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NOVEL MODEL FOR ESTIMATING GAS-SOLID TWO-PHASE FLOW RATE IN A HORIZONTAL PIPE

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ABSTRACT

Dilute and dense conveying systems through pipelines are a common practice in our everyday life. It is used in many industries to convey a mixture of gas and solids from one location to another through pipes. Gas-solid transport is desirable in some industries but unwanted in others. Depending on the density, size, and shape, these solid particles may result in erosion and subsequent damage to piping and other equipment. Understanding the gas-solid two-phase flow dynamics can help develop efficient and cost-effective pipe transport systems, thereby mitigating the problems associated with the gas-solid two-phase flow. Models for estimating volumetric flow rates and other gas-solid two-phase flow properties are scarce as most are very complex, expensive, and unavailable proprietary commercial software. This study, therefore, developed a simple model using the general energy balance equation and relevant mixing theories for estimating the volumetric flow rate of natural gas-solid two-phase flow in horizontal pipes. The results from the model showed that the gas-solid flow rate is a function of pipe diameter, pressure drop, pipe length, solid volumetric concentration, solid-to-gas density ratio, and solid-to-gas friction factor ratio.

Keywords: gas-solid flow, two-phase flow, pneumatic conveying, mathematical modeling.

INTRODUCTION

Over the years, the transportation of two-phase mixtures like gas and solids has been a subject of interest to many researchers due to its complex mechanism and wide application in many industries like food processing, cosmetics, chemical, [1] and petroleum. In some of these industries, the transportation of solids in a gas medium has been applied in transporting grains, sand, cement, talc, solid wastes, flour, minerals, etc. In many instances, air, due to its cost-effectiveness and abundance, is often used to transport solids of sizes between 10 to 5 microns. This technique of using air (or non-reacting gases) is known as pneumatic conveying [2]. A pneumatic conveying system involving a suspension flow with a solid fraction of less than 10% is known as the dilute phase, while the non-suspension flow type is referred to as the dense phase conveying [3]. In the petroleum industry, for instance, gas-solid transport is an inevitable occurrence.

Solid particles like sand, fines, hydrate, and scale crystals can be conveyed with the gas along pipes and flow lines.

In any case, these solids can adversely affect flow line equipment by increasing pumping requirements, pipe erosion, and pressure drops, especially in high-pressure gas conveying systems [4]. It is imperative in gas-solid mixture flow to keep the solid phase dispersed in the gas phase without saltation or deposition. Hence, determining the maximum flow velocity and flow rates for which the solid particles in the bulk fluid will not result in erosion or abrasion and determining the optimum flow requirement for minimizing the pressure losses is significant. To achieve this, a proper understanding of the gas-solid flow system is required to reduce erosion and damage to pipes and accessories, reduce pressure losses, and minimize energy requirements [5].

Understanding the gas-solid system to mitigate the adverse effects of gas-solid flow has led to the development of gas-solid flow models. There are currently two modeling approaches for gas-solid phase flow. They are the Lagrangian for very dilute gas-solid flow (which considers the solid phase as a dispersed phase in the continuous gas phase) and Eulerian (which assumes solid phase volumetric concentration) methods [2]. However, most of these models are very complex as they couple two or more approaches to achieve their desired results. In one such study, Li et al. [4] coupled the discrete element method (DEM), computational fluid dynamics (CFD), and the Eulerian method. Gundogdu et al. [6] coupled the separated flow model and the empirical slip parameters in another study. Most existing models were developed for estimating the pressure drop of gas-solid flow in pipes. Many of these models are embedded in expensive, relatively unavailable proprietary commercial software. Models for estimating the volumetric flow rates of the gas-solid two-phase mixture are rare in the published literature.

The study aims to develop a simple model for estimating gas-solid flow rates in horizontal conveying pipes using the general energy balance equation and appropriate mixing rules.

