Wear 390–391 (2017) 80–83

Contents lists available at ScienceDirect

Wear

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

A new dimensionless number for solid particle erosion in natural gas elbows

Mazdak Parsi[a,*], Abdelsalam Al-Sarkhi[b], Mustafa Kara[a], Partha Sharma[a], Brenton S. McLaury[c], Siamack A. Shirazi[c]

[a] DNV GL USA, Inc. North America Oil & Gas, Katy, TX, United States
[b] Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Saudi Arabia
[c] Erosion/Corrosion Research Center, The University of Tulsa, Tulsa, OK, United States

ARTICLE INFO

Keywords:
Sand erosion
Elbow
Natural gas
Dimensional analysis
Gas-solid flow

ABSTRACT

A 2-D Computational Fluid Dynamics (CFD) model was used to investigate erosion in standard elbows (r/D = 1.5) under different flow and particle conditions. Afterwards, dimensional analysis was performed to first obtain the governing dimensionless groups and then extract self-similar behavior among them when plotted against the ratio of erosion rate/gas velocity. This resulted in the development of a new dimensionless group named penetration rate (Pnr) correlated to dimensionless erosion ratio as $(ER/V_g) \propto (Pnr)^{1.0612}$. This correlation was plotted for different experimental data; the same trend was found.

1. Available empirical correlations

Over the years, various empirical erosion prediction models have been proposed; some of which are listed in Table 1. There are also mechanistic models such as those proposed by Shirazi et al. [5] and the recommended practice of DNV GL RP-O501 [6]. A comprehensive review of available correlations and mechanistic models for erosion prediction can be found in Parsi et al. [7].

Although the correlations in Table 1 are easy to use, they do not include many of the parameters influencing erosion. Furthermore, they have been developed based upon a limited number of erosion data questioning their accuracy when extrapolated. The main goal of the current study was to develop a new dimensionless erosion number that included the principal parameters governing flow and particle response behaviors.

2. Dimensionless number development

A new dimensionless erosion number was developed based on a large set of CFD erosion data. In this context, first, a 2-D CFD-based model was used to generate the erosion data bank. Then, dimensional analysis was performed to extract important dimensionless groups governing the erosion phenomenon in elbows. Afterwards, self-similarity behavior was recognized and a new dimensionless number was developed.

2.1. Erosion modeling in standard elbows

The 2-D model of Zhang et al. [8] implemented in SPPS software of Erosion/Corrosion Research Center (E/CRC) was used to generate the erosion data bank for analysis. This model used flow Reynolds number to interpolate between some pre-saved CFD simulation data and obtain 2-D flow field information. The interpolated data included fluid velocity components, pressure, turbulent kinetic energy and its dissipation rate, and Reynolds stresses.

These data were then used for particle tracking and the particle impact information such as impact location, speed, and angle were computed. In the final step, particle impact information was input in the Arabnejad et al. [9] mechanistic erosion equation, and erosion magnitude in mm/kg was calculated (elbow material was considered as stainless steel 316). It should be noted that in the 2D simulations, a radius of curvature of (r/D) 1.5 was used for elbows. The erosion data bank generated included 183 data points. The SPPS 2-D model has been previously validated against 3-D CFD results and experimental data by Zhang et al. [8].

2.2. Dimensional analysis and self-similar behavior

Liu et al. [10] recently provided a series of similarity criteria between lab and field conditions for erosion in elbows. Accordingly, dimensionless erosion ratio (ER/V_g) is a function of the following three dimensionless groups:

* Corresponding author.
E-mail addresses: Mazdak.Parsi@dnvgl.com, Mazdak-Parsi@utulsa.edu (M. Parsi).

http://dx.doi.org/10.1016/j.wear.2017.07.005
Received 8 April 2017; Received in revised form 12 June 2017; Accepted 5 July 2017
Available online 06 July 2017

Table 1
Available empirical models for erosion prediction.

Source	Correlation	Description
API RP 14E [1]	$V_e = \frac{C}{\sqrt{\rho_m}}$	V_e: erosional velocity in ft/s C: empirical constant ρ_m: fluid mixture density in lb/ft^3
Bourgoyne [2]	$ER = F_e \frac{\rho_p}{\rho_t} \frac{\dot{W}_p}{A_{pipe}} \left(\frac{V_{SG}}{100\alpha_g}\right)^2$	ER: erosion rate in m/s F_e: specific erosion factor ρ_P: particle density in kg/m^3 ρ_t: wall density in kg/m^3 $\dot{W}_p$: sand flow rate in m^3/s A_{pipe}: cross-sectional area in m^2 V_{SG}: superficial gas velocity in m/s α_g: the gas volume fraction
Jordan [3]	$ER = 10^C V_{SG}^{2.349} \dot{W}_p^{0.9535} \left(1 - \left(1 + \frac{1}{2r_c}\right)^{-2}\right)^{\frac{1.8885}{2}}$	r_c: bend radius of curvature The units are similar to those in Bourgoyne's [2] equation.
Salama [4]	$ER = \frac{1}{S_m} \frac{\dot{W}_p V_f^2 d_p}{D^2 \rho_m}$	d_p: particle diameter in microns S_m: geometry dependent constant ER, $\dot{W}_p$, ρ_m and D are in mm/year, kg/day, kg/m^3, and mm, respectively.

