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Empirical modeling of liquid film thickness in vertical annular gas-liquid two-phase flow

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Abstract. Annular flow is one type of gas-liquid two-phase separated flow where gas flows in the center as core and liquid film flows along pipe wall. Annular flow type of two-phase flow has been applied for many industrial applications. Annular flow has a high efficiency of heat transfer. The most important characteristic that affects the heat transfer abilities is the liquid film thickness. This research studies and develops empirical model of liquid film thickness in vertical annular two-phase flow in pipe. The experimental data obtained from four different experiments in literature that measure liquid film thickness in vertical round pipe were compared with the newly developed model of liquid film thickness as well as other seven models in literature. The comparison shows that the results from the proposed model agree with the experimental data in literature better than other models.

1. Introduction

In general, annular flow is described as a fast gas core flowing in the center surrounding by a slow liquid film along pipe wall. The high velocity gas core causes high interfacial shear stress at the gas liquid interface which induces instability at the interface and thereby droplet entrainment into gas core flow. Sometimes, it also induces a wavy interfacial structure. Liquid droplet entrained in the core are undergone the continuous processes of droplet entrainment out of liquid film and droplet deposition into the liquid film. At steady state condition, the rate of deposition and entrainment are equal, leading to an equilibrium entrainment fraction of droplets in the gas core.

Two-phase annular flow is commonly found in many industrial applications, such as water-cooled nuclear reactors, evaporators, boilers, heat exchangers, refrigeration system and petrochemical plants. Annular flow is the most important regime for heat transfer applications such as Boiling Water Reactors (BWR), because annular flow has a high efficiency of heat transfer which is due to the thin liquid film thickness flowing and transferring heat from surface. Sometimes, liquid film thickness may dries out causing overheat of fuel rods and consequently catastrophically damage the core. As a result, it is necessary to understand the characteristic of the liquid film thickness in order to maintain appropriate size of liquid film thickness for high heat transfer rate and prevent the dry out phenomenon.

Many researchers have been conducted experiments on liquid film thickness measurement of annular flow in vertical circular tube. Bousman and McQuillen [1] observed annular two-phase gas-liquid flows in tube with inner diameter of 12.5 mm under Microgravity. To evaluate the effects of liquid viscosity and surface tension to liquid film thickness, the experiment was performed using three types of liquid including water, 50-50 wt% water-glycerin and water-Zonyl FSP. The superficial liquid velocity is ranging from 0.07 to 0.5 m/s, while superficial gas velocity is ranging from 4 to 26.1 m/s. The results show that film thickness decreases with decreasing superficial liquid velocity and increasing superficial gas velocity. Liquid film thickness of water-glycerin and water-Zonyl FSP are 20-30% and 40-50% greater than in the air-water. Fukano and Furukawa [2] investigated the effects of liquid viscosity on liquid film thickness and interfacial shear stress in vertical tube with inner diameter of 26 mm in annular flow. The experimental condition are superficial liquid velocity ranging from 0.04 to 0.1 m/s, superficial gas velocity ranging from 9.7 to 49.9 m/s under ambient pressure and temperature. The dynamic viscosity was varied from 0.85×10^{-6} to $8.6\times10^{-6}\,\mathrm{m^2/s}$ by mixing water and glycerol. Four concentrations of water-glycerol solution were tested including pure water (W09) 45 wt% glycerol solution (G3), 53 wt% glycerol solution (G5) and 53 wt% glycerol solution (G9), were tested.. The experimental results show that liquid film thickness decreases with increasing dynamic viscosity. Ashwood et al. [3] measured gas-water annular two-phase flow in quartz and copper tube with inner diameter of 23.4 mm. Condition of experiment are superficial liquid velocity from 0.04 to 0.34 m/s, superficial gas velocity from 35 to 85 m/s, ambient pressure and temperature. Total Internal Reflection (TIR) and Planer Laser Induced Fluorescence (PLIF) measurement techniques were used to directly measure liquid film thickness. The results from both techniques showed that liquid film thickness increases when increasing superficial liquid velocity and decreasing superficial gas velocity. Schubring et al.[4] explained more detail regarding method of PLIF technique. The results also show similar conclusion as the results experimented by Ashwood et al. [3].

