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Modeling of Liquid Film Behavior in Serpentine Pipe Geometry

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A B S T R A C T

This study investigates the behavior of liquid film thickness along a flow system under varying gas and liquid velocities. The collected data from film probes positioned at various locations of the test facility, were matched with different experimental works using the available models. It was obviously observed that the majority of published correlations didn't present good accuracy for the data of this study, where the pipe diameter is relatively large (i.d.=101.6 mm). However, these models gave better predictions for the data of small-sized pipes (i.d. ≤ 50 mm). Due to this reason, it was necessary to modify some of the published models in order to be fit for all pipe diameters. The modified models were applied for the experimental data of the current study and for those available in a literature which presented accurate results for estimation of liquid film characteristics.

1 Literature Survey on Previous Models

The influence of tubing dimensions on the structure of liquid flowing on the inner pipe's wall (referred to as film) is presented by a number of publications. The attention of these publications is attended for small-sized tubes (i.d ≤ 50 mm), while the modeling of fluid flow in large-sized tubes are rare or even neglected. The majority of previous studies were built on the assumption that the interfacial occurrence is correlated with smooth and small amplitude waves of liquid film, which is reflected on the model's accuracy. Hewitt & Wallis (1963), investigated the occurrence of annular flow regime using the formula presented below (equation 1). They reported that the annular pattern can be formed when a modified Froude number becomes close to one.

$$U_g^* \equiv U_g \sqrt{\frac{\rho_g}{g D_t[\rho_g \alpha + \rho_L(1-\alpha)]}} \gg 1 \tag{1}$$

Where U_g is the velocity of gas phase, U_g* is a modified Froude number, *Dt* is the tubing diameter, α is the gas fraction, *g* symbol donates to force of gravitational, ρ_L and ρ_g donate to liquid and gas densities, respectively.

They observed that U_g* becomes more than 1, when the velocity of gas becomes higher, and confirmed that all values greater than 1 are falling within the range of annular flow, but if the velocity values are less than 1, the pattern falls within the intermittent and/or bubbly flows. A large proportion of models applied in estimating fluid thickness relate the Reynolds number (Re_{Lf}) to dimensionless film thickness (δ^+) as shown in the following formula:

$$\delta^+ = A\, Re_{Lf}^B \quad (2)$$

According to Kosky (1971), the constants (a) and (b) are respectively equal to 0.0512 & 0.875 when the Reynolds number is greater than 1000. In 1985, Asali identified the value of these constants as follows: a = 0.34 and b = 0.6 when the Reynolds number is less than 1000. In 1976, Henstock & Hanratty conducted experiments on vertical upward tubes using water and air as tested fluids and developed the following model:

$$\delta^+ = [\left(0.707 Re_{Lf}^{0.5}\right)^{2.5} + \left(0.0379 Re_{Lf}^{0.9}\right)^{2.5}]^{0.4} \quad (3)$$

It was noted that the correlation (1) did not take into account the impacts of sedimentation and entrainment of liquid droplets, although they may occur when high gas rates are applied. In 1979, Hori et al., addressed the impact of gas velocity on upflow film thickness, see Equation (4). Fukano and Furukawa (1998) took the flow rates into consideration and reported that the equation (1) becomes inaccurate when the δ/Dt ratio is small.

$$\delta/D_t = 0.905\, Re_{GO}^{-1.45} Re_{LO}^{0.90} Fr_{GO}^{0.93} Fr_{LO}^{-0.68} (\mu_L/\mu_w)^{1.06} \quad (4)$$

where μ_w is the water viscosity at 20ºC and μ_L is the water viscosity at surrounding temperature of experiment and Fr_{LO} takes the following formula:

$$Fr_{LO} = U_{sl}/\sqrt{gD_t},\ Re_{GO} = \rho_g U_{sg} D_t/\mu_g \quad (5)$$

In 1998, Fukano and Furukawa used Kosky (1971) and Asali et al. 's (1985) models by applying the entrainment phenomenon and liquid film results obtained by Nishikawa et al. 's (1967). They found that the data of Nishikawa accurately fit both models (Figure 1).

