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Technical Note

A note on the prediction of liquid hold-up with the stratified roll wave regime for gas/liquid co-current flow in horizontal pipes

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This note presents a simple model for prediction of liquid hold-up in two-phase horizontal pipe flow for the stratified roll wave (St + RW) flow regime.

Liquid hold-up data for horizontal two-phase pipe flow [1–6] exhibit a steady increase with liquid velocity and a more dramatic fall with increasing gas rate as shown by Hand et al. [7,8] for example. In addition the liquid hold-up is reported to show an additional variation with pipe diameter. Generally, if the initial liquid rate for the no-gas flow condition gives a liquid height below the pipe centre line, the flow patterns pass successively through the stratified (St), stratified ripple (St + R), stratified roll wave, film plus droplet (F + D) and finally the annular (A + D, A + RW, A + BTS) regimes as the gas rate is increased. Hand et al. [7,8] have given a detailed description of this progression in flow regime development and definitions of the patterns involved. Despite the fact that there are over one hundred models which have been developed to predict liquid hold-up, none have been shown to be universally useful, while only a handful have proven to be applicable to specific flow regimes [9–12]. One of the most intractable regimes to predict has been the stratified roll wave pattern where the liquid hold-up shows the most dramatic change with gas flow rate. It has been suggested that the momentum balance-type models, which give both hold-up and pressure drop prediction, can predict universally for all flow regimes but particularly in the case of the difficult stratified roll wave pattern. Donnelly [1] recently demonstrated that the momentum balance models experienced some difficulties in the prediction of this regime. Without going into lengthy details, these models differ in the assumed friction factor or shear stress on the surfaces within the pipe particularly at the liquid–gas interface. The Baker–Jardine model [13] when tested against the 0.0454 m i.d. data of Nguyen [2] exhibited a wide scatter for both liquid hold-up and pressure drop as shown in Fig. 1. The Andritsos–Hanratty model [14] gave better prediction of pressure drop but a wide scatter for liquid hold-up estimation (cf. Fig. 2) when tested against the 0.0935 m i.d. data of Hand [5]. The Spedding–Hand model [15], shown in Fig. 3 against the data of Hand [5], gave improved performance but was still unsatisfactory with the prediction of hold-up for stratified-type flows. The MARS model of Grolman [6] gave better prediction of hold-up (cf. Fig. 4) but deterioration in the estimation of pressure drop when tested against the data of Nguyen [2]. Thus no method is available that will accurately predict liquid hold-up across the whole range of flow patterns but particularly for the stratified plus roll wavy regime. The position is particularly unfortunate since the stratified-type regimes are perhaps the most predominant pattern found in multiphase lines.

Fig. 5 shows liquid hold-up data for the stratified plus roll wave regime [1–6] in the form of the Lockhart–Martinelli plot [16]. The diameter range of data was wide being from 0.026 to 0.0953 m i.d. The data form a series of curves crossing the Lockhart–Martinelli relation (actually the Turner–Wallis [17] form of the relation), each of which depend on the superficial liquid velocity. These curves exhibit no dependence on diameter but show only a variation with liquid superficial velocity. Spedding and Spence [9,10] reported a similar variation of hold-up with liquid velocity for the annular droplet (A + D) regime. However, the form was different from the present case having some dependence on diameter. A liquid velocity number, the Kutadelaze number, was used in Fig. 5 to show the variation with velocity.

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Nomenclature

g	gravity, ms^{-2}
Ku	Kutadelaze number
l	length, m
P	pressure, kg m^{-1} s^{-2}
$\bar{R}$	hold-up
X	Lockhart–Martinelli parameter $[(\frac{\Delta P}{\Delta l})_{SL}/(\frac{\Delta P}{\Delta l})_{SG}]^{0.5}$
ρ	density, kg m^{-3}
σ	surface tension, kg s^{-2}

Subscripts

A	annular
BTS	blow through slug
D	droplet
F	film
IW	inertial wave
LRW	long roll wave
St	stratified
R	ripple
RW	roll wave
G	gas
L	liquid
S	superficial