Relying on observation on the experimental data, many correlations for predicting liquid film thickness have been developed based on different assumptions. Example of correlations of dimensionless film thickness are summarized in Table 1. Henstock and Hanratty [5] proposed that liquid film thickness is a function of interfacial friction factor ratio and derived for the interfacial friction factor equation. Later Tatterson et al. [6] modified the interfacial friction factor equation by including a function of Reynolds number of the liquid flowing in the wall layer. Hori et al. [7] considered that Reynolds number of liquid and gas, Froude number of gas and liquid, and liquid viscosity are the important parameters for modeling liquid film thickness. Fukano and Furukawa [2] proposed that liquid film thickness is based on gas Froude, liquid Reynolds number and quality. MacGillivray [8] proposed that liquid film thickness is mainly a function of just liquid Reynolds number and quality. Berna et al. [9] reviewed the existed correlations and proposed the new correlation in a form similar to correlation developed by Hori et al. [7], which are a function of Reynolds numbers and Froude numbers of both phases. Ju et al.[10] considered effects of gas and liquid velocity, gas density, and liquid viscosity separately and proposed a tanh function of Weber number, the modified gas Weber number and non-dimensional viscosity number. Unlike other correlations which are referenced with tube diameter, this correlation is based on maximum film thickness, which is defined from flow regime transition criteria proposed by Ishii and Grolmes [11].

Although the empirical correlations are easy to apply since they are usually presented in closed form, it is commonly known that it is almost entirely unreliable when applying to operating cases outside the range of experimental data that used for developing the correlation. It can be implied that the validity of the correlation would be improved if the correlation is developed based on large and wide range of pool of experimental data. The objective of this paper is to construct database experimental data from literature as a means to develop new correlation that has wide operating range.

Table 1. Summary of correlations for liquid film thickness of annular flow.

Reference	Correlation
Henstock and Hanratty [5]	Vertical flow $\frac{\delta}{D}=\frac{6.59F}{(1+1400F)^{0.5}}$ (1) Horizontal flow $\frac{\delta}{D}=\frac{6.59F}{(1+850F)^{0.5}}$ (2) $F=\frac{1}{\sqrt{2}\,\mathrm{Re}_g^{0.4}}\frac{\mathrm{Re}_f^{0.5}}{\mathrm{Re}_g^{0.5}}\frac{\mu_f}{\mu_g}\frac{\rho_g^{0.5}}{\rho_f^{0.5}}$
Tatterson et al. [6]	Vertical flow $\frac{\delta}{D}=\frac{6.59F}{(1+1400F)^{0.5}}$ (3) Horizontal flow $\frac{\delta}{D}=\frac{6.59F}{(1+850F)^{0.5}}$ (4) $F=\frac{\gamma(\mathrm{Re}_f)}{\mathrm{Re}_g^{0.9}}\frac{\mu_f}{\mu_g}\frac{\rho_g^{0.5}}{\rho_f^{0.5}}$ $\gamma(\mathrm{Re}_f)=[(0.707\,\mathrm{Re}_f^{0.5})^{2.5}+(0.0379\,\mathrm{Re}_f^{0.9})^{2.5}]^{0.4}$
Hori et al. [7]	$\frac{\delta}{D}=0.905\mathrm{Re}_g^{-1.45}\mathrm{Re}_f^{0.9}Fr_g^{0.93}Fr_f^{-0.68}\left(\frac{\mu_f}{\mu_{water@20^\circ C}}\right)^{1.06}$ (5)
Fukano and Furukawa [2]	$\frac{\delta}{D}=0.0594\exp(-0.34Fr_g^{0.25}\mathrm{Re}_f^{0.19}x^{0.6})$ (6) $x=\frac{\langle j_g\rangle\rho_g}{\langle j_g\rangle\rho_g+\langle j_f\rangle\rho_f}$
MacGillivray [8]	$\frac{\rho_f\langle j_f\rangle\delta}{\mu_f}=39\,\mathrm{Re}_f^{0.2}\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_f}\right)^{0.5}$ (7)
Berna et al. [9]	$\frac{\delta}{D}=7.165\mathrm{Re}_g^{-1.07}\mathrm{Re}_f^{0.48}\left(\frac{Fr_g}{Fr_f}\right)^{0.24}$ (8)
Ju et al. [10]	$\frac{\delta}{\delta_{\max}}=\tanh(14.22We_f^{0.24}We_g''^{-0.47}N_{\mu_f}^{0.21})$ (9) $We_g'=\frac{\rho_g\langle J_g\rangle^2D}{\sigma}\left(\frac{\Delta\rho}{\rho_g}\right)^{1/4}$ and $N_\mu=\frac{\mu_f}{\sqrt{\rho_f\sigma\sqrt{\frac{\sigma}{g\Delta\rho}}}}$