MATERIALS AND METHOD

Model Development

Using the general energy equation, the energy balance on the whole system between points 1 and 2 in Figure 1 below may be written as:

$$u_2 + p_2 v_2 + \frac{m u_2^2}{2 g_c} + \frac{m g z_2}{g_c} = u_1 + p_1 v_1 + \frac{m u_1^2}{2 g_c} + \frac{m g z_1}{g_c} + Q - w - lw \quad (1)$$

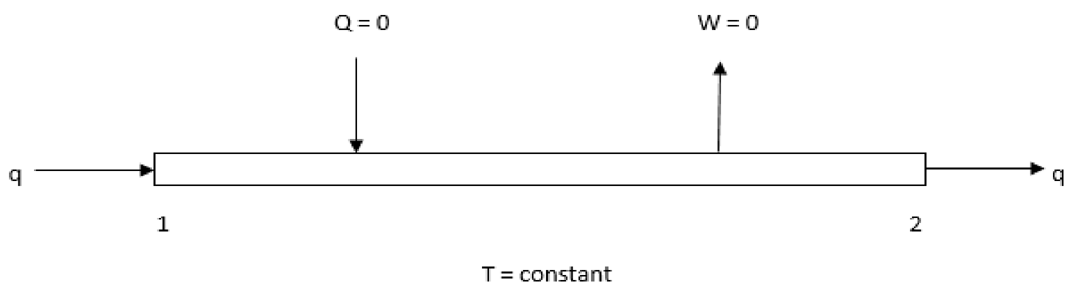

***Fig.1**. A gas transmission line model [14]*

Where: U = internal energy; PV = energy of compression or expansion; $\frac{mu^2}{2g_c}$ = potential energy; Q = heat energy added to the fluid; W = shaft work done by the surrounding on the gas

Dividing Equation 1 through by m to obtain an energy per unit mass balance and writing the resulting equation in differential form yields:

$$dU + d\left(\frac{p}{\rho}\right) + u\left(\frac{du}{g_c}\right) + g\frac{dz}{g_c} + dQ - dw = 0 \tag{2}$$

Assuming the following:

a) The flow is steady state and steady flow.

b) The flow is isothermal in the pipeline.

c) The flow is horizontal.

d) No work is done by or on the gas during flow-across system

But

$$dh = Tds + \frac{dP}{\rho}$$

and

$$dU = dh - d\left(\frac{P}{\rho}\right) = Tds + \frac{dP}{\rho} - d\left(\frac{P}{\rho}\right) \tag{3}$$

Where: h = enthalpy, s = entropy, T = temperature, ρ = density, P = gas pressure, U = internal energy.

Inserting (3) into (2),

$$Tds + \frac{dP}{\rho} + u\frac{du}{g_c} + g\frac{dz}{g_c} + dQ - dw = 0 \tag{4}$$

Clausis inequality for an irreversible process states that

$$ds \geq \frac{-dQ}{T}$$

$$Tds = -dQ + d(lw) \tag{5}$$

Where lw = lost work due to irreversibilities

Substituting (5) into (4),

$$\frac{dP}{\rho} + u\frac{du}{g_c} + g\frac{dz}{g_c} + d(lw) - dw = 0 \tag{6}$$

If no work is done by or on the fluid, $dw = 0$

Then,

$$\frac{dP}{\rho}+u\frac{du}{g_c}+g\frac{dz}{g_c}+d(lw)=0 \tag{7}$$

Considering a more general case of an inclined pipe we have

$$\frac{dP}{\rho}+u\frac{du}{g_c}+g\frac{dL\sin\theta}{g_c}+d(lw)=0 \tag{8}$$

Multiplying through by $\frac{\rho}{dL}$

$$\frac{dP}{dL}+\rho u\frac{du}{g_c dL}+g\frac{\rho\sin\theta}{g_c}+\rho\frac{d(lw)}{dL}=0 \tag{9}$$

Considering pressure drop in the positive direction,

$$\frac{dP}{dL}=\rho u\frac{du}{g_c dL}+g\frac{\rho\sin\theta}{g_c}+\rho\frac{fu^2}{2g_c D} \tag{10}$$

