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A correlation for sand erosion prediction in annular flow considering the effect of liquid dynamic viscosity

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ABSTRACT

Sand erosion is a common problem in oil and gas industry, which may lead to unpredictable failure and economic loss of pipeline systems. Due to the relatively stable state, annular flow is the predominant flow pattern and can simultaneously transport two kinds of materials (such as liquid and gas), which can reduce expenses for oil and gas production. In the present work, an accurate combination of the correlations of entrainment fraction and liquid film thickness is introduced into a modified numerical model, and is validated by experimental data. A series of numerical simulations are designed and performed to investigate the coupling effects of different parameters on erosion, such as the liquid dynamic viscosity, pipe diameter, superficial gas velocity, radius of curvature, superficial liquid velocity and particle size. Based on the knowledge gained from numerical analysis, the dimensionless π groups are proposed as well as a correlation for predicting sand erosion in annular flow, which takes the effect of liquid dynamic viscosity into account. By comparing with the experimental data and other existing correlations, the proposed correlation is confirmed as an effective and concise method, and shows good accuracy in erosion prediction.

1. Introduction

Although sand screens and gravel packs are favorable for restricting particles out of the pipeline systems, particle erosion is still an inevitable phenomenon in the transportation and production of oil and gas considering that seventy percent of the world's oil and gas reserves are entrained with sand [1]. Erosion failure is a common problem arising at the direction-change position of geometries such as elbows, chokes and T-junctions, which results in severe economic loss, environmental pollution and even disasters without the early warning of failure. Therefore, the accurate prediction model of sand erosion is of great necessity for designing equipment and predicting erosion failure in the production.

Due to the advantages of low cost in long-distance transportation, the application of multiphase flow has become increasingly common in oil and gas transportation. In the present work, the single phase flow refers to the flow including only one continuous phase such as liquid phase or gas phase without the entrained solid particles, and the multiphase flow refers to the flow consisting of two different continuous phases without the entrained solid particles. Among various multiphase flow patterns, the annular flow or annular-mist flow is regarded as the dominating flow pattern in oil and natural gas production pipelines [2]. However, the research on the annular flow is still insufficient, and few correlations for erosion prediction in annular flow are proposed by investigators. Thus, it is significant to possess the ability of prediction towards the sand erosion issue under the annular flow.

Since 1983, the empirical or mechanistic prediction erosion models under the condition of multiphase flow were proposed by researchers, but only to a limited degree. Jordan [3] extended the erosion model to multiphase flow on the basis of the erosion model in single phase flow [4] and established the prediction correlation based on the erosion mechanism in multiphase flow. On account of different "effective diameters" for each phase, the multiphase flow is divided into gas and liquid phases and the erosion values can be calculated separately. By adding up the individual erosion ratio of two phases, the erosion ratio can be obtained. McLaury et al. [5,6] also developed a mechanistic model to predict erosion for multiphase flow, which involved pipeline geometry, fluid velocity and properties of sand particles and fluid. Similarly, the model was also developed from the sand erosion model in the single phase flow [4], which was more appropriate for the multiphase flow with extremely low liquid rates. The mixture density and the particle size were taken into consideration in the erosion model for multiphase flow by Salama [7], which was developed from the equation of Salama and Venkatesh [8]. However, the effects of pipe radius of

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Nomenclature

D	pipe diameter (m)
D_c	diameter of the gas core (m)
d_p	particle size (μm)
D_0	reference diameter (mm)
d_F	hydraulic diameter of the liquid film (m)
V_g	average gas velocity in core region (m/s)
V_P	particle-wall impact velocity (m/s)
V_{sg}	superficial gas velocity (m/s)
V_{sl}	superficial liquid velocity (m/s)
V_m	mixture fluid velocity (m/s)
V_d	droplet velocity (m/s)
V_F	liquid film velocity (m/s)
R	curvature radius of the elbow (m)
Re_{SG}, Re_{SL}, Re_{LF}	Reynolds number (dimensionless)
Fr_{SG}	Froude number (dimensionless)
We_{SG}	Weber number (dimensionless)
H_V	Vicker's hardness (Gpa)
K, n	materials property constants (dimensionless)
G	particle size correlation function (dimensionless)
S_m	geometry-dependent constant (dimensionless)
C_1	model/geometry factor (dimensionless)
A_{pipe}	cross sectional area of the pipe (m^2)
N	amounts of cases (dimensionless)
E_r	experimental erosion ratio (mm/kg)
E_{test}	laboratory test data (mm/kg)
E_{pre}	predicted value (mm/kg)
P_{liquid}	sand erosion in the liquid phase (m/s)
P_{gas}	sand erosion in the gas phase (m/s)
Pr	penetration rate (m/s)
Pr'	penetration rate (mm/year)
W	sand flow rate (kg/s)
W_p	sand flow rate (kg/day)
f_E	entrainment fraction (dimensionless)
f_I	interfacial friction factor related to gas mass flux (dimensionless)
F_P	penetration factor for steel based in 25.4 mm (dimensionless)
F_M	material hardness empirical constant (dimensionless)
$F_{r/D}$	radius of curvature penetration factor (dimensionless)
F_S	sand sharpness factor (dimensionless)
X_M, Y_M	modified Lockhart and Martinelli parameters (dimensionless)
Z	parameter related to the interfacial friction and the film thickness (dimensionless)
f_F, f_{SL}	parameters from the Moody diagram for the given Reynolds number (dimensionless)
$(dp/dL)_{SC}$	superficial friction pressure gradient in the core (dimensionless)
$(dp/dL)_{SL}$	superficial liquid friction pressure gradient (dimensionless)