2. Database of experimental data of liquid film thickness measurement in vertical annular gas-liquid two-phase flow

Database of experimental data were collected from literature that provided sufficient data for repeat the experiment. The data must at least includes types of liquid and gas, diameter of tube, and flow rate of liquid and gas. Information regarding flow rate of both phases may be provided as either superficial fluid velocities of both phases or total flow rate and equivalent quality. In this study, the experimental data were collected from Bousman and McQuillen [1], Fukano and Furukawa [2], Ashwood et al. [3], and Schubring et al. [4] as summarized in Table 2. In total, the number of point of experimental data is 265 data points. It should be noted that Ashwood et al. [3] and Schubring et al. [4] are from the same

Table 2. Range of experimental data of liquid film thickness measurement in vertical annular gas-liquid two-phase flow.

Author	Fluids	D (mm)	j_l (m/s)	j_g (m/s)	Data point
Bousman and McQuillen [1]	Air-water	12.7	0.07-0.5	4-26.1	26
Fukano and Furukawa [2]	Air-W09	26	0.04-0.1	9.7-49.9	17
	Air-G3	26	0.04-0.1	9.7-49.9	18
	Air-G5	26	0.04-0.1	9.7-49.9	18
	Air-G9	26	0.04-0.1	9.7-49.9	18
Ashwood et al. [3]	Air-water	23.4	0.063-0.338	32.57-77.95	46
Schubring et al. [4]	Air-water	23.4	0.04-0.34	0.35-0.85	122

research groups. Apart of that, the experimental data were collected from three independent research groups.

3. Comparison of existing liquid film thickness models.

The comparison were performed by using the correlations presented in Table 1 to calculate for predicted film thickness and comparing the predicted results with the experimental data from the constructed database. The mean relative absolute error (MRAE), defined as:

$$MRAE = \frac{1}{N}\sum_{i}^{N}\left|\frac{\delta_{\mathrm{model,i}} - \delta_{\mathrm{exp,i}}}{\delta_{\mathrm{exp,i}}}\right| \times 100\%, \qquad (10)$$

is used as criterion to compare the accuracy of the correlations. The comparison results are shown in Figure 1 and summarized in Table 3. Based on the results, the correlations developed by Fukano and Furukawa [2] and Ju et al. [10] relatively successfully capture the trend of the data in newly constructed database with MRAE of around 20%. It should be noted that the correlation developed by Fukano and Furukawa [2] is best fit with their experimental data with MRAE of 8.1% because it was developed with that set of data.

Table 3. Comparison of mean relative error (MRAE) of correlation with database.

Model	Mean relative absolute error (MRAE)				
	Bousman's data	Fukano and Furukawa's data	Schubring's data	Ashwood's data	Overall
Henstock and Hanratty [5]	44.8%	22.5%	68.7%	52.8%	51.2%
Tatterson et al. [6]	38.5%	25.5%	139.2%	111.5%	94%
Hori et al. [7]	103.7%	121.6%	272.3%	238.3%	209.5%
Fukano and Furukawa [2]	32.2%	8.1%	22.9%	18.8%	19.1%
MacGillivray [8]	25.7%	86.8%	23.8%	23.1%	40.7%