Where,

$$\frac{d(lw)}{dL}=\frac{fu^2}{2g_c D}$$

Considering a horizontal pipe,

$$\frac{dP}{dL}=\rho u\frac{du}{g_c dL}+\rho\frac{fu^2}{2g_c D} \tag{11}$$

Recall,

$$u=\left(\frac{q}{86400}\right)\left(\frac{T}{T_b}\right)\left(\frac{p_b}{p}\right)\left(\frac{z}{1.00}\right)\left(\frac{4}{\pi D^2}\right) \tag{12}$$

Where

q = volumetric flow rate, scfd measured at standard conditions, T_b (°R) and P_b (psia)

But, the total surface area of a cylinder = Area of the two circular ends + Area of the curved surface

$$A_t=2\pi r^2+2\pi rL$$

Where L= length of pipe

But for an open-ended flowing pipe,

$$A=2\pi rL$$

So that,

$$r=\frac{A}{2\pi L}$$

Hence,

$$\pi\left(\frac{D}{2}\right)^2 = \pi\left(\frac{A}{2\pi L}\right)^2 = \frac{A^2}{4\pi L^2} \tag{13}$$

Substituting (13) into (12)

$$u = \left(\frac{q}{86400}\right)\left(\frac{T}{T_b}\right)\left(\frac{p_b}{p_{ave}}\right)\left(\frac{z}{1.00}\right)\left(\frac{4\pi L^2}{A^2}\right) \tag{14}$$

But,

$$\frac{\partial u}{\partial L} = \left(\frac{q}{86400}\right)\left(\frac{T}{T_b}\right)\left(\frac{p_b}{p_{ave}}\right)\left(\frac{z}{1.00}\right)\left(\frac{8\pi L}{A^2}\right)$$

Then, let

$$\frac{\partial u}{\partial L} \approx \frac{du}{dL}$$

So that,

$$\frac{\partial u}{\partial L} = \left(\frac{q}{10800}\right)\left(\frac{T}{T_b}\right)\left(\frac{p_b}{p_{ave}}\right)\left(\frac{z}{1.00}\right)\left(\frac{\pi L}{A^2}\right) = \frac{2u}{L} \tag{15}$$

Substituting equation (15) into equation (11),

$$\frac{dP}{dL} = 2\rho\frac{u^2}{g_c L} + \rho\frac{fu^2}{2g_c D} \tag{16}$$

The pressure difference in the pipe due to the change in height is assumed negligible. An application of mixture theory combining gas and solids is considered. Since solid particles are small, and gas is the continuous phase, gas velocity will adequately overcome the terminal settling velocity of the solids. Hence, $v_g = v_t$. The theoretical analysis and mathematical model for the combined gas-solid flow system (Figures 2 a and b) were developed under the flowing assumptions:

1. The flow is steady-state and steady-flow.
2. The flow is isothermal in the pipeline.
3. The flow is horizontal.
4. There is no work done by or on gas during flow-across system

According to mixture theory [8], the combined flow of gas and solids experiences a total pressure drop given by:

$$\left(\frac{dp}{dl}\right)_{mixture}^{total} = (1-\beta)\left(\frac{dp}{dl}\right)_{gas}^{total} + \beta\left(\frac{dp}{dl}\right)_{solid}^{total} \tag{17}$$

