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Assessment and Development of Two Phase Turbulent Mixing Models for Subchannel Analysis Relevant to BWR

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Abstract

Determination of turbulent mixing rate of two phase flow between neighboring subchannels is an important aspect of sub channel analysis in reactor rod bundles. Various models have been developed for two phase turbulent mixing rate between subchannels. These models show that turbulent mixing rate is strongly dependent on flow regimes; their validity was examined against specific or limited experiments. It is vital to evaluate these models by comparing the predicted two phase turbulent mixing rate with available experimental data conducted for various subchannel geometries and operating conditions. This paper describes evaluation of different models for two phase turbulent mixing rate for both gas and liquid phase against large range of experimental data which are obtained from various subchannel geometries. The results indicate that there is large discrepancy between the predicted and experimental data for turbulent mixing rate. This paper provides important shortcoming of the previous work and need for the development of a new model. In the view of this, a two phase flow model is presented, which predicts both liquid and gas phase turbulent mixing rate between adjacent sub channels of reactor rod bundles. The model presented here is for slug churn flow regime, which is dominant as compared to the other regimes like bubbly flow and annular flow regimes, since turbulent mixing rate is the highest in slug churn flow regime. The present model has been tested against low pressure and temperature air-water and high pressure and temperature steam-water experimental data found that it shows good agreement with available experimental data.

Keywords

Subchannel Analysis, Two Phase Turbulent Mixing Model, Turbulent Mixing Rate

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1. Introduction

The fluid transfer among subchannels is explained by three mechanisms *i.e*. turbulent mixing, void drift and diversion cross flow (Lahey and Moody [1]). The fluid exchange due to turbulent mixing is because of turbulent fluctuation. In this mechanism of fluid exchange, neither net mass transfer nor net volume transfer between adjacent subchannels occurs. Second mechanism is void drift which occurs even in absence of pressure difference. Void drift is due to redistribution of non-equilibrium flow to attain equilibrium flow. Third mechanism is diversion cross flow which occurs due to lateral pressure difference between adjacent subchannels.

1.1. Review of Experiments for Subchannel Analysis

The available experiment on two phase turbulent mixing rate between adjacent subchannels is listed in **Table 1**.

Insights from Previous Experiments

The two phase turbulent mixing experiments are performed by Walton [2], Rudzinski [3], Singh K. S. [4], Kawahara *et al.* [5], Sadatomi *et al.* [6] and Kawahara *et al.* [7]. These experiments provide important insights as given below:

a) The total two phase turbulent mixing rate is sum of liquid and gas phase turbulent mixing rate and it is strongly related to flow regimes. The liquid phase turbulent mixing rate starts at zero quality, which increases in bubbly flow reaches maximum value in slug churn and then decreases beyond churn-annular flow transition. The gas phase mixing rate starts near zero value of quality, which reaches maximum in slug churn flow and then decreases with increase in quality. It is thus rational to consider the turbulent mixing separately in each flow pattern.

b) Two phase mixing rate depends on gap between the subchannels. On increasing the gap between the subchannels, mixing rate increases.

c) The two phase turbulent mixing rate increases with increase in mass flux.

d) The two phase turbulent mixing rate decreases with increase in pressure.

1.2. Review of Models for Subchannel Analysis

The available models on two phase turbulent mixing rate between adjacent subchannels are listed in **Table 2**.

2. Evaluation of Turbulent Mixing Model

In this section, we evaluate the turbulent mixing models like Bues [8] model, Kazimi and Kelly [9] model, Kawahara *et al.* [10] model and Carlucci *et al.* [11] against the data obtained from various subchannel experiments of two phase turbulent mixing as discussed in section 1.1. For evaluation, we have compared the measured (experimental) liquid phase turbulent mixing rate $W'_{l,\exp}$ with predicted liquid phase turbulent mixing rate $W'_{l,cal}$ and measured (experimental) gas phase turbulent mixing rate $W'_{g,\exp}$ with predicted gas phase turbulent mixing rate $W'_{g,cal}$ in two phase flow. The error analysis has been done to find out maximum, minimum and average error between measured and predicted value of both liquid and gas phase turbulent mixing rate. The error analysis shows how predicted value by turbulent mixing models differs from measured experimental values.

