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Experimental and computational modelling of solid particle erosion in a pipe annular cavity

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ABSTRACT

Pipe annular cavities are present in equipment related to the oil and gas and other process industries. The flow in a pipe initially expands into an annular cavity of a given length with a larger pipe diameter before suddenly contracting into a smaller pipe. In this work, air-suspended sands flow through an aluminium pipe annular cavity (diameter ratios, 1.25 and 0.8; cavity length, 10.25 step-heights) in which multi-layer paint erosion and parent material loss information were obtained. It was found that:

- the highest erosion rate occurs on the leading edge of the forward-facing step;
- the forward-facing step shoulder erodes more than the backward-facing step;
- the maximum depth of erosion per unit mass on the curved cavity surface is approximately one third that of the material loss on the pipe surface;
- more material is removed in the downstream half of the cavity than in the upstream half;
- negligible erosion occurs up to 1.7 step-heights downstream from the backward-facing step;
- 198 μm-sized particles remove twice as much material from the pipe surface as 38 μm-sized particles, and value of the particle size exponent is 0.36.

A complementary computational fluid dynamics study using a Lagrangian approach predicted erosion rate at the forward-facing step by the 198 μm-sized particles to within ±30% of experimental values, while that for 38 μm-sized particles are over predicted by up to 100%. It was observed that erosion rate is most accurately predicted on surfaces that experience direct impact with particles compared to erosion predictions on surfaces where erosion is caused by secondary or higher order impacts.

1. Introduction

The study of fluid flows in sudden expansions [1], cavities [2] and sudden contractions [3] has been documented widely in the literature. These studies usually focus on the fluid flow phenomenon occurring within the cavities at various Reynolds numbers and provide reference cases for more complex flows in industrial scenarios. In industry, especially in the oil and gas (e.g. [4], [5]), and minerals industries (e.g. [6]), the flow of fluids through these basic configurations usually contain hard particulate matter which may result in equipment degradation through the mechanism of surface material erosion. The literature on the general mechanisms of particle erosion is vast and several models refer to the work of Finnie [7] which describes the 2 major mechanisms of erosion through deformation wear via normal particle impact and cutting wear due to low angle particle impact [8].

Durst et al. [9] assessed 2 methods (Lagrangian approach and Eulerian approach) to predict particulate two-phase flows in a sudden expansion in a vertical pipe flow. The Lagrangian approach predicts the particle trajectories in the fluid phase as a consequence of the net forces acting on that particle. The Eulerian approach treats the particles as a continuum. The solid–fluid solution is obtained by solving the relevant continuum equations for the fluid and particle phases. The authors concluded that the Eulerian approach is advantageous in flow cases with high particle concentrations and where high void fraction of the flow becomes the main controlling factor. In the production aspects of the oil and gas industry, where low particle concentrations (nominally less than 100 ppm-vol particles) are more often the case, it is more common to use the Lagrangian approach since particulate flows involving large particle accelerations frequently occur here.

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Nomenclature

A, B	adjustable parameters in Eq. (3) (–)
D_1, D_2, D_3	internal diameters as indicated in Fig. 1 (m)
C	Non-Stokesian correction factor. In Stokes regime, $C=1$.
C_v	Solids concentration by volume (ppm)
d_p	monodispersed particle diameter (m)
d_m	mean particle diameter (m)
d_{50}	value of particle diameter at 50th percentile of particles passing sieve (m)
e	specific erosion rate (kg eroded/kg impacting)
E	expansion or contraction ratio, ratio of downstream chamber diameter to upstream chamber diameter (–)
E_L	linear material removal rate (m eroded/s)
$f(\alpha)$	dimensionless wear function defined by Eq. (3) (–)
G_0	overall mass flow rate of sand (kg/s)
h	step height (m)
IPD	inter-particle distance, as defined in Eq. (1)
k	kinetic energy of turbulence (m^2/s^2)
K	scaling parameter in Eq. (2) $(m/s)^{-n}$
l_{ref}	reference length scale (m)
l_b/h	dimensionless distance from backward-facing step
l_f/h	dimensionless distance from forward-facing step
n	adjustable power law exponent in Eq. (2)
n_p	power law exponent for particle size effect in Eq. (4)
p	pressure (Pa)
Q_g	Volumetric flowrate of air flow through test-section (m^3/s)
Re	Reynolds number, $\overline{U}D_1/\nu$ (–)
S	loading ratio in Eq. (1) (kg particles/kg air)
T_g	ambient air temperature (°C)
$\mathbf{u}$	air velocity vector (m/s)
u	local air velocity magnitude (m/s)
$\overline{U}$	free-stream velocity (m/s)
v	impact velocity (m/s)
x, y, z	pipe cavity coordinate system defined in Fig. 1.
W, X, Y, Z	adjustable parameters in Eq. (3) (–)
α	particle impact angle (degrees)
ε	turbulence eddy dissipation rate (m^2/s^3)
φ	adjustable parameter in Eq. (3)
μ	air viscosity (kg/m/s)
ν	air kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)
ρ_p	particle density (kg/m^3)