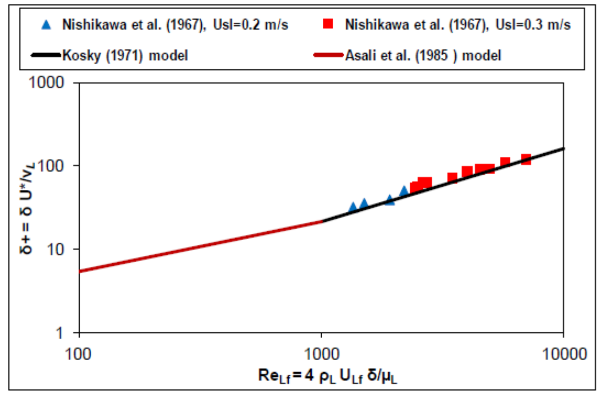


Figure 1: Estimation of Liquid Film As Presented By Fukano and Furukawa

Later on, Fukano and Furukawa (1998) predicted the liquid film by creating equation (6) below and reported that the new equation within 15% of the achieved experimental results.

$$\delta/D_t = 0.0594\ \exp\left(-0.34\, Fr_g^{0.25} Re_{Lf}^{0.19} x^{0.6}\right) \quad (6)$$

Where x is the quality of gas and Froude number (Fr_g) is expressed by the following formula:

$$Fr_g = \frac{U_{sg}}{(gD)^{0.5}} \quad (7)$$

Where U_{sg} is the superficial velocity of gas phase, g = 9.81 m/s^2 and the Reynolds number is:

$$Re_{Lf} = \frac{U_{Lf} D_t}{\nu_L} \quad (8)$$

Where ν_L is the kinematic viscosity of liquid film (m^2/s) and U_{Lf} its measured velocity. They also predicted the frictional pressure gradient and the factor of interfacial friction from liquid film. The achieved results were compared with previous studies such as Hewitt and Hall-Taylor (1970), Kosky (1971), Henstock and Hanratty (1976), Asali et al. (1985), and Ambrosini et al. (1991). It was noted that their equation presented different results. Almabrok (2023), noted that the previous models were only applicable for small-sized pipes. Therefore, he modified some of these models to be applicable for large-sized pipes as well. He stated that the modified models can give promising results when applied for all pipe sizes.

2 Brief Description of The Equipment

The equipment shown in Figure 2 was designed to attain the results of the current experimental work. The Delta-V program and variable pump were supplied to the facility by the air and water, respectively. The equipment comprises four pipes joined together by one 180 degrees bend at the bottom and two 180 degrees bends at the top. These pipes were arranged vertically with internal diameter= 4 inch. There are three liquid film devices positioned on the bottom, middle and top of each vertical pipe.

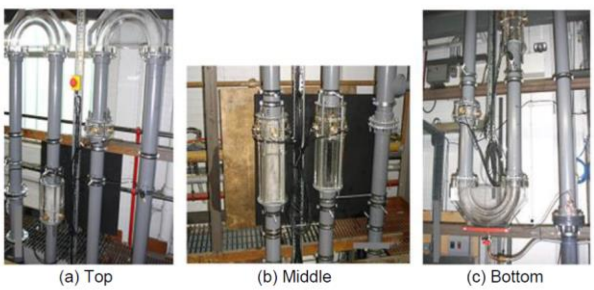


Figure 2: Shows The Three Sections of The Test Facility

3 Analysis of The Achieved Data

The updated models were applied for different pipe sizes to validate their applicability. The accuracy and validation of these models were confirmed by conducting comparative studies collected from different sources.

3.1 Matching The Current Study With Wolf et al.'Study

The impact of pipe diameter was highlighted by performing a comparative study between this work and that published by Wolf et al. (2001), as illustrated in Figure 3. Both studies were experimentally achieved in vertical upflow orientation. The internal diameter of their experimental facility is 31.8 mm , which is smaller than the current facility's diameter (i.d. 101.6 mm).

It was observed that the pipe size plays a critical impact on characteristics of liquid film. For instance when gas velocity is 24.5 m/s, the liquid film in the large-sized pipe (i.d. 101.6 mm) was double that formed in the small-sized pipe (i.d. 31.8 mm). Moreover, different behaviors were noted when gas velocities plotted against liquid film thickness for both pipes. The liquid film for large-sized pipes decreased sharply than that for the smaller ones.

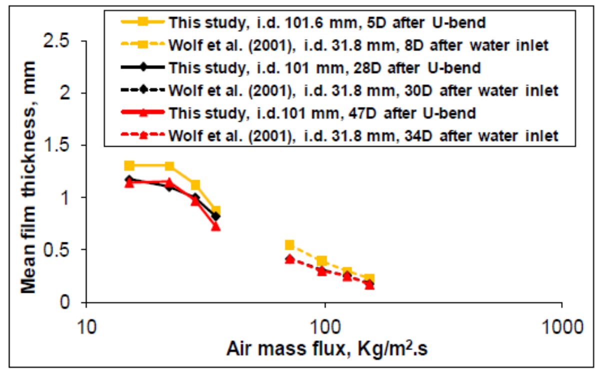


Figure 3: Behavior of Upward Liquid Film in Large and Small-Sized Pipes

3.2 Matching The Current Study With That of McQuillan et al. By Applying Alekseev et al.'s Equation

In 1985 McQuillan et al., determined the specific velocities of gas and liquid that lead to onset of flooding using pipe diameter equal to 31,8 mm. Figure 4, indicates a comparative study between calculation and experiment. The correlation of Alekseev et al. (1972) was applied for the calculation part of two studies which presented accurate results for both experiments (namely, McQuillan et al.'s study and this study). The equation gave good results for the impacts of pipe size and gave good estimation for liquid velocities in the range of transition regions between intermittent and annular flows.