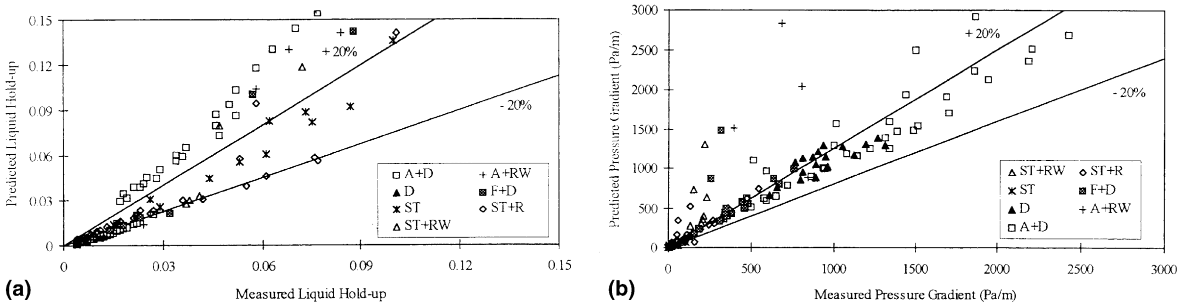

Fig. 1. Measured versus predicted hold-up and pressure gradient for the data of Nguyen (0.0454 m i.d.) using the method of Baker–Jardine [13].

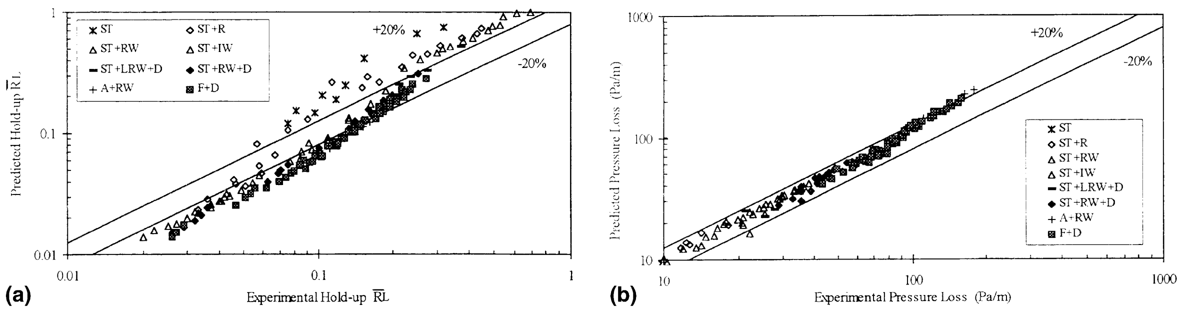

Fig. 2. Measured versus predicted hold-up and pressure gradient for the data of Hand (0.0935 m i.d.) using the method of Andritsos–Hanratty [14].

$$Ku = \bar{V}_{SL}\rho_L^{1/2}\left[[\sigma g(\rho_L - \rho_G)]^{1/4}\right]^{-1}. \tag{1}$$

The Turner–Wallis model [17]

$$\bar{R}_G = [1 + X^{0.8}]^{-0.377} \tag{2}$$

is also shown on Fig. 5, as a dotted line, because it is recommended for the prediction of hold-up with the stratified roll wave regime [5], and closely approximates the Lockhart–Martinelli model. Thus Eq. (2) provided an average prediction of the liquid hold-up overall but failed to adequately handle the extremities of gas flow, resulting in a very wide spread in prediction error for the stratified roll wave regime.

The curves in Fig. 5 showed a steady fall in slope as the Ku number was increased. The slope also showed a dramatic reduction at the points where the regime changed from roll wave to ripple flow and to the smooth

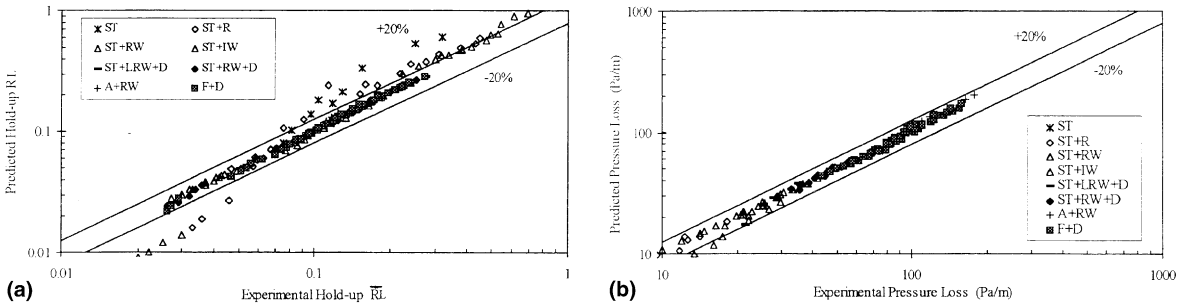

Fig. 3. Measured versus predicted hold-up and pressure gradient for the data of Hand (0.0935 m i.d.) using the method of Spedding–Hand [15].

