Wear 360-361 (2016) 121–136

Contents lists available at ScienceDirect

Wear

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

Similarity criteria of the solid particle erosion in elbows between model experiments and engineering for dry gas and gas–mist flows

Mingyang Liu [a], Haixiao Liu [a,b,*], Rong Kang [a]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form
7 April 2016
Accepted 11 April 2016
Available online 21 April 2016

Keywords:
Solid particle erosion
Erosion testing
Impact wear
Wear modeling
Mapping

ABSTRACT

Solid particle erosion in elbows is a prominent problem encountered in hydrocarbon transportation pipelines, especially for dry gas and gas–mist flows. There is great difference in flow conditions between model experiments and engineering. A set of similarity criteria is proposed to analyze the corresponding relationship between engineering conditions and that in laboratory tests. The similarity criteria aim at building a procedure that can predict the maximum penetration rate and its position in engineering conditions through the corresponding experimental design, reducing the heavy monitoring work in field circumstances. Principal dimensionless numbers on the flow field and particle response behaviors are presented to make up the similarity relationship between engineering cases and laboratory tests, respectively for dry gas and gas–mist flows. For several typical lab tests from the literature, each of them is extrapolated to a series of similar engineering cases which vary in pipe diameter and operating pressure. Then the typical laboratory tests and the corresponding engineering cases are calculated by the validated CFD method and four classic empirical or semi-empirical models to get the dimensionless penetration rates and maximum erosion positions, which are the two dimensionless similarity judgment numbers. The judgment numbers show good equivalence trends for the same series of laboratory test and its corresponding engineering cases. The similarity criteria developed in this study are verified and prove to be rational and efficient in predicting erosion in engineering through model experimental design.

1. Introduction

Erosion caused by solid particles entrained in pipelines is a serious problem involved in the hydrocarbon production systems [1]. The solid particles, which are carried with crude oil and gas extracted from the wells, usually pose accumulative and considerable erosion damage on valves, chokes, blinded tees and elbows. Due to inertia and turbulent dispersion, the particles cross the streamlines which rapidly change direction in these kinds of fittings and then collide on the pipe wall. The damage inevitably reduces the service life of these components, increases the risk of equipment failure and production halts, and may even result in great loss to the industry and threats to the environment. Hence, it is of great significance to efficiently predict the erosion damage, especially the maximum value and its location in vulnerable devices, with the aim of predicting the service life of the components and offering engineering guidance for the oil and gas industry.

Erosion is a complex process involved with numerous factors such as the properties of conveying media, transporting speed, sand flow rate, pipe wall hardness and the geometry of fittings, etc. [2]. For dry gas and gas–liquid mist flows, the momentum can hardly be changed by the carrier fluid when the sand enters the elbow because of the so small disturbance during a very short time. Hence, the sand erosion in pneumatic conveying pipelines for dry gas and gas–mist flows is much more serious than that for annular, churn, slug and totally liquid flows, where the liquid conveying proportion is much greater and in consequence tends to make the particles flow along the streamlines rather than directly impinge on the wall in straight lines. Besides, gas systems operate at higher conveying speed in most situations. In this case, the erosion prediction of pipe elbows for dry gas and gas–mist flows needs focusing on in priority.

There have been many erosion prediction models and procedures proposed by researchers since 1980s. These models and procedures can mainly be classified into two categories. One is

---

[*] Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China. Tel.: +86 2227401510; fax: +86 2227401510.

E-mail address: liuhx@tju.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.wear.2016.04.013
0043-1648/© 2016 Elsevier B.V. All rights reserved.

Nomenclature

A_{pipe}	pipe cross-sectional area (m^2)
C_1	model/geometry factor (dimensionless)
D, D_m, D_p	pipe inner diameter (m)
D_0	standard pipe inner diameter (m)
d, d_m, d_p	sand particle diameter (m)
d'	standard particle diameter (m)
ER	erosion ratio (dimensionless)
Eu, Eu_m, Eu_p	Euler number (dimensionless)
$F(\alpha)$	function of particle–wall impact angle (dimensionless)
F_e	specific erosion factor (dimensionless)
F_M	material hardness empirical constant (dimensionless)
F_P	penetration factor for steel (m/kg)
$F_{r/D}$	penetration factor for elbow curvature radius (dimensionless)
F_S	sand sharpness factor (dimensionless)
f	maximum penetration rate function (m/s)
f_1	dimensionless maximum penetration rate function (dimensionless)
G	particle size correlation function (dimensionless)
g	maximum erosion position function (rad)
g_1	dimensionless maximum erosion position function (dimensionless)
H_V	Vicker's hardness of pipe wall material (GPa)
K	material constant (dimensionless)
k	particle property constant (dimensionless)
k_1, k_2, k_3	particle property exponents (dimensionless)
N	number of calculated cases (dimensionless)
n	velocity exponent (dimensionless)
n_1, n_2	material hardness and particle property exponents (dimensionless)
Pr, Pr_m, Pr_p	penetration rate (m/s)
Re, Re_m, Re_p	pipe Reynolds number (dimensionless)
r, r_m, r_p	elbow curvature radius (m)
S_p	geometry-dependent constant (dimensionless)
St	Stokes number (dimensionless)
V'	standard particle–wall impact speed (m/s)
V_{pc}	particle–wall impact speed (m/s)
V_S, V_{Sm}, V_{Sp}	superficial velocity of carrier fluid (m/s)
V_{SG}, V_{SGm}, V_{SGp}	superficial gas velocity (m/s)
V_{SL}, V_{SLm}, V_{SLp}	superficial liquid velocity (m/s)
W, W_m, W_p	sand mass flow rate (kg/s)
X_{pre}, X_{test}	predicted value and measured datum (m/s)