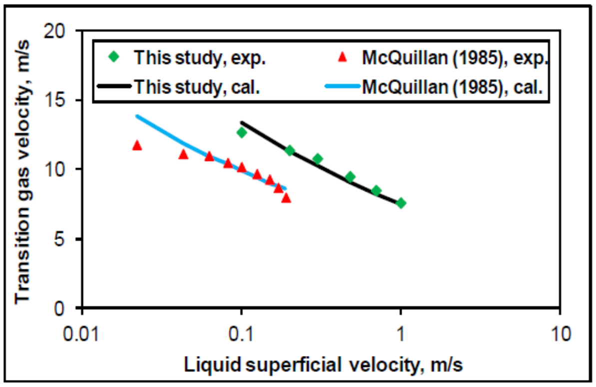
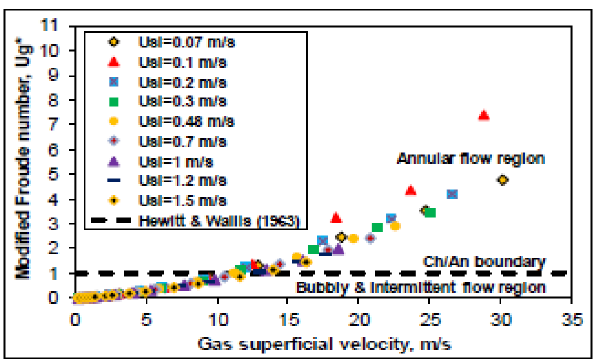
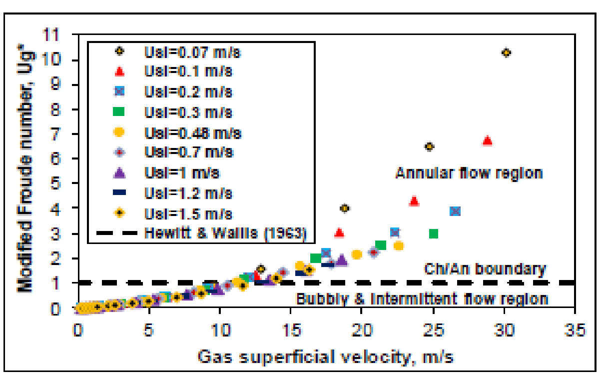


Figure 4: Shows The Data of The Current Study and McQuillan et al.'s Data Using Alekseev et al. 's Equation

Hewitt and Wallis correlation was also applied for current experimental data of liquid film which was presented as a good estimation (Figure 5). It was clearly noted that the dominant flow regime was annular, however intermittent and bubbly flow regimes also existed.



(a)



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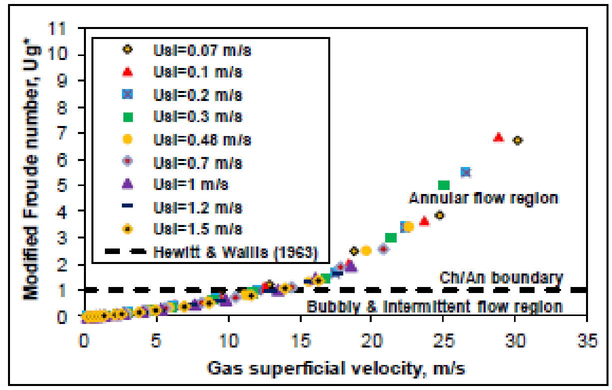


(c)

Figure 5: Application of Modified Froude Number For The Data of The Current Study

3.3 Matching The Current Liquid Film Data With Kosky and Asali Models

The empirical models of Kosky (1971) and Asali et al. (1985) were further matched with the experimental results of the present study (Figure 6), with scattering clearly observed above and below the fit line. This occurred as a result of the model being developed without accounting for droplet entrainment. This study found, however, that a significant number of entrainments were seen across the range of flow velocities. This will lead to an extreme decrease in the liquid film thickness attached to the pipe wall.

