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An Alternative to API 14E Erosional Velocity Limits for Sand Laden Fluids

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Abstract

The current practice for eliminating erosional problems in piping systems is to limit the flow velocity (V_e) to that established by the recommended practice API RP 14E based on an empirical constant (C-factor) and the fluid mixture density (ρ_m) as follows:

$$V_e = \frac{C}{\sqrt{\rho_m}} \qquad (1)$$

The API criterion is specified for clean service (non-corrosive and sand-free) and it is noted that the C-factor should be reduced if sand or corrosive conditions are present. The validity of the equation has been challenged on the basis that the API RP 14E limits on the C-factor can be very conservative for clean service and is not applicable for conditions when corrosion or sand are present. Extensive effort has been devoted to develop an alternative approach for establishing erosional velocity limits for sand laden fluids. Unfortunately, none of these proposals have been adopted as a standard practice because of their complexity. This paper will review the results of these studies and proposes an alternative equation that is as simple as the API 14 E equation. This alternative Equation has the following form:

$$V_e = S\,\frac{D\sqrt{\rho_m}}{\sqrt{W}} \qquad (2)$$

The value of the S-factor depends on the pipe geometry, i.e. bend, tee, contraction, expansion, etc. Using the units for mixture flow velocity (V_e) in m/s, fluid mixture density (ρ_m) in kg/m^3, pipe diameter (D) in mm and sand production (W) in kg/day, the value of the S-factor is 0.05 for pipe bends. The accuracy of the proposed equation for predicting erosion in pipe bends for fluids containing sand is demonstrated by a comparison with several multi-phase flow loop tests that cover a broad range of liquid-gas ratios and sand concentrations.

Introduction

Erosion is defined as the removal of material from a solid surface by the repeated application of mechanical forces. These forces are induced by solid particles, liquid droplets, or cavitation. Liquid impingement erosion occurs when liquid drops or liquid jet repeatedly impact the solid surface. Erosion may be attributed to removal of the metal, the inhibited film, and/or protective corrosion scales. In order to avoid erosion damage, the current oil industry practice for sizing process piping, flow lines, pipelines, and tubing is to limit the flow velocity to the maximum erosional velocity as calculated by the following API RP 14 E equation (API, 1981, 1991):

$$V_e = \frac{C}{\sqrt{\rho_m}} \qquad (3)$$

where:

V_e	=	fluid erosional velocity, ft/sec
C	=	empirical constant;
	=	100 for continuous service and 125 for intermittent service. Consideration should be given to reducing these values if solids production (sand) is anticipated. In the latest API RP 14E (1991) higher C-values of 150 to 200 may be used when corrosion is controlled by inhibition or by employing corrosion resistant alloys.
ρ_m	=	gas/liquid mixture density at flowing pressure and temperature, lb/ft^3

The original API criterion is specified for clean service (noncorrosive and sand-free), and it is noted that the C-factor should be reduced if sand or corrosive conditions are present. However, no guidelines are provided for these reductions. It has been argued by several investigators that the API RP 14E relation is extremely conservative under these conditions and this led to the changes in the 1991 edition. However, the recent changes imply that a C-factor of 100 is acceptable for corrosive systems and a C-factor of 150 to 200 is acceptable for inhibited systems.

In this paper, the basis for the API RP 14E equation will be investigated and the current industry practice in its application will be examined. The paper will then focus on examining the validity of the API 14E equation for sand laden fluids and present several models that are being advanced by the industry to predict sand erosion in piping systems. A new simplified model will be proposed and its accuracy will be examined using a large number of two-phase (liquid-gas) flow loop experiments.

Basis of the API RP 14E Erosional Velocity Equation

The basis and the source of this API RP 14E equation have been the subject of speculation in several papers and reports. Several suggestions were offered for the basis of this equation. These suggestions are summarized in **Table 1**.

Salama and Venkatesh (1983) suggested that the form of the API equation is the same as equations predicting pressure drop, erosion rate due to liquid impingement, or shear stress on the corrosion inhibitor. Salama and Venkatesh derived a C-factor of 80 to 100 for typical limits on pressure drop for high capacity wells, a C-factor of 300 for limiting erosion due to liquid impingement, and a C-factor of 35,000 for preventing the stripping of corrosion inhibitor layers.

Heidersbach (1985) suggested that the equation was adapted from petroleum refinery practice where flow velocities are kept low to minimize pumping requirement, which is expensive at high flow velocities.

