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Probabilistic modeling of slug frequency in gas/liquid pipe flow using the Poisson probability theory

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ABSTRACT

Slug frequency is a critical characteristic of two-phase slug flow in pipes that impacts production system operation, design and flow assurance aspects. For example, slug frequency is not only a required input for mechanistic models to predict pressure gradient and liquid holdup, but also is related to pipeline erosion/corrosion rates, pipeline structural integrity and stability and downstream separation and process facilities sizing. Conversely, slug frequency is the least accurately predicted parameter in two-phase flow, due to the high uncertainty of slug frequency predictive empirical correlations and models. Comprehensive studies by Zabaras (2000) and by Al-Safran (2009) showed that the error in existing slug frequency correlations' predictions averages around 75% for horizontal flow and 115% for horizontal and inclined flows. Therefore, this study, as oppose to previous studies, aims to develop a probabilistic model to predict slug frequency and quantify the associated probability. The proposed model can predict the P10, P50, and P90 of slug frequency predictions for a given flow condition. These probability values can be propagated in a mechanistic model to predict the expected, low- and high-end values of pressure gradient and liquid holdup that can be used for efficient pipeline and downstream facility design and optimum operation. In addition, these probability values are important in predicting the possible maximum and minimum corrosion/erosion rates to efficiently design corrosion inhibitor program, which has a significant impact on project economic. For transient slug tracking model such as OLGA, application of the proposed slug frequency probabilistic model can be to calculate the Delay Constant Parameter, the time interval between two initiated slugs, which requires a probabilistic distribution to quantify its uncertainty and impact on the slug tracking predictions.

Poisson probability theory is proposed in this study to model slug frequency predictions in horizontal pipeline. A Poisson probability model is used because of its suitability to predict the probability associated with events occurring during a specific time interval, such as slug frequency in a pipeline. In addition, a new slug frequency empirical correlation is proposed to predict the mean slug frequency in a horizontal pipeline, which is used in the Poisson probability modeling. Validation study of the slug frequency empirical correlation show a very good results, especially for the tuned model. In addition, the slug frequency Poisson probabilistic modeling predicted the probability associated with a specific value or range of slug frequency, slug frequency confidence interval for a given probability value, and the expected range of slug frequency values under normal operation.

1. Introduction

Two-phase slug flow is the most common and complex flow pattern encountered in oil field production and transportation of hydrocarbon mixture in horizontal and near-horizontal pipelines. Slug flow is described by series of slug units each consists of liquid slug followed by long gas bubble flowing above liquid films as shown in Fig. 1. Slug frequency is the number of slugs passing through a specific point along the pipeline per unit time. Among slug flow characteristics, slug frequency is a critical characteristic due to its impact on operation and flow assurance risks such as flooding of downstream facilities, pipeline erosion and corrosion, pipeline structural integrity and wellhead pressure fluctuation. Therefore, a slug frequency predictive model, empirical or mechanistic, is an essential part of any slug flow model. Slug frequency is required as an input in mechanistic two-phase flow models to predict slug flow behavior such as pressure drop and liquid holdup in pipes.

Several correlations have been developed to predict slug frequency, ranging from simple correlations such as Gregory and Scott (1969) and Heywood and Richardson (1978) to more

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Nomenclature

d	diameter
E	expected
F	frequency
f	friction factor
g	gravitational accl.
h	height
H	holdup
L	length
m	milli
N	number, random var.
n	data point
p	probability
r	partial corrl. coef.
S	slip factor
v	velocity
x	independent variable

Greek letters

α	gas void fraction, const.
β	coefficient, const.
ε	residual error
Φ	dimensionless function
γ	constant
θ	inclination angle
Θ	dimensionless function
ρ	density
Ψ	dimensionless function

Subscripts

avg	average
Fr	Froude number
g	gas
L	liquid
m	mixture
Re	Reynolds no.
s	slug
SL	superficial liquid
Sg	superficial gas

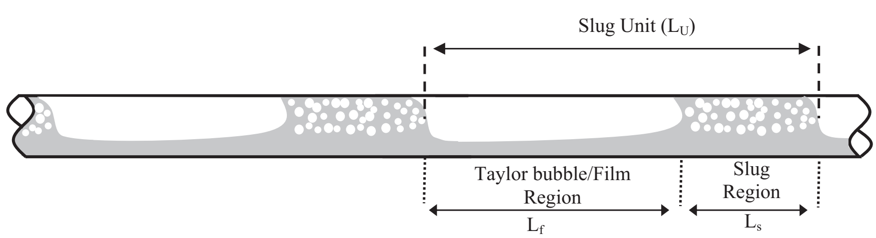

Fig. 1. Slug flow structure and slug unit.

complicated ones that take into account pipe length and mechanistic variables, such as Shea et al. (2004) and Hill and Wood (1990, 1994) correlations and Taitel and Dukler (1977) mechanistic model. A detailed description of the all existing correlations and models is presented in Al-Safran (2009, 2012). However, all these correlations and models are deterministic and none of them has the ability to predict the probability associated with the predicted slug frequency value. In the following literature review, we present only the recently developed correlations, which were not included in literature review referenced above.

1.1. *Gokcal et al. (2010) correlation*

Gokcal et al. developed a slug frequency correlation for horizontal pipes that takes into account liquid viscosity. Although their correlation has not been validated with high liquid viscosity data, it was only verified against low viscosity published data (1.3–11 mPa s), which showed that the correlation is sensitive to liquid viscosity and has better performance than existing correlations for higher viscosity oils. The correlation is given as follows.

$$F_s = 2.623\frac{v_{SL}}{N_f^{0.612}(d)} \quad (1)$$

where N_f is a dimensionless parameter given as

$$N_f = \frac{d^{3/2}\sqrt{\rho_L(\rho_L-\rho_G)g}}{\mu_L} \quad (2)$$

1.2. *Schulkes (2011) correlation*

Schulkes (2011) developed a dimensionless slug frequency correlation based on a wide range of experimental data using several dimensionless groups that include almost all two-phase flow parameters. Although his approach is thorough, some of the included independent parameters have a weak correlation with slug frequency and strong correlation among each other, causing multi-co-linearity in the proposed correlation. Schulkes correlation is given as

$$F_s = \Psi(\alpha)\times\Phi\left(N_{Re,L}\right)\times\Theta\left(\theta, N_{Fr}\right) \quad (3)$$

where

$$\Psi(\alpha) = 0.016\alpha(2+3\alpha) \quad (4)$$

$$\Phi\left(N_{Re,L}\right) = \begin{cases} 12.1N_{Re,L}^{-0.37} & \text{for} \quad N_{Re,L} < 4000 \\ 1 & \text{for} \quad N_{Re,L} \geq 4000 \end{cases} \quad (5)$$

$$\Theta\left(\theta, N_{Fr}\right) = \begin{cases} 1+\dfrac{2}{N_{Fr}}\sin(\theta)\sqrt{|\theta|} & \text{for} \quad |\theta| \leq 0.17 \\ \dfrac{1.8}{N_{Fr}}\times\left(0.6+2\theta-\theta^2\right) & \text{for} \quad |\theta| > 0.17 \end{cases} \quad (6)$$

where α is no-slip gas void fraction $(\alpha = v_{Sg}/v_m)$, N_{Fr} is the Froude number $(N_{Fr} = v_{SL}/\sqrt{gd})$, $N_{Re,L}$ is liquid Reynold's number $(N_{Re,L} = \rho_L v_{SL} d/\mu_L)$ and θ is inclination angle in degrees. Schulkes