$$\begin{cases} \pi_1 = \frac{\rho_g V_g D}{\mu_g} \\ \pi_2 = \frac{d_p}{D} \\ \pi_3 = \frac{\rho_p}{\rho_g} \end{cases} \tag{1}$$

which are the gas Reynolds number (Re), particle diameter (d_p) to pipe diameter (D) ratio, and particle density (ρ_p) to gas density (ρ_g) ratio, respectively. μ_g is the gas viscosity. The dimensionless erosion ratio is defined as the ratio of erosion rate (ER) to gas velocity (V_g) each with the unit of m/s. Through CFD modeling, Liu et al. [10] showed that to simulate engineering field conditions in the lab, these dimensionless groups must be identical (i.e. $\pi_{ilab} = \pi_{i\,field}$ i = 1–3).

Here, the procedure to extract the self-similar relationship between the dimensionless erosion ratio and the relevant dimensionless groups (π_1-π_3) is explained. The individual dimensionless groups do not demonstrate self-similarity when plotted against ER/V_g. A power law relationship can be established by combining the three dimensionless parameters into one group:

$$\pi_4 = Re^{1.372} * \left(\frac{d_p}{D}\right)^{3.41} * \left(\frac{\rho_p}{\rho_g}\right)^{1.45} \tag{2}$$

It should be noted that particle Stokes number (St) can be obtained from combining the three dimensionless groups used and therefore, it is not considered as a separate dimensionless group. Fig. 1 shows the relation between π_4 and ER/V_g suggesting the need for inclusion of a reference particle diameter to collapse all data on one single line. The reference diameter can be any diameter such as the maximum or minimum diameter. Therefore, a new dimensionless number, Pnr, can be developed as shown in Eq. (3). A particle reference diameter (d_{p_ref}) of 400 µm was selected.

$$Pnr = Re^{1.372} * \left(\frac{d_p}{D}\right)^{3.41} * \left(\frac{\rho_p}{\rho_g}\right)^{1.45} * \left(\frac{d_{p\_ref}}{d_p}\right)^{3.1} \tag{3}$$

As illustrated in Fig. 2, the new dimensionless number (Pnr) shows self-similar behavior regardless of the pipe diameter, particle size, gas velocity, and gas density. It is seen how all data points collapse on the same line. Accordingly, the following trend line can be established:

$$\frac{ER}{V_g} = 2.2855 \times 10^{-12} (Pnr)^{1.0612} \tag{4}$$

3. Correlation validation

104 erosion data points available in the literature were used to examine the validity of the model. This included 84 laboratory experimental data points [2,4,11–17] as well as 30 test-case results obtained via 3D CFD simulations for large pipe diameters and/or high gas pressure flows [18]. Bourgoyne [2] data were divided into 2 sets: one set for elbow radius of curvature of r/D = 1.5, and the other for larger radius of curvatures.

These 104 data points are demonstrated on a log-log plot in Fig. 3a where the dashed line indicates Eq. (4). Favorable agreement between the data points and the correlation developed can be noticed. Fig. 3b

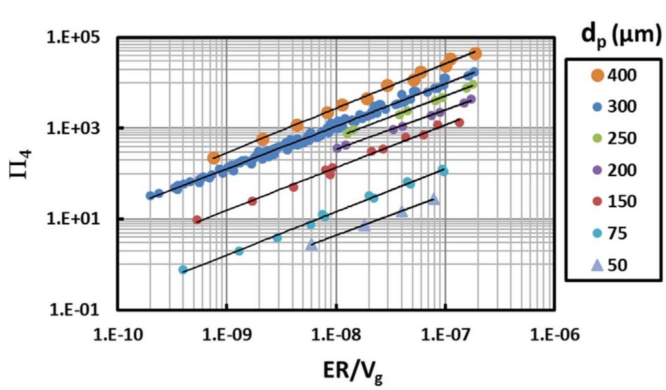

Fig. 1. π_4 versus dimensionless erosion ratio (ER/V_g) for different particle sizes. A particle size ratio can be used to collapse lines for different particle sizes on one single line.

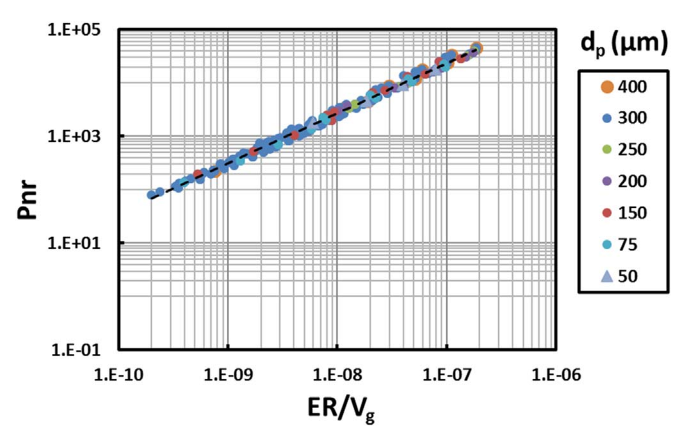

Fig. 2. Self-similarity: Pnr versus dimensionless erosion ratio (ER/V_g) for different particle sizes.