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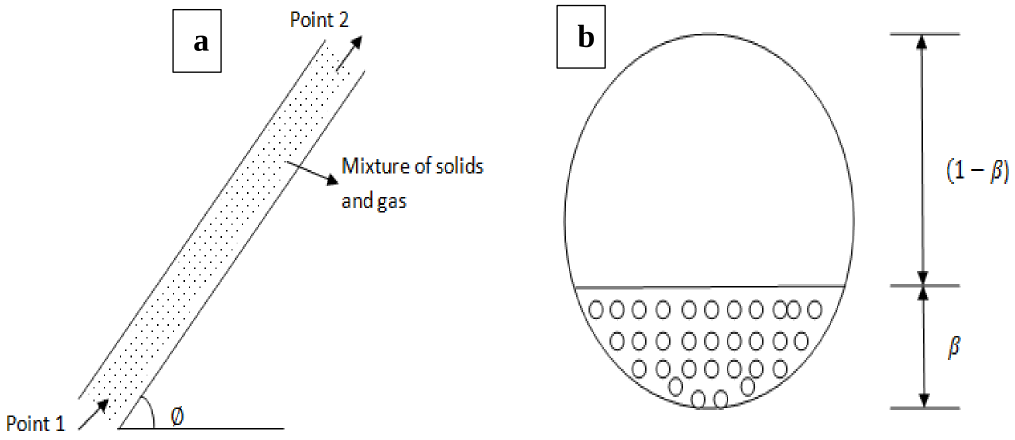

Fig.2. *(a) Flow of a mixture of gas and solid in an inclined pipe [8]*
(b) Cross-section of pipe showing the solid volumetric concentration β

The total pressure drop in a gas pipeline is given as [9]

$$\left(\frac{dp}{dl}\right)_{gas}^{total} = \left(\frac{dp}{dl}\right)_{friction} + \left(\frac{dp}{dl}\right)_{elevation} + \left(\frac{dp}{dl}\right)_{acceleration} \tag{18}$$

The above equation is fully expressed as:

$$\left(\frac{dp}{dl}\right)_{gas}^{total} = \frac{\rho u du}{g_c dL} + g\frac{\rho_s \sin\theta}{g_c} + \frac{\rho f u^2}{2 g_c D} \tag{19}$$

From (16), equation (18) can be expressed as follows for inclined pipes

$$\left(\frac{dp}{dl}\right)_{gas}^{total} = 2\rho_g \frac{u^2}{g_c L} + \frac{g\rho_g \sin\theta}{g_c} + \frac{\rho f_g u^2}{2 g_c D} \tag{20}$$

Or

$$\left(\frac{dp}{dl}\right)_{gas}^{total} = \frac{\rho u^2}{g_c}\left(\frac{2}{L} + \frac{f}{2D}\right) + \frac{g\rho_g \sin\theta}{g_c} \tag{21}$$

Similarly, according to Ortega-Rivas [10], the total pressure drop for particulate solids transported pneumatically in inclined pipes is also given by

$$\left(\frac{dp}{dl}\right)_{solid}^{total} = \left(\frac{dp}{dl}\right)_{friction} + \left(\frac{dp}{dl}\right)_{elevation} + \left(\frac{dp}{dl}\right)_{acceleration} \tag{22}$$

Which is fully expressed as:

$$\left(\frac{dp}{dl}\right)_{solids}^{total} = \frac{\rho_s {u_p}^2}{g_c} + \frac{\rho_s g \sin\theta}{g_c} + \frac{\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{1/2}\left(\frac{G_s}{G}\right)E_g \tag{23}$$

Where

$$E_g = \frac{\rho_g f_g u^2}{2g_c D}$$

Considering a pipe section in Figure 2b with solid (particle) and gas concentration and combining Equations 20 and 23,

$$\left(\frac{dp}{dl}\right)_{mixture}^{total} = (1-\beta)\left\{2\rho_g \frac{u^2}{g_c L} + \rho \frac{f_g u^2}{2g_c D} + \frac{g\rho_g \sin\theta}{g_c}\right\} + \beta\left\{\frac{\rho_s u_p^2}{g_c} + \frac{\rho_s g \sin\theta}{g_c} + \frac{\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{1/2} \frac{G_s}{G}\frac{\rho_g f_g u^2}{2g_c D}\right\} \quad (24)$$

