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Abrasion erosion modeling in particulate flow

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ABSTRACT

Solid particle erosion is of great importance to many industries including oil and gas production, drilling, process and transportation of minerals including oil sands. The particles that may cause erosion are of various sizes, shapes and hardnesses. These particles may impact the surface at various speeds and angles, and the influence of these parameters is characterized to some extent in the literature. Experimental and numerical studies have shown that when particles are transported by liquid (e.g. slurry transport in the pipe) or dense gas, the particle impact angles are very low. The impact angles in these cases are sometimes less than the smallest value that can be obtained in a direct impingement erosion test in gas. In this work, the mechanistic erosion equation developed previously is extended to near zero impact angles for sharp particles. The abrasion erosion equation is developed by introducing an initial penetration of the sharp particle in the equation of the motion. This initial penetration may be attributed to the sharp particle rotation and/or turbulent flow fluctuations of the carrier fluid near the wall. The empirical constants are obtained from submerged erosion experiments in liquid. The equation has been implemented in a commercially available Computational Fluid Dynamics (CFD) code (ANSYS FLUENT) to calculate erosion for a submerged impingement jet geometry, and the result is compared with the experiment. It is shown that by neglecting the abrasive term in the erosion equation, the specimen mass loss does not match the experimental measured mass loss. While by including the abrasive term, the total mass loss of the specimen agrees well with the experimental data. Moreover, the erosion pattern becomes closer to the experimentally measured pattern especially farther from the center of the highly eroded area where abrasive wear is expected to dominate.

1. Introduction

Many industrial processes involve particulate multiphase flow in which the carrier phase is continuous and the solid phase is dispersed in the carrier phase. A mixture of water, oil, gas and sand particles is an example of particulate flow in oil and gas industry. Sand particles that impact the wall at high velocity can cause severe erosive damage to the production, process and transportation facilities in the petroleum industry [1]. Power plants and aerospace industries also deal with particulate flows and may suffer from solid particle erosion.

Erosive wear, commonly known as erosion, is defined as material loss resulting from impact of solid particles on the material surface. In complex piping systems, with sand particles present in the fluid, particles sliding or hitting the material surface will result in material deformation, cutting, fatigue cracking or a combination of these. The type of erosion depends on many factors including but not limited to particle shape and size, material brittleness and ductility, and particle impact speed and angle. Meng et al. [2] presented a list of wear mechanisms caused by particle impact used commonly in the literature. From this list, abrasive wear is defined as a combination of cutting, fatigue failure and material transfer.

When slurries are transported through a pipe at a typical bulk velocity, the particles settle at the lower pipe wall due to gravitational forces. This creates a dense, sliding bed of particles that moves slower than the fluid along the pipe [3,4]. This action of the solid bed inflicts erosive damage on the pipe walls. This is the wear mechanism better known as abrasive wear and is one of the main wear mechanisms in slurry erosion. The remaining particles above the bed are assumed to be suspended by turbulence effects and particle lift forces. These effects cause particles to impinge the pipe walls, and this erosion effect is called impact based erosion. Slurry erosion of materials due to the impingement and/or abrasive motion of solid particles is a major problem in various components in fracturing equipment dealing with injection of particles and proppants and transport of cuttings in the oil and gas industry. There are many cases in industry where the particle impact angle is very low (less than 5°). Fig. 1 shows CFD simulation and particle tracking results for a 4" elbow where the fluid is water and the tracked particles are 150 μm. The left figure is a surface contour

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Nomenclature

A	Area (m^2)
c	Particle concentration (kg/kg)
C_1	Cutting erosion constant
C_2	Deformation erosion constant
ER	Erosion ratio (kg/kg)
F	Force (N)
F_s	Particle sharpness factor
K	Ratio of vertical to horizontal projected contact area
m	Particle mass (kg)
n	Ratio of contact area to the removed area
P	Material flow pressure (Pa)
R	Particle size (m)
t	Time (s)
U	Velocity (m/s)
U_{tsh}	Deformation erosion threshold velocity
x	Particle tip horizontal location (m)
y	Particle tip vertical location (m)
y_o	Particle initial penetration (m)
θ	Impact angle (deg)
ρ	Density (kg/m^3)

plot of impact velocity and on the right is a surface contour plot of average impact angle. It is observed that the maximum impact angle is less than 4°, considering a liquid viscosity of 1 cP. So, for a more viscous fluid, the particle impact angle would be even less and a typical erosion equation may not be valid.