Rybicki (1987) suggested that the API form of the equation can be derived from the following water hammer equation (Engel, 1955):

$$P = \frac{\alpha}{2} c \rho V \tag{4}$$

Where:

P is the water pressure due to impact
α is a shape factor for the liquid
C is the speed of sound in the liquid which equals to $(K/\rho)^{1/2}$
ρ is the density of the liquid
K is the bulk modulus of the liquid

The above equation can be re-written as follows:

$$V = \frac{\left(\frac{2P}{\alpha\sqrt{K}}\right)}{\sqrt{\rho}} = \frac{C}{\sqrt{\rho}} \tag{5}$$

Gipson (1989) suggested that the value of the C-factor in the API equation is the same as the value required to avoid excessive noise in a piping system. For piping system, excessive noise is eliminated if the piping velocity head is less than 1.3 psi. This is achieved by limiting the flow velocity to that corresponding to a C-factor of 110.

Deffenbaugh and Buckingham (1989) proposed that the API 14E equation was adopted based on the average of a similar formula that was used by several companies with constants varying between 80 to 170. The selection of a constant of 100 was based on the consensus of the committee, rather than on any available data.

Smart (1990) suggested that the API formula has no theoretical justification, and it is an empirical formula that was apparently derived from experience in steam power plants for use in multi-phase steam condensate piping system and attributed it to Keeth (1946). However, Keeth's paper does not provide any information on velocity limitations, it only discusses corrosion erosion problems in boiler feed pumps and the application of steels containing Cr.

Smart (1990, 1991) stated that the API 14E committee intended for the equation to be applied to uninhibited oil and gas production in carbon steel piping and, therefore, the velocity limits using a C-factor of 100 is intended for corrosive service. It is not clear how this argument can be correct since unacceptable corrosion rates may result in uninhibited oil and gas production at velocities much lower than the API RP 14E limiting velocity.

Coker (1990) stated the index based on velocity head can indicate whether erosion-corrosion may become significant at a particular velocity and can be used to determine the range of mixture densities and velocities below which erosion-corrosion should not occur. This index is $\rho_m V_m^2 \leq 10{,}000$ (units of ft/sec and lb/ft^3). Coker attributed this index to Coulson and Richardson (1977).

In examining Coker's reference of Coulson and Richardson (1977), the following statement was found on Page 91, "Two-phase systems are often accompanied by erosion, and many empirical relationships have been suggested to avoid this condition. An indication of the velocity at which erosion becomes significant may be obtained from:

$$\rho_m V_m^2 = 15{,}000 \tag{6}$$

where ρ_m is the mean density of the two-phase mixture (kg/m^3) and V_m the mean velocity of the two-phase mixture (m/s)." In units of lb/ft^3 and ft/sec, the constant becomes 10,000 and the above equation becomes the same as the API RP 14E equation. Unfortunately, Coulson and Richardson (1977) did not provide any reference for their equation, and in a private communication with Richardson, he could not identify the source. Although Coulson and

Richardson (1977) did not make any reference to corrosion when presenting the above equation, it is not clear why Coker (1990) added the word corrosion and attributed it to Coulson and Richardson.

Patton (1993) suggested that the equation was developed by the United States Navy during World War II, and used a C-value of 160 for solids-free fluids in carbon steel piping. He also suggested that the equation was, subsequently, incorporated in API RP 14 E and a C value of 100 was adopted. Patton did not provide any reference to the Navy's work.

Both Salama and Venkatesh (1983), and Heidersbach (1985) suggested that the API equation was based on limits on pressure drop in pipes. As an extension to this argument to two-phase flows, it is possible to write the following equation to predict pressure drop in two phase horizontal pipes:

$$\frac{\delta P}{\delta L}=\left(\frac{0.00045}{D^{1.2}}\right)\ \left(V_m\sqrt{\rho_m}\right)^{1.62} \qquad (7)$$

Where:

$\delta P/\delta L$ is the pressure drop per unit length in psi/ft
D is pipe diameter in inches
V_m is the mixture Velocity in ft/sec
ρ_m is the mixture density in lb/ft^3

The comparison between predictions made by Equation 2 for several two phase flows and those made using Beggs and Brill (1973) correlation is shown in **Figure 1**. Beggs and Brill correlation was used because it was identified as the most accurate over a wide range of conditions (Behnia, 1991).

All of the above explanations attempted to rationalize the validity of the form of the API 14E equation. Several authors attempted to rationalize the validity of the C-factor limit. However, none of the references succeeded in providing evidence supporting the use of a C-factor of 100 or 150 to avoid erosion.

Application of the API RP 14E Erosional Velocity Equation

Although the source and validity of the API 14 E erosional velocity equation is being questioned by many, its use within the oil industry is wide spread. However, many companies are using higher values for the C-factor than suggested in the API RP 14E document. Deffenbaugh and Buckingham (1989) reported that Mobil does not limit flow velocities, and Arco uses a C-factor of 200 for continuous service and C-factor of 250 for intermittent service when corrosion is controlled and if sand can be avoided. Deffenbaugh and Buckingham (1989) presented data developed by Arco on velocity effect of inhibited systems (with and without solids) on carbon steel and 316 stainless steel for pipes, elbows, and chokes. The results showed that for straight pipe section, no erosion/corrosion was observed for C-factors up to 500. For other components, no erosion/corrosion was reported for C-factors up to 300, even with sand.