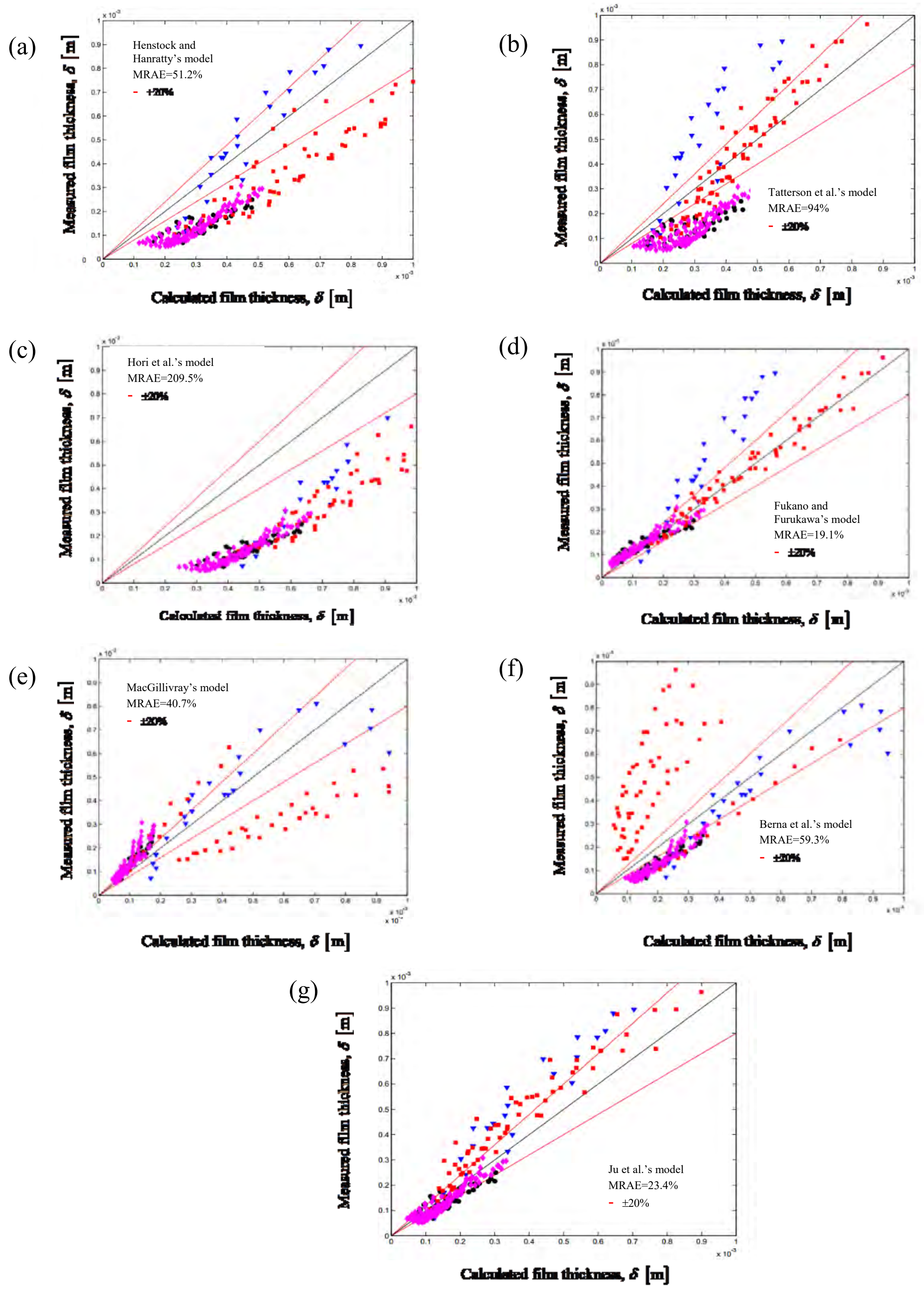

Figure 1. Comparison of calculated and measured liquid film thickness where ▼ represents data from Bousman and McQuillen [1], ■ represents data from Fukano and Furukawa [2], ● represents data from Ashwood et al. [3] and ♦ represents data from Schubring et al. [4] for correlations developed by (a) Henstock and Hanratty [5], (b) Tatterson et al. [6], (c) Hori et al. [7], (d) Fukano and Furukawa [2], (e) MacGillivray [8], (f) Berna et al. [9] and (g) Ju et al. [10].