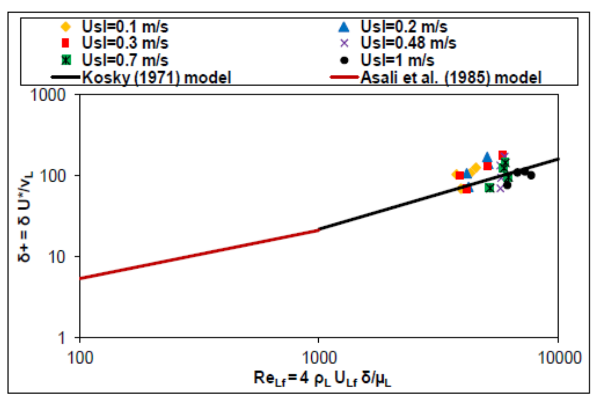


Figure 6: Estimation of Film Thickness Achieved From This Study Using Models of Kosky and Asali et al.

The entrainment data presented by Asali et al's (1985) model, who employed a small- sized pipe (i.d.= 22.9 mm) did not give a good estimation either (Figure 7). This then supports the assumption that the pipe size has a significant impact on the characteristics of liquid film.

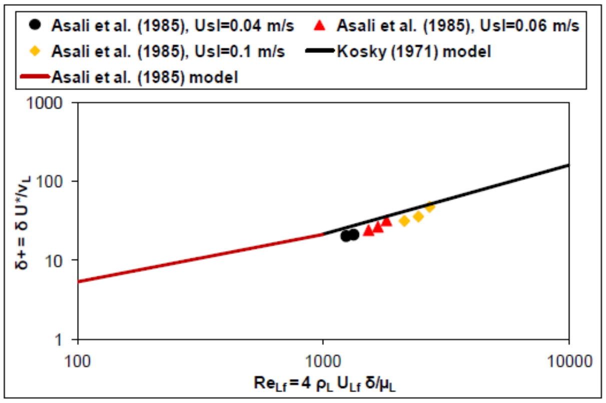


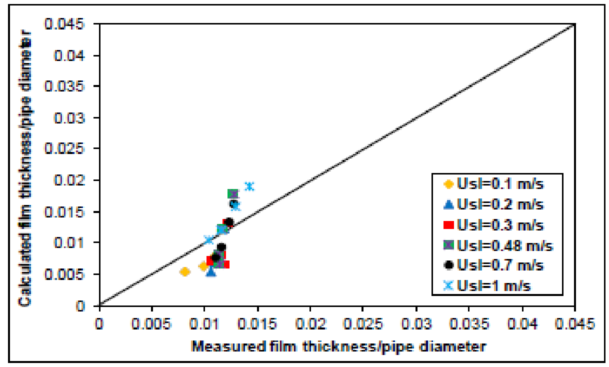
Figure 7: Entrainment Data of Asali et al. (1985) to Predict The Film Thickness Using Kosky (1971) Model

3.4 Matching The Film Thickness Data With Henstock & Hanratty (1976), Fukano & Furukawa (1998) and Hori et al. (1979) Models

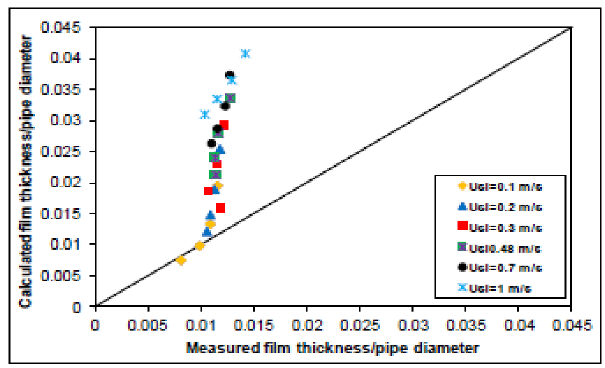
Film thickness data was compared to the mathematical models proposed by Henstock and Hanratty (1976), Fukano and Furukawa (1998) & Hori et al. (1979). The previously mentioned Equation (i.e., Eq. 3) which based on the Henstock and Hanratty (1976) model was utilized to determine the dimensionless liquid film ($^{\delta}/_{D_t}$) in relation to the liquid film Reynolds number, which can be expressed as:

$$Re_{Lf} = 4\rho_L U_{Lf}\delta/\mu_L \tag{9}$$

Figure 8 (a) displays the calculated dimensionless film data (δ/D) using Henstock & Hanratty model against the measurement data of this study. It is evident that there is a typically constant trend in both the observed values and the computed dimensionless film thickness. The estimation did not, however, entirely agree with all points. The approach did not take droplet entrainment into account, which explains the disparity. In the same way, Figure 8 (b & c) respectively, compares the dimensionless film thickness with those estimated by Fukano and Furukawa and Hori et al. It appears that there is a big difference between the computed and experimental data for the most liquid velocities. This can confirm that these models are only suitable for small pipes. Therefore, it is necessary to modify the mentioned models to fit all pipe diameters.