Heidersbach (1985) reported that Phillips does not use RP 14E to determine production rates. Erichsen (1988) reported that one North Sea operator produced from a condensate well at a velocity of 286 ft/sec (C-factor of 726) for 1050 days (@ 2.9 years) until a failure occurred in the AISI 4140 carbon steel tubing at the flow coupling upstream of the SCSSV. The failure of the coupling was attributed to liquid impingement caused by the fluids exiting the 2-inch downhole safety valve into the 3.9-inch tubing. The flow coupling was replaced by L80-13 Cr material and no failure was reported, but the velocity was also reduced. Erichsen (1988) also reported that another North Sea operator has used a C-factor of 300 as upper limit for Gullfaks subsea water injectors. The tubing for these injectors are L80-13 Cr. One should not, however, be surprised if corrosion failure occurs in this system at the joints because of the susceptibility of 13 Cr to crevice corrosion and pitting.

Results by Camach (1988) showed no erosion damage for N-80 steel after repeated impact by liquid slug at a velocity of 100 ft/sec, which corresponds a C-factor of 800. When erosion damage was observed, it was attributed to the presence of microscopic solid particles in the liquid. Three month tests conducted at a velocity corresponding to a C-factor between 220 and 260 in a seawater flow loop containing fiberglass pipes and pipe bends of CuNi and stainless steel (Saetre, 1991). The tests were concluded without any erosion damage in the fiberglass, CuNi, or stainless steel.

Single (distilled water) and two-phase (water and nitrogen) flow loop test results on simulated tubular joints (Salama, 1996) showed that, providing corrosion can be suppressed, a C-factor of 400 can be used without any concern for erosion. The results show that there is no difference between erosion/corrosion rate for a C-factor of 40 and that of 400. The results also show that at a C-factor of 400, carbon steel showed no signs of erosion when corrosion was suppressed by cathodic protection. High corrosion rates were, however, observed when the steel joints were not cathodically protected. This high corrosion rate was unexpected because the oxygen level was very low. However, experimental results (Salama, 1993) have confirmed that corrosion rates in a deaerated system can be high when the pH value is low, which was the situation in this case.

Since corrosion rates can be influenced by flow velocity, C-factor values higher or lower than 100 are possible depending on the operating condition. Even for systems that rely on inhibitors to suppress corrosion, the use of a C-factor of 150 to 200 as suggested by API RP 14E can be risky unless the inhibitor is evaluated using a flow loop testing at the operating C-factor. In many cases, inhibitors that provide good protection under stationary conditions lose their effectiveness at higher velocities even at C-factors lower than 100 (Greving. 1991). However, there are inhibitors that maintain their effectiveness even at a C-factor of 400 (Greving, 1991). Therefore, extreme care must be taken in selecting inhibitors for systems operating at high C-factors.

Sand Erosion

Unlike erosion in sand-free systems where erosion rate is related to two parameters, i.e. mixture density and flow velocity, erosion due to sand is influenced by several factors including fluid characteristics (flow rate, composition, density, viscosity), sand characteristics (concentration, impact velocity, impact angle, number of particles hitting the surface, shape/sharpness, hardness, size distribution, density), component geometry (bend, Tee, choke, joint), and material properties (hardness, microstructure). There exists an extensive data base that can be used to characterize erosion rate of different materials. These data are generally presented using the following equation:

$$E_r = A\ V_p^n\ F(\alpha) \qquad (8)$$

where:

E_r is erosion ratio measured as the ratio between the mass of metal loss and the mass of sand hitting the target material.

A and n are experimentally determined constants that depend on the material properties. For ductile materials the value of n is in the range of 2 to 3. For brittle material n can be as high as 6.

V_p is the impact velocity of the sand particle on the metal surface. This velocity depends on the flow conditions, the geometry of the component, and sand properties (density and size).

$F(\alpha)$ is a function whose value varies between 0 and 1 depending on the impact angle. The function depends on the target material ductile/brittle behavior. The value of $F(\alpha)$ is maximum for ductile materials such as steel at impact angles of 20 to 40°, and for brittle materials such as ceramics at 90°.

The difficulty in calculating erosion rates is in predicting the proper values of particle impact angle, α, and velocity, V_p, whose values depend on: fluid density, fluid viscosity, sand particle diameter, sand density, pipe diameter, and pipe geometry (Elbow, Tee, Choke, etc.). Also, the amount of sand hitting the target is influenced by the flow conditions, sand concentration and the geometry of the component, therefore, it may not be the same as the total amount of sand in the flow. One can account for these factors through the use of computational fluid dynamic (CFD) analyses and particle tracking simulation models.