Where β = solid-volumetric-concentration (-), U_p = particle-velocity relative to gas-velocity(ft/s), $u_p = u - u_t$, with u = gas-velocity (ft/s), u_t = terminal setting velocity(ft/s) of a particle given by

$$u_t = \frac{x_p^2(\rho_s - \rho_g)g}{18\mu_g g_c} \quad (25)$$

f_s= particle-friction-factor (-), f_g= mood friction-factor (-), G_s= flux of solid particles (lbm/ft^{2}s), $G_s = p_s u_p$, G = flux of gas, Where $G = \rho_g u$, D = pipe-diameter(in), L = pipe-length (ft), A_t= total-surface area of pipe = πD(r + l), g_c= conversion-factor = 32.17 lbm-ft/ bf-S^2, π= 3.1428571429, ρ_g= gas density (lbm/ft^3), ρ_s = particle density (lbm/ft^3), x_p = particle diameter (ft), u_g = gas viscosity (cp).

Assuming gas velocity just equals the particle's terminal settling velocity in horizontal gas pipes, Equation 24 reduces to:

$$\left(\frac{dp}{dl}\right)_{mixture}^{total} = (1-\beta)\left\{2\rho_g \frac{u^2}{g_c L} + \rho \frac{f_g u^2}{2g_c D}\right\} + \beta\left\{\frac{\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{1/2} \frac{G_s}{G}\frac{\rho_g f_g u^2}{2g_c D}\right\} \quad (26)$$

On further simplification,

$$\left(\frac{dp}{dl}\right)_{mixture}^{total} = (1-\beta)2\rho_g \frac{u^2}{g_c L} + (1-\beta)\frac{\rho_g u^2 f_g}{2g_c D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{1/2}\left(\frac{G_s}{G}\right)\frac{\rho_g f_g u^2}{2g_c D} \quad (27)$$

Recall that,

$$G = \rho u \quad (28)$$

So that,

$$\frac{G_s}{G} = \frac{\rho_s u_p}{\rho_g u} \quad (29)$$

But for steady-state flow $u_p = u$ so that,

$$\frac{G_s}{G} = \frac{\rho_s}{\rho_g} \tag{30}$$

Substituting (30) into (27) and changing, $\frac{dp}{dl} to \frac{\Delta p}{L}$ we have

$$\frac{\Delta p}{L} = (1-\beta)2\rho_g \frac{u^2}{g_c L} + (1-\beta)\frac{\rho_g u^2 f_g}{2g_c D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} \frac{\rho_g f_g u^2}{2g_c D} \tag{31}$$

$$\frac{\Delta p}{L} = \frac{2\rho_g u^2}{g_c}\left\{\frac{(1-\beta)}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} . \frac{f_g}{4D}\right\} \tag{32}$$

From Equation 14,

$$u = \left(\frac{q}{86400}\right)\left(\frac{T}{T_b}\right)\left(\frac{p_b}{p_{ave}}\right)\left(\frac{z}{1.00}\right)\left(\frac{4\pi L^2}{A^2}\right)$$

Making u^2 the subject of the formula in (32), we have,

$$u^2 = \frac{\Delta p g_c}{\left\{\frac{1-\beta}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} \frac{f_g}{4D}\right\}2\rho_g L} \tag{33}$$

Inserting (32) into (33),

$$\left(\frac{qTp_b z 4\pi L^2}{86400 T_b p A^2}\right)^2 = \frac{\Delta p g_c}{\left\{\frac{1-\beta}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} \frac{f_g}{4D}\right\}2\rho_g L} \tag{34}$$

$$\left(\frac{TP_b z L^2}{6875.49 T_b P_{ave} A^2}\right)^2 q^2 = \frac{(P_1 - P_2)g_c}{\left\{\frac{1-\beta}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} \frac{f_g}{4D}\right\}2\rho_g L} \tag{35}$$

Making q^2 the subject,

$$q^2 = \left(\frac{6875.49 T_b P_{ave} A^2}{TP_b z L^2}\right)^2 \frac{(P_1 - P_2)g_c}{\left\{\frac{1-\beta}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2} \frac{f_g}{4D}\right\}2\rho_g L} \tag{36}$$