(a)



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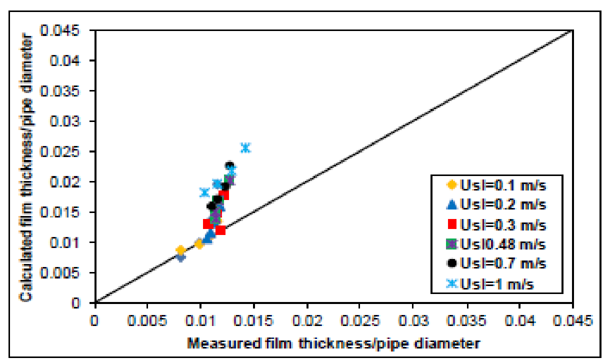
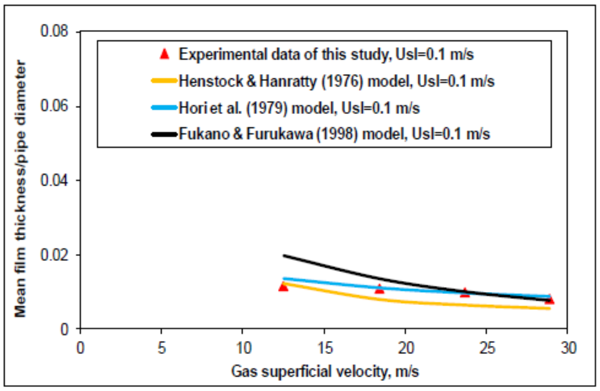


(c)

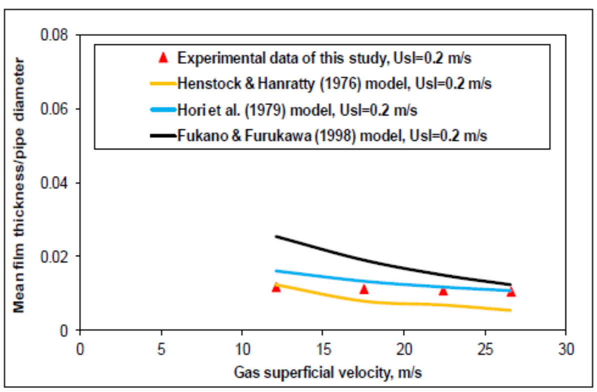
Figure 8: Shows The Dimensionless and Calculated Liquid Film Using The Models of Henstock & Hanratty,(a), Fukano & Furukawa (b) and Hori et al. (c)

Matching the current experimental data of liquid film with the models of Henstock & Hanratty (1976), Hori et al. (1979) and Fukano & Furukawa

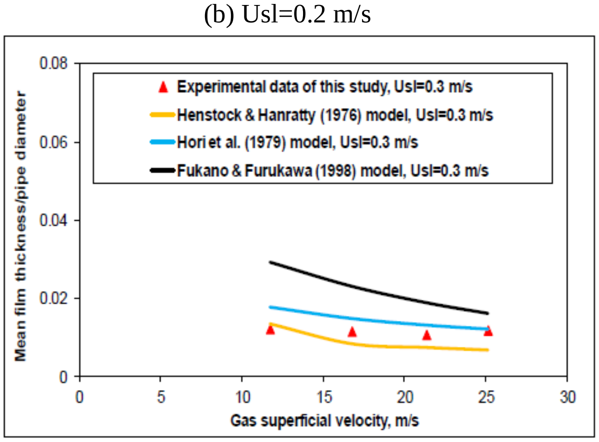
(1998) shows similar behavior, see Figure 9 (a-f). Obviously, the models gave good performance for all gas velocities and for liquid velocity = 0.1 m/s. Only Fukano & Furukawa was relatively poor in prediction for the most gas velocities. For liquid velocities = 0.7 and 1 m/s, Henstock & Hanratty model shows a better prediction with the current data. On the other hand, Hori et al. (1979) and Fukano & Furukawa (1998) models presented very poor estimation.