$$\text{Max. Error} \quad E_{\max,i} = \max\left(\frac{W'_{i,cal} - W'_{i,\exp}}{W'_{i,\exp}} \times 100\right) \tag{1}$$

$$\text{Min. Error} \quad E_{\min,i} = \min\left(\frac{W'_{i,cal} - W'_{i,\exp}}{W'_{i,\exp}} \times 100\right) \tag{2}$$

The average error is calculated as

$$\text{Average Error} = \frac{\sum_{i=1}^{n} E_i}{n} \% \tag{3}$$

where $n =$ no. of data points and

Table 1. Description of available data on two phase turbulent mixing rate.

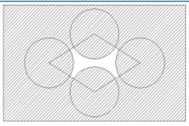
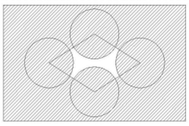
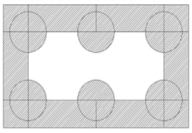
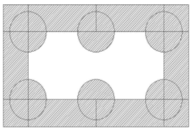
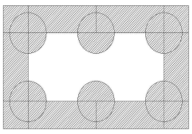
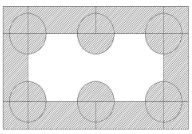
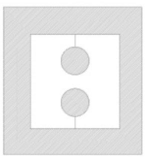
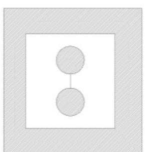
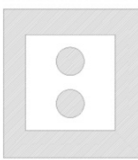
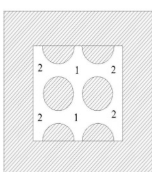
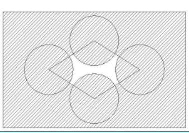
S. No.	Experiment	Subchannel array	Geometrical Description	Working Fluid	Total mass flux	Flow pattern
1.	Walton [2] [T-T subchannel Experiment]		$d=1.97\times10^{-2}$ $S=1.02\times10^{-3}$ $D=3.9\times10^{-3}$ $P/d=1.05$ $A=3.39\times10^{-5}$	Water and air	90 to1000 Kg/m^2s	annular flow
2.	Rudzinski [3] [T-T and S-S subchannel experiment]		$d=1.97\times10^{-2}$ $S=1.02\times10^{-3}$ $D=3.9\times10^{-3}$ $P/d=1.05$ $A=3.39\times10^{-5}$	Water and air	680 to 2030	bubbly, slug, churn and annular
			$d=2.08\times10^{-2}$ $S=0.89\times10^{-3}$ $D=8.75\times10^{-3}$ $P/d=1.04$ $A=5.24\times10^{-5}$			
3.	Singh [4] [S-S subchannel experiment with varying gap width]		$d=1.98\times10^{-2}$ $S=2.03\times10^{-3}$ $D=9.6\times10^{-3}$ $P/d=1.10$ $A=1.69\times10^{-4}$	Water and air	40 to 1080	bubbly, slug, churn and annular
			$d=2.08\times10^{-2}$ $S=0.89\times10^{-3}$ $D=8.7\times10^{-3}$ $P/d=1.04$ $A=1.52\times10^{-4}$			
			$d=2.13\times10^{-2}$ $S=0.38\times10^{-3}$ $D=8.3\times10^{-3}$ $P/d=1.02$ $A=1.43\times10^{-4}$			
4.	Kawahara *et al.* [5] [R-R subchannel experiment with varying gap number *i.e.* 1centre, 2side and 3 gap]		$d=1.2\times10^{-2}$ $S=2.1\times10^{-3}$ $D=1.57\times10^{-2}$ $P/d=1.17$ $A=4.07\times10^{-4}$	Water and air	100 to 1000	bubbly, slug, churn and annular
			$d=2.08\times10^{-2}$ $S=0.89\times10^{-3}$ $D=8.75\times10^{-3}$ $P/d=1.04$ $A=5.24\times10^{-5}$			
			$d=1.2\times10^{-2}$ $S=6.3\times10^{-3}$ $D=1.57\times10^{-2}$ $P/d=1.17$ $A=4.07\times10^{-4}$			
5.	Sadatomi *et al.* [6], [Multichannel experiment S-S(1-1) and R-R(2-2) subchannel experiment]		$d=1.6\times10^{-2}$ $S=4\times10^{-3}$ $D=1.43\times10^{-2}$ $P/d=1.25$ $A=1.94\times10^{-4}$ $d=1.6\times10^{-2}$ $S=4\times10^{-3}$ $D=1.12\times10^{-2}$ $P/d=1.25$ $A=1.38\times10^{-4}$	Water and air	100 to 2000	bubbly, slug, churn and annular
6.	Kawahara *et al.* [7] [T-T subchannel experiment]		$d=1.2\times10^{-2}$ $S=1.0\times10^{-3}$ $D=3.19\times10^{-3}$ $P/d=1.08$ $A=1.66\times10^{-5}$	Water and air	100 to 2000	bubbly, slug, churn and annular