Although many authors have examined slurry erosion and abrasion erosion of materials, very few have developed models that can be used to determine erosion caused by abrasive wear. Hashish [5] conducted an experimental and theoretical study of an abrasive jet and developed a model utilizing the theory originally proposed by Finnie [6]. Jain et al. [7,8] presented a stochastic methodology to evaluate the interaction between spherical abrasive grains and a workpiece surface in abrasive flow machining. The models developed in these works are for a specific geometry and cannot be applied to other configurations. Much research [9–12] has been conducted in the literature to determine slurry erosion, but they used empirical models based on experiments with gas to determine slurry erosion. In this study, a new semi-mechanistic abrasion erosion equation has been developed based on the experimental data from direct impingement testing and microscopic images of the eroded specimens. The previous work on the development of erosion equations has been extended to near zero impact angles. The new equation is implemented via a user defined function (UDF) into a commercially available CFD code (ANSYS FLUENT) and is used to simulate a submerged slurry jet, and the results are compared with the experimental data.

2. Abrasion erosion modeling

There are many studies of slurry flows in the literature conducted on erosion to develop an erosion equation theoretically or empirically [13–19]. The application of empirical correlations is limited to the experimented materials with specific particles and impact conditions, and theoretical formulations may not be in agreement with experimental data as they have been developed with many simplifying assumptions. Moreover, most of the equations are developed for impact angles greater than 15 degrees. For the cases where the impact angle is very low (≈ 1°), the abrasion erosion equation should be used to calculate erosion.

The model development is based on cutting erosion modeling assuming the same conditions for the particle motion in the development of a mechanistic erosion equation [20]. The forces in the x and y (Fig. 2) directions resist against the motion of the particle with respect to the surface, but for a sharp particle, there is an initial penetration to the surface that is caused by sharp particle rotation and/or turbulent flow fluctuations or by particle-particle interaction in a dense slurry flow.

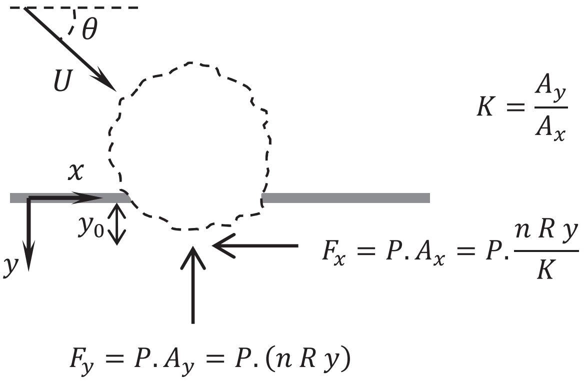

Fig. 2. Force balance of particle cutting into the surface.

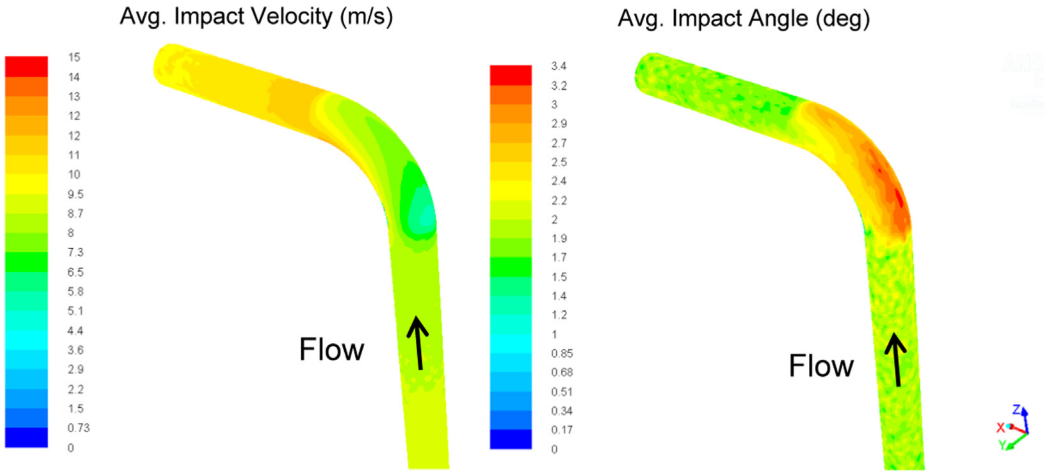

Fig. 1. Average particle impact velocity and angle (V_{SL}=15 m/s, D=4″).