There are six models that have been developed within the industry for predicting sand erosion in piping systems. These models are based on work done by Salama and Venkatech of Conoco (1983), Svendeman and Arnold of SouthWest Research (1994), Morud and Kvernvold of DNV (1994), Shirazi, et al, of Tulsa University (1993, 1994) and Birchenough, et al, of AEA (1993) and Lockett, et al, of AEA (1997). All models are limited to erosion predictions in simple pipe geometries such as pipe bends and tees.

Salama and Venkatech's model (1983) is a closed form equation whose predictions are accurate for mainly gas systems. The model was verified using sand erosion data in air flow. This model suggests the following equation for erosion prediction in steel with yield strength of 50 to 80 ksi:

$$ER = S_k \frac{W V^2}{D^2} \qquad (9)$$

Where:

ER is erosion rate in mpy
W is sand flow rate in lb/day.
V is fluid flow velocity in ft/sec.
D is pipe internal diameter in inches.
S_k is a geometry dependant constant.

Salama and Venkatech (1983) suggested the following values for S_k:

S_k = 0.038 (for short radius bends)
S_k = 0.019 (for ells and tees)

Svendeman and Arnold (1993) using correlations derived by Bourgoyne (1989) recommended the same equation proposed by Salama and Venkatech (1983), but proposed different values for S_k. Their values for gas systems are as follows:

S_k = 0.017 (for long radius elbow and ells)
S_k = 6×10^{-4} (for plugged tees)

AEA developed two models. The first model was based entirely on experimental correlations and it has the following form:

$$ER = M\ (C_1 + C_2\ V_m\ \sqrt{\rho_m}) \qquad (10)$$

Where:

C_1 and C_2 are constants whose values depends on materials (steel, 13 Cr and duplex) and flow pattern (bubble, churn, annular)

The difficulty with this AEA model is that under certain flow conditions the values of C_1 or C_2 become zero. For a constant sand production rate (kg/day), the AEA model suggests that the erosion rate is independent of the flow velocity in cases when the value of C_1 is zero, and inversely proportional to the velocity in the cases when C_2 is zero (note that M in the above equation refers to sand concentration). Recognizing these objections, AEA developed another erosion model that is available in a spread sheet form and has the following form:

$$ER = F\,(a\,V_l^n + b\,e^{-cV_l}) \tag{11}$$

Where:

a, b and c are functions of the gas velocity.

F is a function of several non-dimensional groups that relates values from experiments to the values under the process conditions.

The models developed by Tulsa University and DNV are similar in their attempts to incorporate flow conditions in the erosion prediction model. The Tulsa model relies on empirical formulas to account for particle tracking while the DNV model allows actual calculations, though simplified, of the trajectories of the sand particles. While all other models predict a single value that corresponds to the maximum erosion rate, the DNV model predicts erosion rate distribution along a pipe bend based on calculations of impact velocity and angle at all locations.

The models developed by Salama and Venkatesh, Tulsa University and DNV incorporate the standard erosion equation:

$$E_r = A\,V_p^n\,F(\alpha) \tag{12}$$

However, the values of the constants are different. While the value of n in Salama and Venkatesh's model is 2, the value is 1.73 in the Tulsa University's model and 2.6 in the DNV's model. The value used in Tulsa's model appears to be low.

Although each model claims to be verified based on experimental data, their predictions for the same case can vary by two orders of magnitude. Resolution of these differences is critical because while one model shows that certain operating conditions are acceptable, another model shows them unacceptable, which makes it necessary to reduce production rate.

Proposed Sand Erosion Model

Extensive effort has been devoted to develop an approach for establishing velocity limits for sand laden fluids. Unfortunately, none of these proposals have been adopted as a standard practice because of their complexity. There is a need for a reliable, yet simple, equation, as simple as the API RP 14 E equation, to establish erosion rate or erosional critical velocity for fluids containing sand. Although the equation proposed by Salama and Venkatesh (1983) is simple, it is not very accurate when applied to two-phase (gas-liquid) flow systems. When proposing their equation (Equation 9), they suggested that the fluid properties have an effect on erosion rate, but they selected the constant of the equation based on calibration with sand erosion in air. Not surprising that their equation becomes increasingly conservative as the liquid-gas ratio increases, i.e., as the mixture density (ρ_m) increases. In addition, they did not account for the sand particle size which is known to have an effect on erosion rate for particles less than 400 microns. Above 400 microns, the effect of sand particles becomes negligible. Note that for the same amount of sand, the number of particles decreases as the size of the particles increases.

The new equation being proposed in this paper is based on modifying Equation 9 by incorporating the effect of fluid mixture density and particle diameter as follows:

$$E_p = \frac{1}{S_p}\,\frac{V_m^2\,d}{D^2\rho_m} \tag{13}$$

The accuracy of Equation 13 is demonstrated by comparing its predictions with measured erosion rates in pipe bends from flowloop experiments conducted under different flow conditions, liquid-gas ratios, sand size, pipe size, and by different investigators. The results of this comparison are presented in Table 2 and shown in **Figure 2**. The value of S_p, as well as the value of other constants that will be derived later by reformatting Equation 4, are given in **Table 2**.