Table 3 Comparison of mean relative error (MRAE) of model.

Model	Mean absolute percentage error (MAE)				
	Bousman's data	Fukano and Furukawa's data	Schubring's data	Ashwood's data	Overall
Henstock and Hanratty [5]	44.8%	22.5%	68.7%	52.8%	51.2%
Tatterson et al. [6]	38.5%	25.5%	139.2%	111.5%	94%
Hori et al. [7]	103.7%	121.6%	272.3%	238.3%	209.5%
Fukano and Furukawa [2]	32.2%	8.1%	22.9%	18.8%	19.1%
MacGillivray [8]	25.7%	86.8%	23.8%	23.1%	40.7%
Berna et al. [9]	33.5%	58.4%	65.1%	60%	59.3%
Ju et al. [10]	27.8%	19.9%	26.2%	18.8%	23.4%
New	14.4%	15.1%	15.2%	11.5%	14.5%

4. New correlation development

As previously mentioned that the correlation developed by Ju et al. [10] shows relatively good agreement with the newly constructed database, the newly developed correlation was developed with the correlation developed by Ju et al. [10] as a basis. For simplicity for application, the newly developed correlation was developed in term of common dimensionless film thickness which is the film thickness normalized by tube diameter instead of maximum film thickness as proposed by Ju et al. [10]. The functional form of the new correlation for dimensionless film thickness is expressed as:

$$\frac{\delta}{D} = C_1 \tanh(C_2 \,\mathrm{We}_f^{n_1}\, \mathrm{We}_g^{"n_2}\, \mathrm{N}_\mu^{n_3}). \tag{11}$$

Three dimensionless parameters, same as chosen by Ju et al. [10], are used to represent the effects of velocities of both phases, liquid viscosity, surface tension, and difference in fluid density to film thickness. It should be noted that the effects of viscosity is isolated and dedicated only in non-dimensional viscosity number, firstly proposed by Ishii and Grolmes [11] and defined as:

$$N_\mu = \frac{\mu_f}{\sqrt{\rho_f \sigma \sqrt{\dfrac{\sigma}{g\Delta\rho}}}}. \tag{12}$$

The modified gas Weber number, which was firstly proposed by Sawant [12] and defined as:

$$We_g^{*} = \frac{\rho_g \langle J_g \rangle^2 D}{\sigma}\left(\frac{\Delta\rho}{\rho_g}\right)^{1/4}, \tag{13}$$

was introduced to include the effect of difference in fluid density.

Based on the newly constructed database, the newly developed correlation is expressed as:

$$\frac{\delta}{D} = 0.0725 \tanh(34.11 \,\mathrm{We}_f^{0.2186}\, \mathrm{We}_g^{"-0.5926}\, \mathrm{N}_\mu^{0.2251}). \tag{14}$$

As shown in Table 3, the results from the newly developed correlation show good agreement with experimental data from four different experiments with total MRAE of 14.5%. Figure 2 shows the comparison between experimental data from each experiment and the correlation proposed by Ju et al. [10] as well as the newly developed correlation. The predictive results from the newly developed correlation out performs the correlation developed by Ju et al. [10] for all shown experiment sets.

It is important to note that although both correlations share the similar functional form, the correlations were developed based on different sets of data. The newly developed correlation was developed based on experimental data from database that collected from four different experiment sets,

