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# EVALUATION OF MODELS FOR HORIZONTAL GAS-NON-NEWTONIAN SLUG FLOW

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**Abstract.** Several correlations from the literature for frequency, liquid fraction in the liquid slug and translational speed in slug flow were adapted and compared with experiments with shear-thinning fluids. New correlations were proposed to describe the data obtained. The closure equations were incorporated into two mechanistic models of slug flow, and the impact of the change in each expression was analysed. With the modified models, it was possible to obtain errors of less than 20% in the prediction of the pressure loss for flows of non-Newtonian fluids.

**Keywords:** slug flow, shear-thinning, non-Newtonian, unit cell model

## 1. INTRODUCTION

Slug flow is one of the most important two-phase flow patterns in industrial applications; however, most of the studies in the literature have only considered liquids with Newtonian behaviour. For non-Newtonian fluids, several fundamental features of the flow may be affected. Here, the existing modelling approaches will be extended and tested for these cases.

## 2. COMPUTATIONAL PROCEDURE

Mechanistic models for slug flow usually require some sort of specification of closure relations obtained through empirical or semi-empirical methods. Here, a total of 7 models or correlations for frequency, 7 for slug holdup and 4 for translational velocity were compared. Two unit cell models were analysed for pressure drop: Dukler & Hubbard (1975) (illustrated in Fig. 1) and Orell (2005). These are fully described in Bandeira et al. (2016).

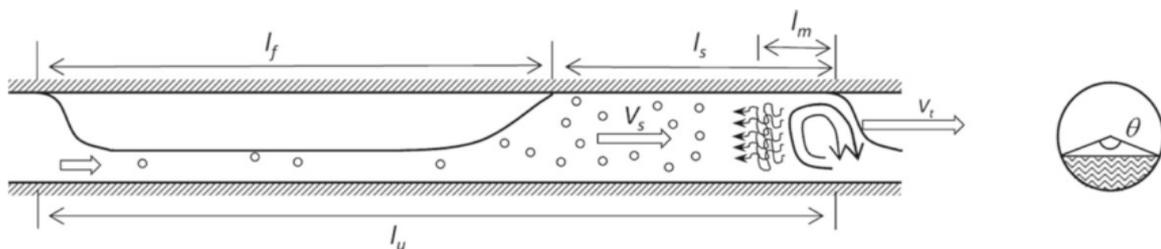


Figure 1: Unit cell structure. Taken from Bandeira et al. (2016)

Most of the existing models were developed for Newtonian fluids and as such, assume that the liquid has a fixed value of viscosity. In order to properly test the formulations, whenever the liquid viscosity was required in an expression, the value of apparent viscosity for pipe flow of power-law fluids was considered, i.e.:

$$\mu_{\text{eff}} = \frac{m \left(6 + \frac{2}{n}\right)^n D^{1-n} V^{n-1}}{8\rho} \quad (1)$$

where  $\mu_{eff}$  is the apparent viscosity,  $m$  is the consistency parameter,  $n$  is the flow index,  $D$  is the pipe diameter,  $V$  is the flow velocity and  $\rho$  is the fluid density.

Formulations for slug flow characteristics were evaluated with the data of Baungartner et al. (2017) for experiments with air and solutions of CMC (presenting shear-thinning behaviour). The experiments were performed in a horizontal pipe with total length of 11.5m and internal diameter of 44.2mm. Flow rates and pressure gradient were measured, and slug properties were acquired through image processing. The flow behaviour index  $n$  was determined through rheological characterization and varied from 0.619 to 1.

### 3. RESULTS AND DISCUSSION

The best models for frequency, slug holdup and translational velocity obtained total RMS errors of 34.2, 30.2 and 11.0%, respectively. The poor performance of frequency and holdup formulations led to the proposal of two new formulations for these variables, based on the data of Baungartner et al. (2017).

For the slug frequency  $\nu_s$ , an adaptation of the expression of Schulkes (2011) was developed:

$$\nu_s = \Psi(\alpha)\Phi^{mod}(Re_{SL})\Theta(\beta, Fr_L)\frac{V_m}{D} \quad (2)$$

where

$$\Phi^{mod}(Re_{SL}) = \begin{cases} \Phi(Re_{SL}), & n > n_{crit} \\ 6.94Re_{SL}^{-0.17}, & n \leq n_{crit} \end{cases} \quad (3)$$

where  $V_m$  is the mixture velocity and  $n_{crit}=0.8$ . This modification assures that the original expression be recovered in the case of Newtonian fluids.

Figure 2 shows the performance of the currently proposed equation in comparison to the original form of Schulkes. Despite the large scatter of points, it is clear that the original correlation has a general trend of underestimating the present frequency data. The correction herein, on the other hand, managed to describe the measurements quite well, with a large portion of the predictions lying within the 20% threshold of the experimental values.