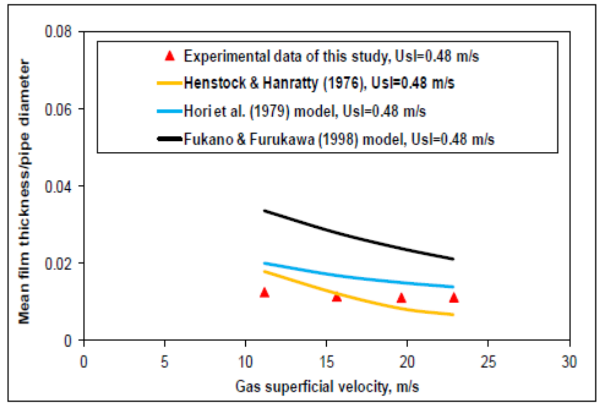
(a) Usl=0.1 m/s



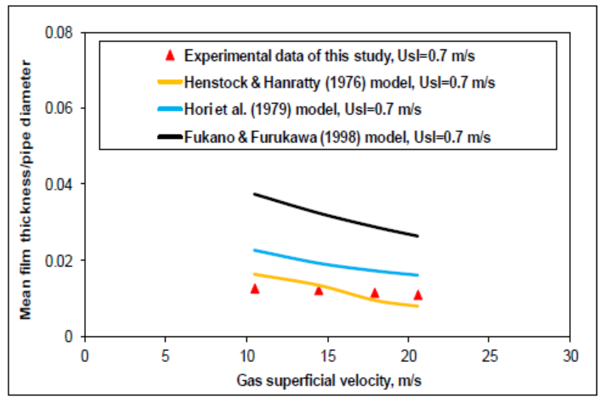
(b) Usl=0.2 m/s



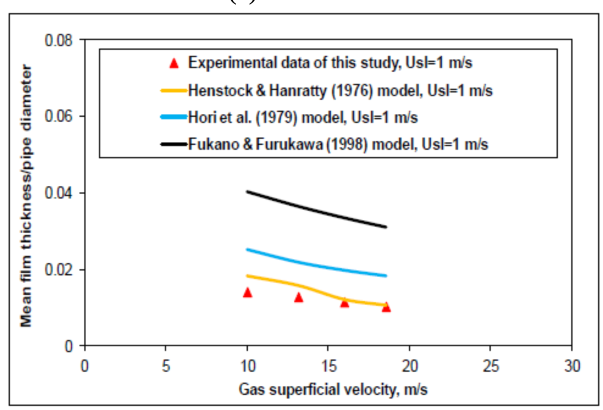
(c) Usl=0.3 m/s



(d) Usl=0.48 m/s



(e) Usl=0.7 m/s



(f) Usl=1 m/s

Figure 9: Dimensionless Liquid Film Against Gas Velocities For A number of Liquid Velocities Using The Models of Henstock & Hanratty, Hori et al. and Fukano & Furukawa

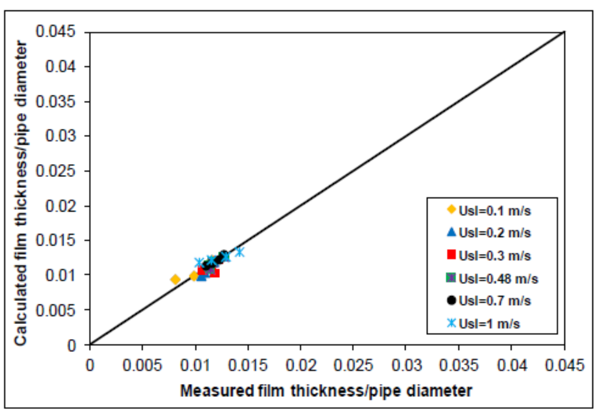
3.5 Modification of Hori et al. (1979) and Fukano & Furukawa (1998) Models

The liquid film measured by the present study was further predicted against the work reported by Wolf et al. (2001). Both studies applied Fukano & Furukawa (1998) and Hori et al. (1979) models, as previously mentioned in Figure 8 (b) and (c) respectively. It can be seen from Figure 9 (a-f) that the current study was close to Henstock & Hanrraty (1976) for all gas velocity values. However, it doesn't give good predictions for Fukano & Furukawa (1998) and Hori et al. (1979). Therefore, the modified models of Fukano & Furukawa (1998) and Hori et al. (1979) were used to give better predictions for the liquid film measured by the current experimental facility, as presented in equations (10) and (11) respectively.