Greek letters

α	particle–wall impact angle (rad)
Δ, Δ_m	absolute roughness (m)
Δ_{min}	minimum absolute roughness (m)
Δp, Δp_m, Δp_p	pressure drop at an elbow (Pa)
ζ	systematic deviation coefficient (dimensionless)
θ, θ_m, θ_p	position of maximum penetration rate (rad)
μ, μ_m, μ_p	viscosity or weighted average viscosity of carrier fluid (Pa s)
μ_G, μ_{Gm}, μ_{Gp}	gas viscosity (Pa s)
μ_L, μ_{Lm}, μ_{Lp}	liquid viscosity (Pa s)
ξ	local resistance coefficient in 90° angle (dimensionless)
π_1, π_2, π_3, π_4, π_5, π_6, π_7, π_8, π_9	dimensionless similarity numbers (dimensionless)
π	value of straight angle (rad)
ρ, ρ_m, ρ_p	density or weighted average density of carrier fluid (kg/m^3)
ρ_G, ρ_{Gm}	gas density (kg/m^3)
ρ_L, ρ_{Lm}	liquid density (kg/m^3)
ρ_s, ρ_{sm}, ρ_{sp}	sand particle density (kg/m^3)
ρ_t	pipe material density (kg/m^3)

empirical or semi-empirical models, which try to predict erosion rates by using macroscopic parameters such as sand flow rate, pipe size, superficial velocities and properties of the carrier fluid. Svedeman and Arnold [3] proposed a model to estimate the speed limit in elbows and tees based on the recommended practice by the American Petroleum Institute (API) [4]. Salama and Venkatesh [5] proposed an empirical model of penetration rates for field elbows and tees, and then modified it to predict erosion in multiphase flow by taking a weighted average of the fluid density [6]. Bourgoyne [7] presented an empirical model of estimating the penetration rates in diverter systems based on experimental data, which is mainly used to predict erosion for single-phase (gas or liquid only) flow and gas–mist flow. The model developed by DNV [8] estimated the erosion of a series of typical fittings by using the average impact angle of large amounts of particles and an impact speed index. McLaury and Shirazi [9] developed the erosion prediction model for multiphase flow based on the "stagnation length" concept by Shirazi et al. [10], which was used to calculate the characteristic particle impact velocity. The empirical or semi-empirical models are generally fitting functions of macroscopic parameters, and the deep mechanisms of pipe flow, particle motion and material damage are not taken into account. Hence, the application of these models is within the range of specific conditions. The other is generalized erosion prediction procedures, which resolve the erosion process into three parts in time sequence: the flow field of carrier fluid, the motion of particles and the collision induced damage. McLaury [11] proposed an erosion prediction procedure that analyzed all the three steps above. Wang et al. [12] proposed a simplified two-dimensional numerical method of analyzing particle trajectories within the elbow. Edwards [13] improved and applied the generalized procedure in the commercial software of computational fluid dynamics (CFD). Mazumder et al. [14] presented a new mechanistic model of predicting erosion in elbows for different flow patterns. Chen et al. [15] proposed a comprehensive procedure that combined the mechanistic analyses and numerical simulation approaches to estimate erosion in elbows for a series of multiphase flow systems. Zhang et al. [16] modified the particle near-wall behaviors and developed the two-dimensional numerical procedure based on mechanistic analyses. Zhang et al. [17] presented a probability model to predict sand erosion for fully developed straight pipe flow condition. Liu et al. [18] proposed a simplified CFD-based procedure to calculate the penetration rates in elbows for annular flow. Liu et al. [19] developed a probability model to analyze the impact-rebound-impact behavior of sand in elbows for gas flow. The generalized prediction procedures focus on the mechanisms of every step of the erosion process, providing a more detailed analysis, while much more computational parameters are introduced into the calculation. But still, it is the predominant research approach at present.