Equation 13 can be re-written to predict erosion rate (mm/yr) in terms of sand production rate (kg/day) as follows:

$$ER = \frac{1}{S_m}\,\frac{W\,V_m^2\,d}{D^2\rho_m} \tag{14}$$

For oil and gas production, typical sand size is 250 micron and in general erosion rate in the order of 0.1 mm/yr (4 mpy) is considered tolerable. Therefore, the erosional velocity limit can be given in the following form:

$$V_e = S\,\frac{D\sqrt{\rho_m}}{\sqrt{W}} \tag{15}$$

Sometimes, operators establish operating conditions based on a certain tolerable sand concentration. The above equation (Equation 13) can be rewritten in terms of sand concentration as follows:

$$ER = \left(\frac{1}{S_c}\right) M\,d\,V_m^3 \tag{16}$$

Typically, a tolerable sand concentration of 5 ppm is specified and a sand size of 250 micron is considered. Considering a tolerable erosion rate of 0.1 mm/year (4 mpy), the critical erosional mixture velocity for elbows is: V_e = 11.7 m/s.

Proposed Erosional Velocity Limits

The accuracy of the form of Equation 13 is clearly demonstrated as shown in Figure 2. The value of the constant S_p and the other related constants for the different pipe geometries can be derived based on experimental results as given in **Table 3** or by detailed CFD analysis for the required geometry. Based on the extensive experimental data base presented in Table 3, it is recommend that the value of the constants should be limited to those identified for elbows. The constants are validated based on tests conducted by four independent laboratories. The constants based on the work by Bourgoyne appears to be high and therefore cannot be used without further validation. In the proposed equation, the effect of pipe bend was not considered because test results did not show a major difference between erosion in 1 1/2 and 5 D elbows. For plugged tee, both CFD analysis and limited experimental work suggest that the erosion rate is lower than that for elbows. But the effect decreases as the liquid to gas ratio increases. This observation is also illustrated by Bourgoyne's work.

Using Equation 15 as the basis, the following is the recommended equation for establishing erosional velocity limits for oil and gas production:

$$V_e = \frac{D\sqrt{\rho_m}}{20\sqrt{W}} \quad (17)$$

Conclusions and Recommendations

1. For solid-free, noncorrosive fluids, providing pressure drop is not a concern, the maximum flow rate can be established using the following form of API RP 14E equation:

$$V = \frac{400}{\sqrt{\rho_m}} \quad (18)$$

Where:

V is the maximum fluid velocity limit in ft/sec
ρ_m is the gas-liquid mixture density at flowing pressure and temperature in lb/ft^3.

2. For sand-free, corrosive fluids, inhibitors exist that are effective at flow velocities corresponding to C-factors higher than 300. However, it is very important that the effectiveness of the inhibitor be evaluated in a flowloop at these high velocities. For multi-phase pipelines, the effectiveness of the corrosion control program depends on the proper transport of the inhibitors in the pipeline.

3. For sand-laden fluids, the maximum flow rate limit can be established using the following equation:

$$V_e = \frac{D\sqrt{\rho_m}}{20\sqrt{W}} \quad (19)$$

4. At high flow rates, the presence of sand enhances the corrosion of steel in both uninhibited and inhibited solutions due to erosive wear of protected corrosion product and/or depolarization of anodically/cathodically controlled corrosion process by plastic deformation of the metal surface. At low flow rates where sand settling occurs, sand has no effect on corrosion rates in uninhibited solutions, but it can have a profound effect on the rates in inhibited solutions.

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Nomenclature

(units are as stated here, unless noted otherwise in the text of the paper)

Erosion Measurements

E_r = erosion ratio in kg/kg, which is the ratio between the mass of metal loss and the mass of sand hitting the target material
E_p = erosion parameter in mm/kg, which is the ratio between the penetration in the metal and the mass of sand hitting the target material
ER = erosion rate in mm/year, which is the rate of penetration in the metal by erosion

Sand

W = sand flow rate in kg/day
M = sand concentration ppm (by weight), which is the ratio of mass of sand to mass of fluid
d = sand size in micron (typical value 250 micron). [Note: The effect of d on ER becomes negligible above 400 micron. Therefore, for d> 400, the limit of 400 is used.]
ρ_s = sand density in kg/m^3 (typical value 2650 kg/m^3)

Fluids

V_l = liquid superficial velocity in m/sec
V_g = gas superficial velocity in m/sec
V_m = fluid mixture Velocity in m/sec
= $V_l + V_g$
V_e = erosional velocity limit, m/s
ρ_l = liquid density in kg/m^3
ρ_g = gas density in kg/m^3
ρ_m = fluid mixture density in kg/m^3
= $(\rho_l V_l + \rho_g V_g)/V_m$