Greek letters

α	characteristic impact angle (rad)
ρ_t	density of pipe wall material (kg/m^3)
ρ_g	density of gas core (kg/m^3)
ρ_l	liquid phase density (kg/m^3)
ρ_c	no-slip core density (kg/m^3)
ρ_m	the mixture density (kg/m^3)
μ_m	mixture fluid dynamic viscosity (Pa·s)
μ_l	liquid dynamic viscosity (Pa·s)
σ	surface tension (Pa·m)
δ	liquid film thickness (m)
δ^+	film thickness (dimensionless)
$\underline{\delta}$	film thickness, δ/D (dimensionless)
τ_I	interfacial shear stress (N/m^3)
π_1, π_2, π_3, π_4, π_5	dimensionless numbers (dimensionless)

curvature and liquid viscosity were not considered in the process of erosion prediction. The procedure by DNV RP 0501 [9], which was proposed based on the numerical results, model equations and experimental data, presented a comprehensive guideline for sand erosion in various kinds of common geometries including blind tees, flexible pipes, smooth and straight pipes, reducers, elbows and welded joints. The DNV model can be available for conservative estimates on sand erosion. Mazumder et al. [10] proposed a mechanistic model of sand erosion for annular flow, which considered the differences in the sand impact velocities under the condition of gas and liquid phases, respectively. However, the variables such as the mixture density, particle diameter and liquid viscosity were not completely reflected if the radius of curvature is 1.5. Moreover, the mechanistic model was not applicable to other materials except for steel. From the experimental results [11,12], it was showed that dissimilar erosion ratios were observed in different multiphase flow patterns with the same flow conditions. However, it is remarkable that the multiphase flow pattern is not clearly specified in most of the existing sand erosion models, which may be not applicable to the condition of annular flow.

The shortage of erosion prediction precision results from the complicated properties of annular flow. The liquid dynamic viscosity is one of the essential parameters that influence the erosion ratio under different flow patterns. The combination effects of liquid dynamic viscosity and particle size were investigated by several researchers [13,14]. Okita et al. [13] concluded that the erosion ratio for 20 and 150 μm sand decreased with increasing liquid dynamic viscosity, while the erosion ratio for 300 μm sand was almost unchanged with increasing liquid dynamic viscosity. The multiphase flow experiments in the horizontal direction were conducted by Kesana et al. [14]. The results also revealed that the erosion trend was somewhat different for larger and smaller particles as the liquid viscosity increased. The erosion ratio decreased by a factor of 2 and 1.5 for the 150 μm and 300 μm sand from 1 cP to 10 cP, while the erosion results were slightly increased for the 20 μm sand from 1 cP to 10 cP. Vieira et al. [15] also performed experiments in annular flow to make an investigation on the influences of different factors on erosion ratios. It should be noted that the erosion ratios varied little with increasing liquid dynamic viscosity under lower superficial gas velocity, whereas, significantly changed under higher superficial gas velocity. In general, the laboratory tests show that the erosion ratio gets significant decline with increasing liquid viscosity. However, it should be emphasized that the effect of liquid viscosity is not taken as a key consideration in the prediction models as mentioned above.

The present work is an extension of the work by Liu et al. [16] and aims to establish a correlation for sand erosion prediction in annular flow considering the effect of fluid viscosity. A large number of erosion simulations using the method of computational fluid dynamics (CFD) are performed at first to investigate the coupling effects of different parameters, such as the pipe diameter, superficial gas velocity, radius of curvature, superficial liquid velocity, particle size and liquid dynamic viscosity. Based on the knowledge gained from numerical analysis, the dimensionless π groups are proposed as well as a correlation for predicting sand erosion in annular flow, which takes the effect of liquid dynamic viscosity into account. By comparing with the experimental data and existing other correlations, the proposed correlation is confirmed in both concision and accuracy. The proposed correlation can be