The study of sudden expansions in erosion studies is important since this is one of the several generic configurations that is most susceptible to erosion damage under certain operating conditions [10]. The radial velocity developed downstream of the expansion forces particles towards the wall. The high level of turbulent kinetic energy in that region also contributes to forcing particles towards the wall. Both of these mechanisms combine to further enhance the erosion in the larger diameter pipe [10].

Nugroho et al. [10] employed commercially available Computational Fluid Dynamics (CFD) code to predict sand erosion in sudden expansion flows using sand suspended in an air flow for diameter ratios (E) ranging from 1.25 to 2. The diameter ratio is defined as the ratio of the downstream pipe diameter to the upstream pipe diameter. Their CFD results were validated with experimental data. They assumed a dilute concentration of sand in their model to justify their use of one-way coupling between the fluid and the particles. Both approaches show that maximum erosion rate, in terms of thickness loss per mass of erodent passage through the geometry, decreases with increasing expansion ratio. This suggests that pipe arrangements where diameter ratios are small may pose an increased erosion risk in plant equipment. Areas of risk include pipe joints, weld bead protrusions, shallow cavities, chokes and sudden contractions.

Table 1 summarises the relevant literature on erosion studies related to sudden expansions or contractions in pipes, cavity flows and/or a combination of these. The majority of the work in sand erosion has been conducted in the liquid phase, while only limited studies have been conducted in the gas phase [10]. Additionally, all the studies have focussed on particles larger than 150 μm and none have investigated erosion with smaller particles. With a recent increase in global demand for natural gas as one alternative for crude oil [11], it is surprising that there is a dearth of erosion research in gas-dominant flows related to expansion flows. The present work builds on previous sand erosion research at CSIRO (Commonwealth Scientific and Industrial Research Organisation) addressing the needs in the minerals industry, which encounters mainly high solids concentration slurries flowing through various piping systems. The authors have explored methods to understand sand erosion in water on various geometries through multi-layer paint erosion modelling (e.g. [12–14]), employed computational fluid dynamic simulations to predict erosion in cylinder-in-pipe configurations [15] and used surface profilers to more accurately determine eroded surfaces [16]. More recently research of solid particle erosion around a hole in low solids concentration pneumatic (gas-dominant) systems has been conducted [17,18].

The current research contributes to the understanding of gas-dominant flows through the study of a potentially critical erosion risk amongst oil and gas companies – particulate erosion at stepped interfaces in low solids concentration pneumatic systems, commonly found in oil and gas facilities. The work involved conducting simultaneous multi-layer paint erosion experiments and physical material loss erosion experiments in a 6061-T6 aluminium annular pipe cavity, and measuring the eroded surface with a high-resolution surface metrology device (using a coordinate measurement machine – CMM). The experimental arrangement is described in Section 2, while the experimental results are presented in Section 4.1. These results are complemented by respective CFD simulations of the pipe cavity in Section 3 under similar conditions. The CFD analysis of the experimental system follows in Section 4.2, which uses the commercial CFD code ANSYS-CFX13 in combination with an experimentally derived erosion model based on the work of Chen et al. [25], using the methodology of Wong et al. [17,26]. Key results are then discussed in Section 5 and conclusions drawn in Section 6.

2. Experimental methodology

2.1. Apparatus

In order to investigate the progressive erosion of an aluminium pipe cavity (Fig. 1) by silica sand, a laboratory scale experimental apparatus was designed and built. The test section and experimental rig is shown schematically in Fig. 2. The apparatus comprises an open-circuit wind tunnel with a circular cross-section of diameter 101.6 mm (4″). A 75 kW blower draws ambient air into the system and air flow rate is determined by measuring the pressure drop across a 250 mm-diameter (ID) conical inlet at the entrance to the blower. The wind tunnel has three main