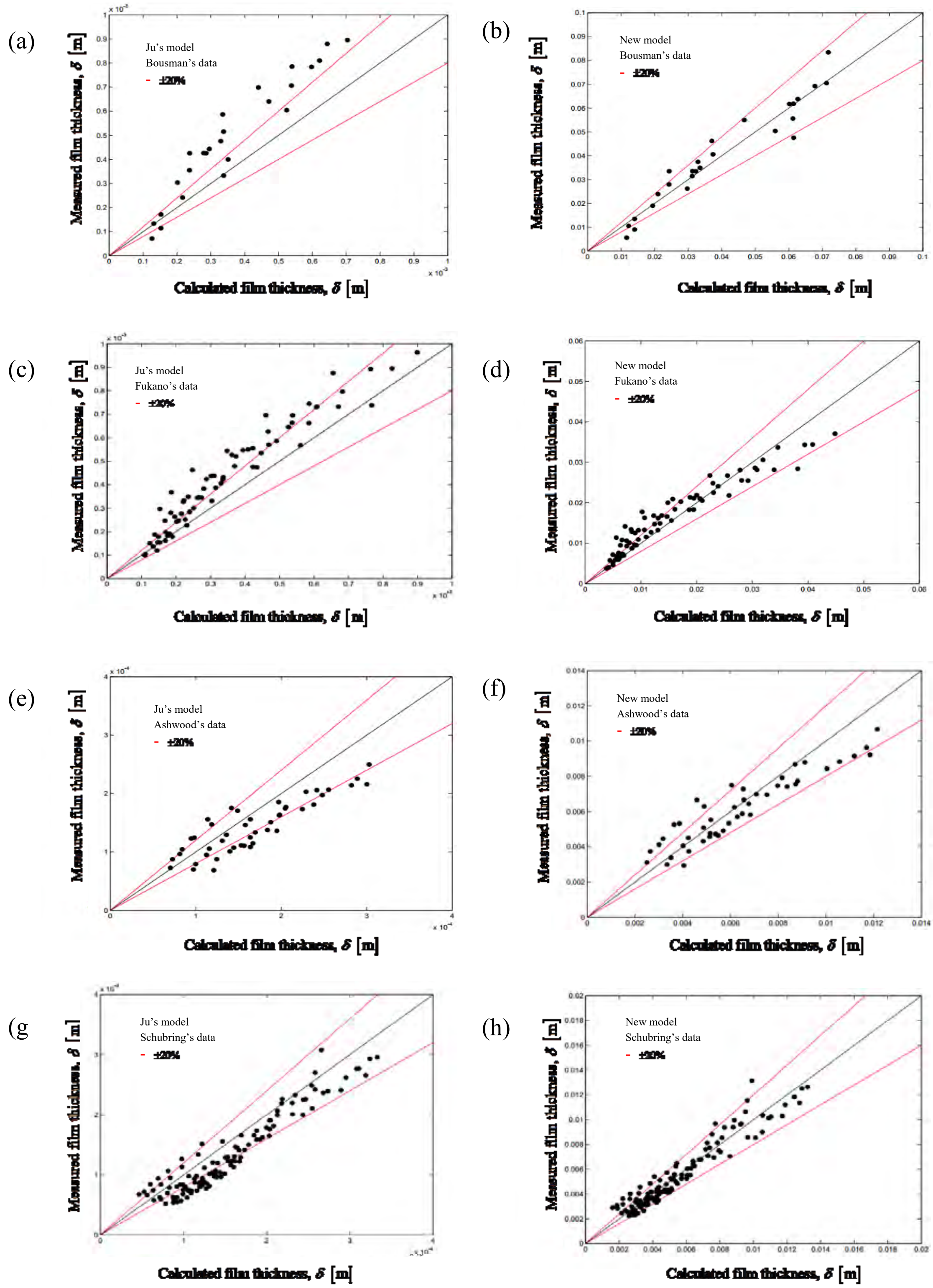

Figure 2. Comparison of the correlation proposed by Ju et al. [10] and the newly developed correlation with each set of experimental data summarized in Table 2.

while Ju et al. [10] used experimental data from three different data sets which one of them was closed experimental data that conducted by their own group. It can be implied that in addition to better accuracy as MRAE decreases by nearly 10%, the validity ranges and reliability of the newly developed correlation should also be better than the original correlation.

4. Conclusion

The database of experimental data of liquid film thickness measurement was constructed. The 265 data points were obtained from four literatures which are from three independent research groups. With wide operating ranges of data, the newly developed correlation for liquid film thickness was developed by improving the correlation developed by Ju et al. [10]. The newly developed correlation agrees well with experimental data in database with mean relative absolute error of 14.5%.

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