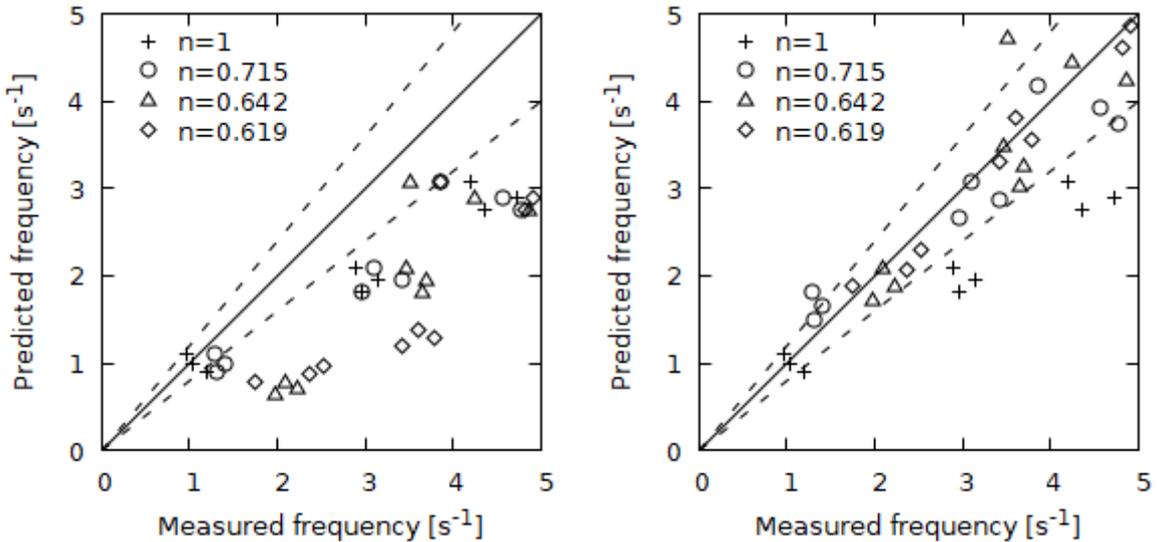


Figure 2: Comparison between measured and predicted slug frequency: Schulkes (2011) (left) and expression proposed here (right).

For slug holdup, the theory of Brauner (2001) was used as a basis for developing the following expression:

$$8n^{1.5} \left( \frac{6mV_m^n f^{n/2}}{2^{n/2}(\rho_L - \rho_G)gD^{n+1}} \right)^{\frac{1}{n+1}} = \tilde{d}_{\max} \quad (4)$$

where  $f$  is the friction factor,  $g$  is the gravity acceleration,  $\rho_L$  and  $\rho_G$  are the liquid and gas densities. The maximum bubble diameter is given by the theory of Brauner.

With the modified expressions, the errors decreased to 20.6 and 11.4% for frequency and holdup, respectively.

The impact of the closure relations on the predictions of the mechanistic models was quantified through a systematic alteration from a base setup for Newtonian fluids (using the expressions of Blasius; Schulkes, 2011; and Andreussi et al., 1993). The friction factor of Anbarlooei et al. (2015) was evaluated, as well as the proposed correlations. The description of each configuration of equations is shown in Tab. 1. For configuration 4 of the Orell model, the increase of viscosity due to bubbles in the slug was omitted.

Table 1 – Description of the configurations for the unit cell models.

Conf.	Dukler & Hubbard			Orell	
	Friction factor	Frequency	Slug holdup	Friction factor	Slug holdup
0	Blasius	Schulkes	Andreussi et al.	Blasius	Andreussi et al.
1	Anbarlooei et al.	Schulkes	Andreussi et al.	Anbarlooei et al.	Andreussi et al.
2	Blasius	Schulkes	New	Blasius	New
3	Blasius	New	Andreussi et al.	Anbarlooei et al.	New
4	Anbarlooei et al.	New	New	Anbarlooei et al.	New

Tables 2 and 3 show the resulting RMS errors for the pressure drop predictions. The change of the friction factor formulation resulted in a very significant improvement of the results. The best configurations presented total errors of 22.1 and 14%, compared to 39.4 and 27.6% of the unchanged models.

Table 2 – Pressure drop errors for different configurations of the model of Dukler & Hubbard (1975).

Conf.	$E_{\text{Newtonian}}$ [%]	$E_{\text{non-Newtonian}}$ [%]	$E_{\text{all}}$ [%]
0	27.7	42.6	39.4
1	26.6	24.1	24.8
2	26.3	20.4	22.1
3	26.6	37.0	34.7
4	26.3	28.1	27.6

Table 3 – Pressure drop errors for different configurations of the model of Orell (2005).

Conf.	$E_{\text{Newtonian}}$ [%]	$E_{\text{non-Newtonian}}$ [%]	$E_{\text{all}}$ [%]
0	6.0	31.7	27.6
1	6.3	15.8	14.0
2	6.4	48.0	41.7
3	6.2	37.9	33.0
4	7.2	17.7	15.8

Figures 3 and 4 show the comparisons between measured and predicted pressure gradients for the original and the best configuration of each model. The original models show a strong tendency to overestimate the pressure drop in the non-Newtonian fluid cases. The systematic deviation decreases significantly when improved closure relations are adopted.