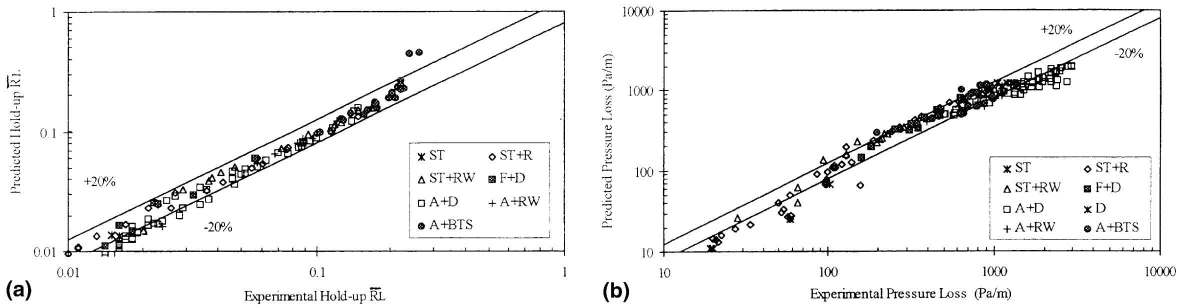

Fig. 4. Measured versus predicted hold-up and pressure gradient for the data of Nguyen (0.0454 m i.d.) using the MARS model of Grolman [6].

stratified condition. In addition at the stratified roll wave to ripple transaction an effect of diameter also appeared. At higher gas rates the transition to film plus droplet showed similar but less dramatic effects of slope change and the appearance of a diameter effect. It is recommended that the relation of Eq. (3),

$$\bar{R}_{\mathrm{L}} = (0.205Ku^{-0.12} + 0.06Ku^{-1.6})X^{[-0.87\log Ku+0.725]} \quad (3)$$

be used for prediction of liquid hold-up with horizontal stratified roll wave flow. Eq. (3) achieved prediction of data [1–6] within a total error spread of ±10%. The standard deviation of the error will be much less in absolute value. It should be noted that the error spread is half of that used in Figs. 1–4.

Eq. (3) is of importance because it can accurately predict hold-up in a regime that occurs very often in pipe line flow. The prediction of the occurrence of this regime can be achieved by using the universal flow regime map of Spedding and Cooper [18]. Once the prediction of liquid hold-up can be made it should be possible to achieve accurate estimations of the pressure loss, etc., for this flow regime using the momentum balance relations.

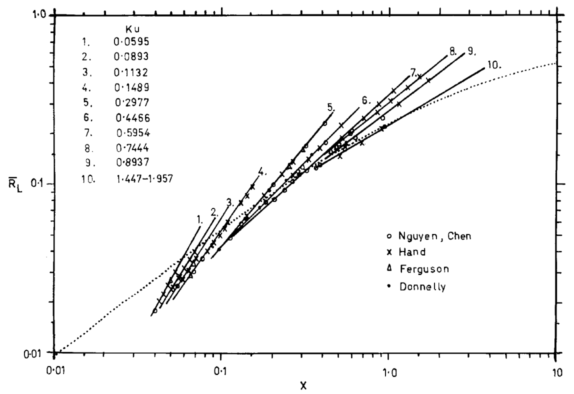

Fig. 5. Stratified plus roll wave liquid hold-up data of Donnelly (0.0259 m i.d.) [1], Nguyen and Chen (0.0454 m i.d.) [2,3], Ferguson (0.0501 m i.d.) [4] and Hand (0.0935 m i.d.) [5], tested against the productive model of Eq. (3). Lockhart–Martinelli correlation using the Turner–Wallis model.

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