Pipe Geometry

D = pipe internal diameter in mm

Constants

- C= the C-factor is an empirical constant specified by API 14RP 14E to predict the erosional velocity limit, V_e (in ft/sec)
- S= the S-factor is a geometry dependent constant, specified in this paper for typical operating conditions (tolerable erosion rate of 0.1 mm/yr (4 mpy) and sand size of 250 micron) to predict the erosional velocity limit, V_e (in m/sec)
- S_p= a geometry dependent constant, specified in this paper and used to predict E_p in terms of flow parameters.
- S_m= a geometry dependent constant, specified in this paper and used to predict ER given sand rate (W) and other flow parameters.
- S_c= a geometry dependent constant, specified in this paper and used to predict ER given sand concentration (M) and other flow parameters.

Note that the parameters S, S_p, S_m, S_c are all related. As an example: S_m equals $365/S_p$ to convert E_p to ER.

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TABLE 1--SPECULATIONS REGARDING THE ORIGIN OF API RP 14 E EROSIONAL VELOCITY EQUATION

Reference	Suggested Basis
Salama and Venkatesh (1983)	Pressure drop, liquid impingement, and stripping of inhibitors.
Heidersbach (1985)	Pumping requirement
Rybicki (1987)	Water Hammer
Gipson (1989)	Avoid excessive noise
Deffenbaugh and Buckingham (1989)	Average of similar formula used by different companies
Smart (1990)	Experience in multiphase steam condensate piping.
Coker (1990)	Avoid erosion-corrosion (Referencing Coulson and Richardson, 1977.)
Coulson and Richardson (1977)	Avoid erosion
Smart (1991)	Uninhibited oil and gas production of carbon steel.
Patton (1993)	Application by the U.S. Navy during WW II for solid-free carbon steel piping