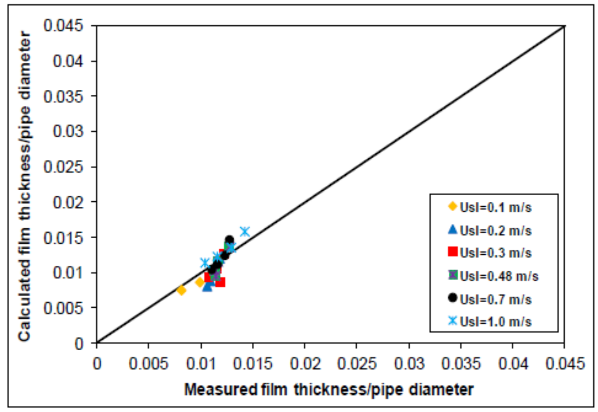
$$\delta/D_t = 0.0196\ \exp\left(-0.18\, Fr_g^{0.2} Re_{Lf}^{0.11} x^{0.22}\right) \quad (10)$$

$$\delta/D_t = 0.67\ Re_{GO}^{-1.48} Re_{LO}^{0.9} Fr_{GO}^{0.98} Fr_{LO}^{-0.8} (\mu_L/\mu_w)^{0.7} \quad (11)$$

These modified models were plotted in Figure 10 (a) and (b). Matching the gas velocities with average liquid film using the new equations was also studied (Figure 11 (a-f)). Obviously, the new correlations presented a good prediction for this study, and also gave reasonable estimation for the data reported by Wolf et al. (2001). This means that the created equations can be applied for all pipe sizes.

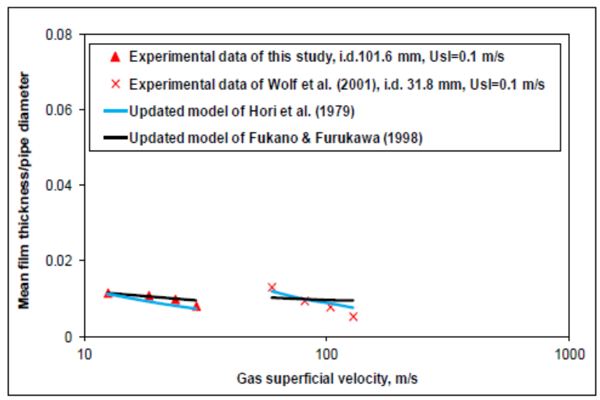


(a)

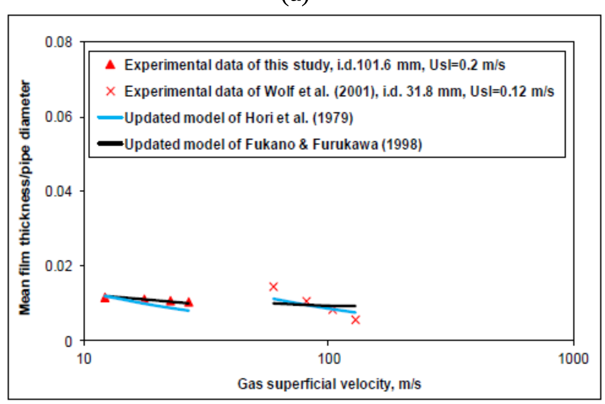


(b)

Figure 10: Shows The Dimensionless and Calculated Liquid Film Using The Modified Models of Fukano & Furukawa (a) & Hori et al. (b)



(a)



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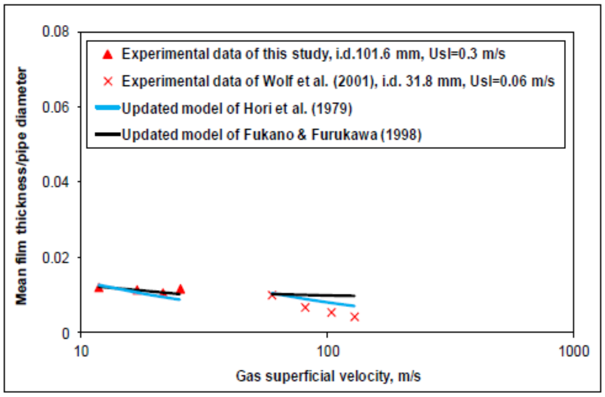

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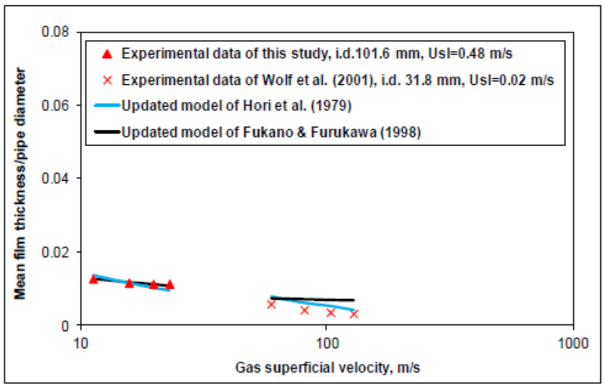