Taking the square root of both sides,

$$q = \left(\frac{6875.49 T_b P_{ave} A^2}{T P_b z L^2}\right)\left[\frac{(P_1 - P_2) g_c}{\left\{\frac{(1-\beta)}{L} + (1-\beta)\frac{f_g}{4D} + \frac{\beta\pi}{8}\left(\frac{f_s}{f_g}\right)\left(\frac{\rho_s}{\rho_g}\right)^{3/2}\frac{f_g}{4D}\right\} 2\rho_g L}\right]^{1/2} \tag{37}$$

Where f = Moody's friction factor, dimensionless, u = gas velocity, ft/s, ρ = gas density, lbm/ft^3, D = internal pipe diameter, ft, L = pipe length, ft, g_c = conversion factor = 32.17 lbm-ft/lbf-s^2, A = curved surface area of pipe = $2\pi rL$, π = pi = 3.1428571429, T_b = base temperature, ^oR, P_b = base pressure, psia, P_1 = inlet pressure of the gas, psia, P_2 = outlet pressure of the gas, psia, T = average temperature of the gas, R, Z = average compressibility of gas, dimensionless, q = gas flow rate (Scfd).

RESULTS AND DISCUSSION

Equation 37 and Table A1 of the appendix were used to analyze the results. The developed model in this study has a similar structure to many gas flow rate models, including the Weymouth, Panhandle A, and B equations. However, new parameters that are not common to other models, like solid-to-gas density ratio, solid-to-gas friction factor ratio, and solid volumetric concentration or ratio, which are significant in accurately modeling the gas-solid flow, have been incorporated.

Figure 3a shows the relationship between volumetric flow rate and internal pipe diameter with varying solid concentrations. From the graph, the flow rate increases with an increase in the pipe diameter for a given fluid velocity. This is because the volumetric flow rate is a direct function of the pipe diameter for a given velocity (maximum velocity needed to prevent erosion). Also, the flow rate decreases for a fixed pipe ID as the solid concentration ratio increases. This trend is because an increase in the solid concentration increases the weight of the bulk fluid. Due to gravity, the solid particles tend to restrict flow [11]. This result agrees with Sun et al. [3], who observed that superficial gas velocities (flow rates) decreased as solid concentration increased.

Figure 3b shows that increasing solid concentration as the solid-to-gas density ratio (a function of particle size) increased also reduces the flow rate. This result also agrees with the work of Sun et al. [3], who observed that an increase in particle sizes increases solid concentration.

Figure 3c shows that flow rate decreases with increasing pipe length and solid friction factor. The decrease in flow rate due to increasing pipe length is because fluid energy required for transportation decreases (increasing frictional energy losses) with increasing pipe length [12]. The increase in the solid friction factor (which increases shear stresses between the particle-particle and the particle-pipe walls) often emanates from an increase in solid concentration or solid loading ratio [13]. As a result, the resistance to flow increases. This result agrees with the study of Jones and Williams [14].

The developed model in this study has demonstrated the vital relationship between the flow rate of a natural gas-solid multiphase flow system with the system's solid volumetric concentration, pipe diameter, pipe length, solid-to-gas density ratio, and solid or particle friction factor. These relationships will help engineers better to understand the dynamics of gas-solid two-phase pipe flow. Validation of the results of this study with experimental and field data is further required