TABLE 2--MEASURED AND PREDICTED EROSION RATES

Vgs m/s	Vls m/s	V mix m/s	Rho mix kg/m^3	d sand micron	D pipe mm	Bend R # D	ER meas mm/kg	ER pred. mm/kg	Pred/Meas
30	1	31	34.48	150	49	5	5.52E-04	8.71E-04	1.6
30	0.5	30.5	18.65	150	49	5	2.46E-03	1.56E-03	0.6
20	5.8	25.8	226.59	150	49	1.5	5.19E-05	9.18E-05	1.8
20	3.1	23.1	136.19	150	49	1.5	6.93E-05	1.22E-04	1.8
15	5	20	251.72	150	49	5	6.38E-05	4.96E-05	0.8
15	1	16	64.66	150	49	5	1.47E-04	1.24E-04	0.8
10	5	15	334.87	150	49	5	1.35E-05	2.10E-05	1.6
10	0.7	10.7	67.57	150	49	5	7.01E-05	5.29E-05	0.8
8	0.2	8.2	26.63	150	49	1.5	1.23E-04	7.89E-05	0.6
3.5	4	7.5	534.41	150	49	5	4.60E-06	3.29E-06	0.7
9	6.2	15.2	413.50	250	26.5	5	1.80E-04	9.95E-05	0.6
14.4	1.5	15.9	102.70	250	26.5	5	2.30E-04	4.38E-04	1.9
14.6	1.5	16.1	101.70	250	26.5	5	4.20E-04	4.54E-04	1.1
34	2.1	36.1	67.20	250	26.5	5	2.83E-03	3.45E-03	1.2
35	1	36	37.30	250	26.5	5	6.56E-03	6.18E-03	0.9
34.3	0.5	34.8	24.10	250	26.5	5	7.20E-03	8.94E-03	1.2
37	0.7	37.7	28.20	250	26.5	5	8.03E-03	8.97E-03	1.1
38.5	0.5	39	22.60	250	26.5	5	8.03E-03	1.20E-02	1.5
44	1.5	45.5	42.50	250	26.5	5	1.05E-02	8.67E-03	0.8
51	0.6	51.6	21.50	250	26.5	5	1.34E-02	2.20E-02	1.6
52	0.7	52.7	23.00	250	26.5	5	1.33E-02	2.15E-02	1.6
9.15	0	9.15	1.20	300	52.5	1.5	2.14E-03	3.80E-03	1.8
12.2	0	12.2	1.20	300	52.5	1.5	3.81E-03	6.75E-03	1.8
15.25	0	15.25	1.20	300	52.5	1.5	7.52E-03	1.05E-02	1.4
18.3	0	18.3	1.20	300	52.5	1.5	9.16E-03	1.52E-02	1.7
21.35	0	21.35	1.20	300	52.5	1.5	1.22E-02	2.07E-02	1.7
24.4	0	24.4	1.20	300	52.5	1.5	1.62E-02	2.70E-02	1.7
27.45	0	27.45	1.20	300	52.5	1.5	1.80E-02	3.42E-02	1.9
30.5	0	30.5	1.20	300	52.5	1.5	2.04E-02	4.22E-02	2.1
21.35	0	21.35	1.20	300	52.5	1.5	4.44E-03	2.07E-02	4.7
30.5	0	30.5	1.20	300	52.5	1.5	1.56E-02	4.22E-02	2.7
86	0.53	86.53	7.93	250	52.5	2.625	1.27E-01	4.28E-02	0.3
92	0.53	92.53	7.50	250	52.5	2.625	1.21E-01	5.18E-02	0.4
89	0.12	89.12	2.68	250	52.5	2.625	1.08E-01	1.34E-01	1.2
84	0.53	84.53	8.09	250	52.5	2.625	9.34E-02	4.00E-02	0.4
72	0.53	72.53	9.23	250	52.5	3.25	5.37E-02	2.58E-02	0.5
84	0.12	84.12	2.77	250	52.5	3.25	7.51E-02	1.16E-01	1.5
92	0.12	92.12	2.64	250	52.5	3.25	9.94E-02	1.46E-01	1.5
107	0.53	107.53	6.62	250	52.5	3.25	1.05E-01	7.92E-02	0.8
32	0	32	1.20	250	52.5	1.5	8.11E-03	6.43E-03	0.8
47	0	47	1.20	250	52.5	1.5	4.91E-03	1.39E-02	2.8
72	0	72	1.20	250	52.5	1.5	1.40E-02	3.25E-02	2.3
93	0	93	1.20	250	52.5	1.5	2.83E-02	5.43E-02	1.9
98	0	98	1.20	250	52.5	1.5	3.53E-02	6.03E-02	1.7
98	0	98	1.20	250	52.5	1.5	3.54E-02	6.03E-02	1.7
103	0	103	1.20	250	52.5	1.5	3.76E-02	6.66E-02	1.8
122	0	122	1.20	250	52.5	1.5	2.15E-01	9.34E-02	0.4
167	0	167	1.20	250	52.5	1.5	1.82E-01	1.75E-01	1.0
169	0	169	1.20	250	52.5	1.5	1.91E-01	1.79E-01	0.9
177	0	177	1.20	250	52.5	1.5	2.38E-01	1.97E-01	0.8
177	0	177	1.20	250	52.5	1.5	2.53E-01	1.97E-01	0.8
178	0	178	1.20	250	52.5	1.5	2.26E-01	1.99E-01	0.9
203	0	203	1.20	250	52.5	1.5	2.61E-01	2.59E-01	1.0
205	0	205	1.20	250	52.5	1.5	2.09E-01	2.64E-01	1.3
222	0	222	1.20	250	52.5	1.5	2.32E-01	3.09E-01	1.3
108	0	108	1.20	250	52.5	1.5	7.11E-02	7.32E-02	1.0
109	0	109	1.20	250	52.5	1.5	6.10E-02	7.46E-02	1.2
108	0	108	1.20	250	52.5	1.5	5.50E-02	7.32E-02	1.3
104	0	104	1.20	250	52.5	1.5	6.45E-02	6.79E-02	1.1
108	0	108	1.20	250	52.5	1.5	8.06E-02	7.32E-02	0.9
108	0	108	1.20	250	52.5	1.5	6.59E-02	7.32E-02	1.1
107	0	107	1.20	250	52.5	1.5	4.82E-02	7.19E-02	1.5
111	0	111	1.20	250	52.5	1.5	5.80E-02	7.73E-02	1.3
107	0	107	1.20	250	52.5	1.5	5.92E-02	7.19E-02	1.2
106	0	106	1.20	250	52.5	1.5	5.13E-02	7.05E-02	1.4
103	0	103	1.20	250	52.5	1.5	3.96E-02	6.66E-02	1.7
104	0	104	1.20	250	52.5	8.5	2.39E-02	6.79E-02	2.8
118	0	118	1.20	250	52.5	5	1.20E-01	8.74E-02	0.7
109	0	109	1.20	250	52.5	6	7.57E-02	7.46E-02	1.0
112	0	112	1.20	250	52.5	6	9.46E-02	7.87E-02	0.8
0	11.49	11.49	1100.00	250	52.5	3	1.18E-06	9.07E-07	0.8