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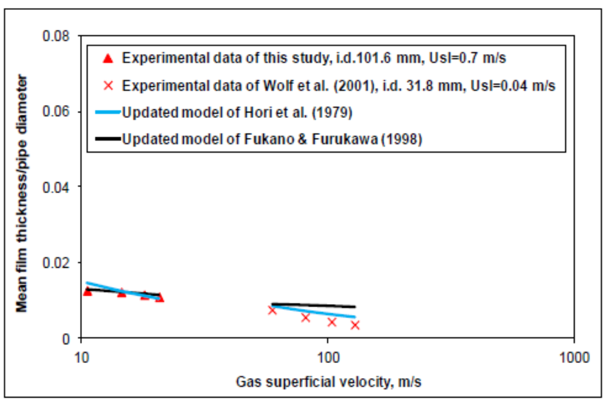

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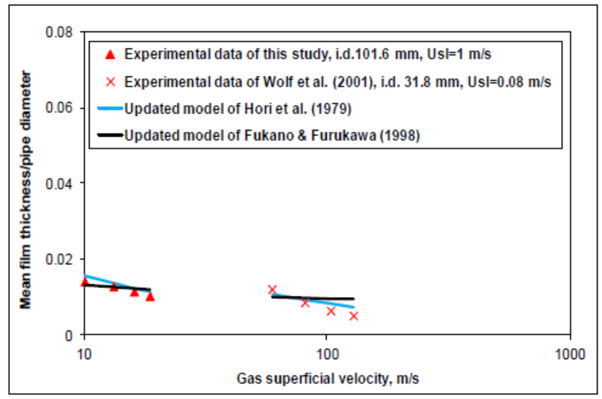

(f)

Figure 11 Matching The Upward Liquid Film Data Achieved From This Study With That Conducted By Wolf et al., Using Both Modified Models of Hori et al. & Fukano & Furukawa

4 Conclusions

The theoretical correlations didn't provide accurate predictions for liquid film in case of low gas flow rates where the liquid film is relatively thick. This means that the previous models were only considered the small-sized pipes. Moreover, these models neglected the entrainment of liquid droplets into the pipe center. However, the pipe diameter and liquid entrainment were noted to play a crucial role in fluid behavior. This led to inaccurate estimation of liquid film thickness. Due to this reason, it was necessary to update the published models in order to be applicable for all pipe sizes. From this study it is obviously noted that the updated models successfully presented good results.

References

Alekseev, V.P., Poberezkin, A.E. and Gerasimov, P.V. (1972). Determination of flooding rates in regular packing. Heat Transfer Soviet Research, 4, pp. 159-163.

Almabrok A. (2023). Modified empirical models for predicting liquid film thickness in different-sized vertical pipes, Sirte University Scientific Journal (SUSJ), Sirte University, Sirte – Libya.

Ambrosini, W., Andreussi, P. and Azzopardi, B. J. (1991). A physically based correlation for drop size in annular flow. International Journal of Multiphase Flow, 17, pp. 497-507.

Asali, J. C., Hanratty, T. J., and Andreussi, P. (1985). Interfacial drag and film height for vertical annular flow. AIChE Journal, 31, pp. 895-902.

Fukano, T. and Furukawa, T. (1998). Prediction of the effects of liquid viscosity on interfacial shear stress and frictional pressure drop in vertical upward gas-liquid annular flow. International Journal of Multiphase Flow, 24, pp. 587-603.

Henstock, W. H. and Hanratty, T. J. (1976). The interfacial drag and the height of the wall layer in annular flows. AIChE Journal, 22, pp. 990-1000.

Hewitt, G. F. and Hall-Taylor, N. S. (1970). Annular Two-Phase Flow. Pergamon, Oxford, UK.

Hewitt, G. F. and Wallis, G. B. (1963). Flooding and associated phenomena in falling film in a vertical tube. Multiphase flow symposium, Philadelphia, pp. 62-74.

Hori, K., M. Nakazatomi, K. Nishikawa, and Sekoguchi, K. (1979). On ripple of annular two-phase flow: effect of liquid viscosity on characteristics of wave and interfacial friction factor. Bulletin of the JSME.

Kosky, P.G. (1971). Thin liquid films under simultaneous shear and gravity forces. International Journal of Heat and Mass Transfer, 14, pp.1220-1224.

McQuillan, K. W., Whalley, P. B. and Hewitt, G. F. (1985). Flooding in vertical two phase flow. International Journal of Multiphase Flow, 11, pp. 741-760.

Wolf, A., Jayanti, S. and Hewitt, G. F. (2001). Flow development in vertical annular flow. Chemical Engineering Science, 56, pp. 3221-3235.