area is studied in Fig. 4b, as expected, influenced by both particle size and flow rate. Clearly, for a same flow rate, larger particles remove more material than smaller particles due to their higher kinetic energy. For a same particle diameter distribution, the damage of the particles striking the coupon increases with Reynolds number.

The correlation between the thickness of removed material with particle size distribution and Reynolds number is illustrated. At Re = 20,300, the damage caused by Mesh 150 particles are, on average, 30% higher than the damage cause by Mesh 320. For Re = 29,200 and 34,100, the damage from the larger particles are, respectively, 33% and 34% higher than the damage originated from the smaller particles.

4. CONCLUSION

The present work examines the effects of Reynolds number, impact angle and particle size distribution on erosive wear through numerical and experimental analysis. A comparison between some experimental results and numerical simulations is presented.

The numerical investigations required the development of custom libraries on OpenFOAM to compute both erosive damage and partially inelastic particle-wall collisions. Using two sets of particle size distribution and three Reynolds numbers, it was possible to extract the normalized removed thickness along the centreline of the eroded plate.

The results show that erosion wear is highly dependent on the kinetic energy of the particle at impact. The larger the size of the particle or the larger its velocity, the larger is the damage it causes. A correlation between the thickness of removed material with particle size distribution and Re is presented. For low Re, the distinction between the damage caused by particles of various sizes is small.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Arabnejad, H., Mansouri, A., S, S. and McLaury, B., 2015. “Development of mechanistic erosion equation for solid particles”. *Wear*, Vol. 376, pp. 1194–1199.

Brennen, C.E., 2005. *Fundamentals of multiphase flow*. Cambridge university press.

Elhimer, M., Praud, O., Marchal, M., Cazin, S. and Bazile, R., 2017. “Simultaneous piv/ptv velocimetry technique in a turbulent particle-laden flow”. *Journal of Visualization*, Vol. 20, No. 2, pp. 289–304.

Grant, G. and Tabakoff, W., 1975. “Erosion prediction in turbomachinery resulting from environmental solid particles”. *Journal of Aircraft*, Vol. 12, No. 5, pp. 471–478.

Haider, A. and Levenspiel, O., 1989. “Drag coefficient and terminal velocity of spherical and nonspherical particles”. *Powder technology*, Vol. 58, No. 1, pp. 63–70.

Lin, N., Arabnejad, H., Shirazi, S., McLaury, B. and Lan, H., 2018. “Experimental study of particle size, shape and particle flow rate on erosion of stainless steel”. *Powder technology*, Vol. 336, pp. 70–79.

Meng, H. and Ludema, K., 1995. “Wear models and predictive equations: their form and content”. *Wear*, Vol. 181, pp. 443–457.

Oka, Y. and Yoshida, T., 2005. “Practical estimation of erosion damage caused by solid particle impact: Part 2: Mechanical properties of materials directly associated with erosion damage”. *Wear*, Vol. 259, No. 1-6, pp. 102–109.

Parsi, M., Najmi, K., Najafifard, F., Hassani, S., McLaury, B.S. and Shirazi, S.A., 2014. “A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications”. *Journal of Natural Gas Science and Engineering*, Vol. 21, pp. 850–873.

Zhang, Y., Reuterfors, E., McLaury, B., Shirazi, S. and Rybicki, E., 2007. “Comparison of computed and measured particle velocities and erosion in water and air flows”. *Wear*, Vol. 263, No. 1-6, pp. 330–338.

7. RESPONSIBILITY NOTICE

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