TABLE 2--Continued

116	0	116	1.20	250	52.5	2.125	1.64E-01	8.45E-02	0.5
141	0	141	1.20	250	52.5	2.875	1.75E-01	1.25E-01	0.7
107	0	107	1.20	250	52.5	2.875	1.21E-01	7.19E-02	0.6
141	0	141	1.20	250	52.5	2.875	1.74E-01	1.25E-01	0.7
107	0	107	1.20	250	52.5	2.875	1.36E-01	7.19E-02	0.5
111	0	111	1.20	250	52.5	3.25	1.12E-01	7.73E-02	0.7
141	0	141	1.20	250	52.5	3.25	2.07E-01	1.25E-01	0.6
141	0	141	1.20	250	52.5	3.25	1.91E-01	1.25E-01	0.7
148	0	148	1.20	250	52.5	3.25	2.09E-01	1.38E-01	0.7
111	0	111	1.20	250	52.5	4.5	5.26E-02	7.73E-02	1.5
81	0.53	81.53	8.35	250	52.5	8	1.33E-03	2.89E-03	2.2
70	0.53	70.53	9.46	250	52.5	8	2.02E-03	1.91E-03	0.9
127	0	127	1.20	250	52.5	8	1.59E-03	2.43E-03	1.5
141	0	141	1.20	250	52.5	8	6.33E-03	3.00E-03	0.5
141	0	141	1.20	250	52.5	8	1.22E-03	3.00E-03	2.5
76	0.12	76.12	2.94	250	52.5	8	2.11E-04	3.58E-04	1.7

TABLE3--VALUES OF SAND EROSION CONSTANTS				
Geometry	S_p	S_m	S_c	S
Elbow (1.5 and 5D) [reference for test data: this paper, Tolle, Weiner and Bourgoyne] (39 tests)	2000	5.5	2×10^7	0.05
Seamless and cast Ell (1.5 to 3.25 D) [reference for test data: Bourgoyne) (40 tests)	12,000	33	1.2×10^8	2.2
Plugged Tee (gas-liquid) [reference for test data: Bourgoyne] (2 tests)	25,000	68	2.5×10^8	3.2
Plugged Tee (gas flow) [reference for test data: Bourgoyne] (4 tests)	500,000	1,379	5.1×10^9	14

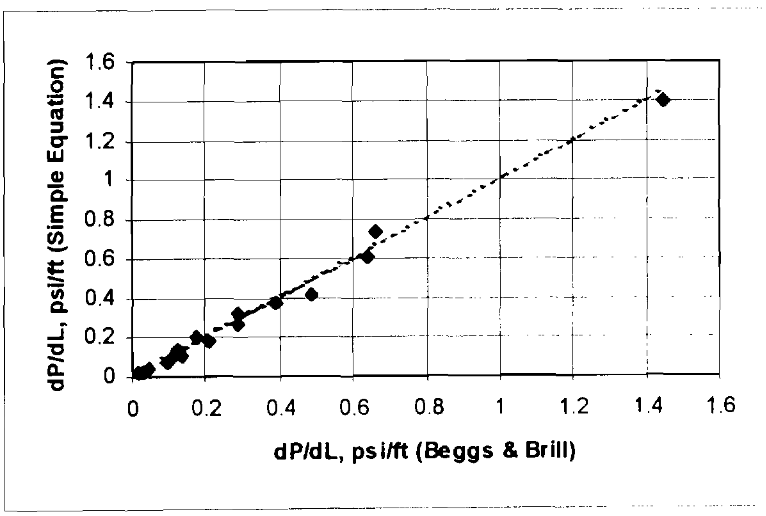

Fig. 1--A comparison between predictions made using the proposed equation and those made using Beggs and Brill Correlations

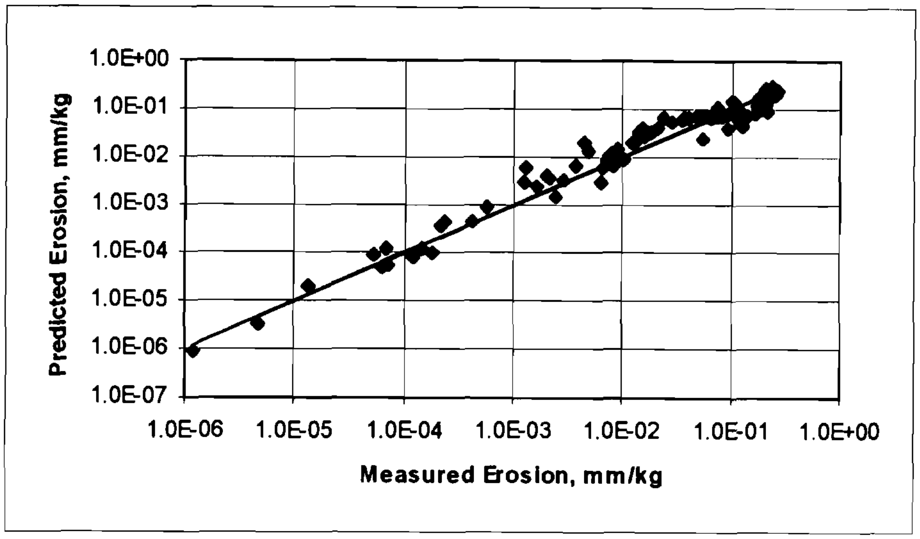

Fig. 2--A comparison between measured and predicted sand erosion in pipe bends.