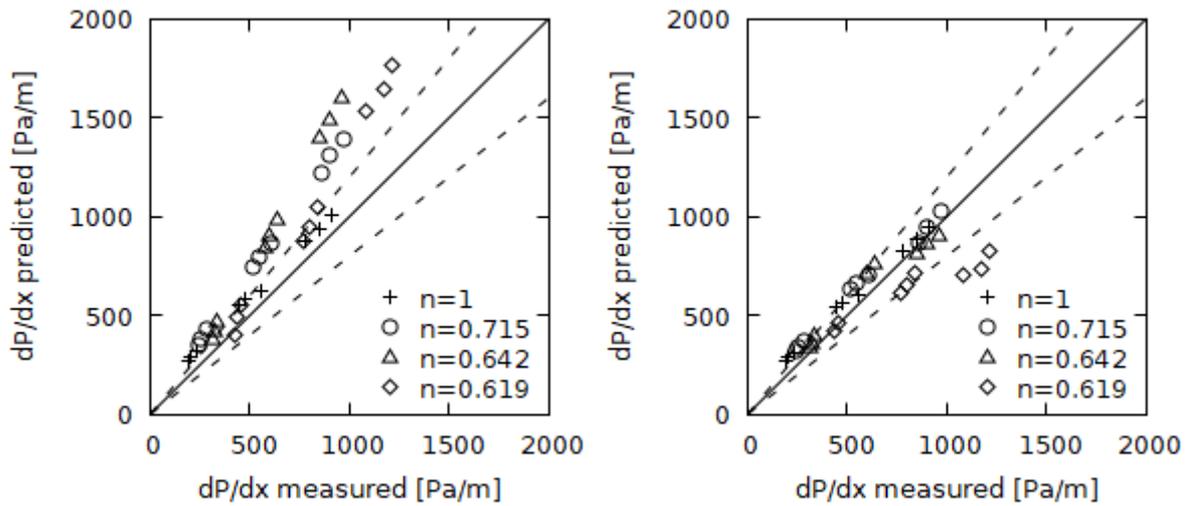


Figure 3: Comparison between measured and predicted pressure gradient for different setups of the Dukler & Hubbard (1975) model: configuration 0 (left) and configuration 2 (right).

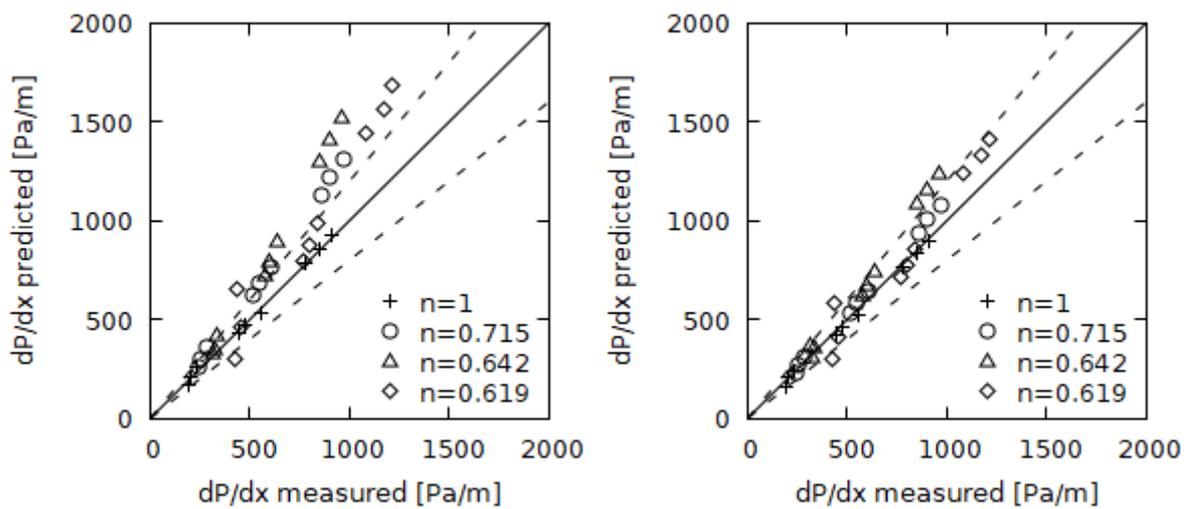


Figure 4: Comparison between measured and predicted pressure gradient for different setups of the Orell (2005) model: configuration 0 (left) and configuration 1 (right).

#### 4. CONCLUSIONS

The non-Newtonian behaviour of the liquid phase may cause drastic changes in the slug flow properties that cannot be properly predicted by existing models. Here, expressions were proposed to describe changes in slug frequency and aeration, accounting for shear-thinning effects. With the proposed expressions, the errors in frequency and holdup decreased to 20.6 and 11.4%, respectively. Furthermore, an analysis of the effect of the closure relations on pressure drop predictions was performed, and it was observed that simple modifications to mechanistic models were able to decrease the errors in pressure drop from 27.6 to 14%.

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