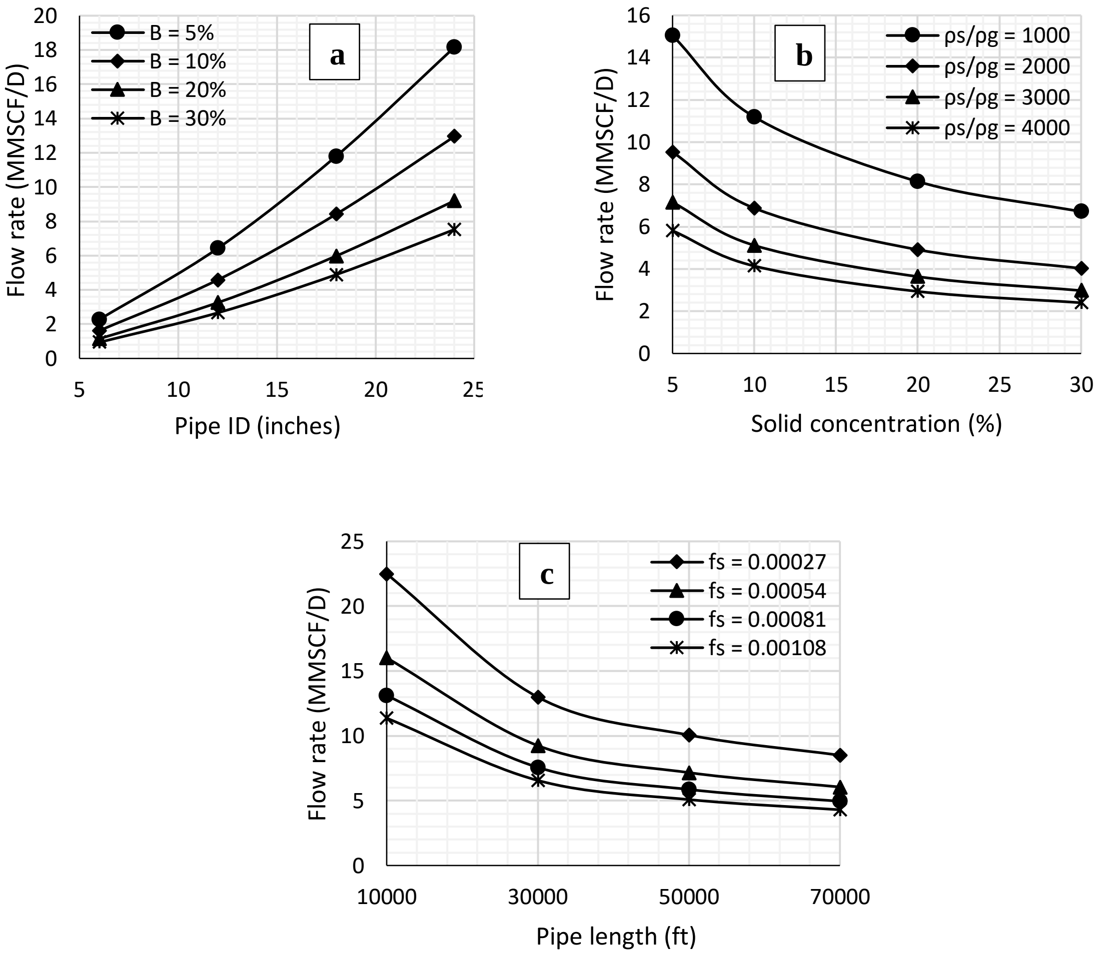

Fig.3. *Variation of volumetric flow rate and (a) pipe ID and solid concentration, (b) solid-to-gas density ratio and solid concentration, (c) solid friction factor and pipe length.*

CONCLUSION

A good understanding of the dynamics of natural gas-solid flow in pipes will help develop efficient and cost-effective pipe transport systems. The available models for investigating natural gas-solid two-phase flow are mostly commercial software which is relatively unavailable, expensive, and very complex. This study has developed a simple-to-use model for estimating the flow rate of natural gas-solid two-phase flow in pipes. From the results, we can conclude that the gas-solid two-phase flow rate increases with increasing pipe diameter and decreases with increasing volumetric solid concentration, solid-to-gas density ratio, solid-to-gas friction factor, and pipe length.

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APPENDIX

Table A1. Parameters used in model analysis

Inlet Pressure (psi)	Outlet pressure (psi)	$Z_{average}$	Base pressure, Pb (psi)	Base Temperature, Tb (°R)	Average Pipe temperature (°R)	g_c (ft^2/s)	Gas friction factor fg
1,300	1,000	1.25	14.7	520	564	32.2	0.04

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