Table 2. Description of available models on two phase turbulent mixing rate.

S. No	Model	Principle	Equation derived for turbulent mixing rate
1	Bues' model [8],	The total turbulent mixing rate is formulated for two regimes. A physical model is developed for the first region *i.e.* bubbly-slug region and it is combined with an empirical fit for the second region *i.e.* annular region	$W_I' = W_{l,sph}' + B_1\left(\frac{AG}{D}\right)\frac{\rho_l}{\rho_g}\left(\frac{s-1}{s}\right)x$ $W_{II}' = W_{g,sph}' + \left(W_p' - W_{g,sph}'\right)\left(\frac{1-\left(\frac{x_0}{x_p}\right)}{\frac{x}{x_p}-\left(\frac{x_0}{x_p}\right)}\right)$
2	Kazimi and Kelly's [9]	It is based on Bues' model [10] which shows dependence of mixing rate on flow regimes. They proposed a correlation between the velocity fluctuation due to two phase turbulent mixing and the velocity fluctuation due to single phase turbulent mixing	$W_q' = \rho_q \alpha_{gap,q} S\left(\frac{\varepsilon}{l}\right)_{tph}$, $\left(\frac{\varepsilon}{l}\right)_{tph} = \left(\frac{\varepsilon}{l}\right)_{sph}\theta$
3	Kawahara *et al.* [10]	This model is for slug churn flow regime. In this model, the liquid phase turbulent mixing rate is the sum of three independent component mixing rate due to turbulent diffusion, convective transfer and pressure difference	$W_l' = W_{l,td}' + W_{l,ct}' + W_{l,pd}'$, $W_g' = \rho_g\left(\sum S\right)\tilde{V}_g$
4	Carlucci *et al.* [11] model	It is based on the principle that total phasic turbulent mixing rate is sum of homogenous turbulent mixing rate and incremental turbulent mixing rate	$W_l' = W_{l,\text{hom}}' + \Delta W_{l,tph}'$, $W_g' = W_{g,\text{hom}}' + \Delta W_{g,tph}'$

$$E_i = \left(\frac{W_{i,cal}' - W_{i,\exp}'}{W_{i,\exp}'}\times 100\right) \tag{4}$$

2.1. Evaluation of Model of Bues [8]

Bues [8] model, the calculated liquid and gas turbulent mixing rate shows large discrepancy, when compared against measured liquid and gas phase mixing rate as seen in **Figure 1(a)** and **Figure 1(b)** respectively.

2.2. Evaluation of Model of Kazimi and Kelly [9]

In Kazimi and Kelly's [9], the calculated liquid and gas turbulent mixing rate shows large discrepancy, when compared against measured liquid and gas phase mixing rate as seen in **Figure 2(a)** and **Figure 2(b)** respectively.

2.3. Evaluation of Model of Kawahara *et al.* [10]

Kawahara *et al.* [10], the calculated liquid and gas turbulent mixing rate shows large discrepancy, when compared against measured liquid and gas phase mixing rate as seen in **Figure 3(a)** and **Figure 3(b)** respectively.

2.4. Evaluation of Model of Carlucci *et al.* [11]

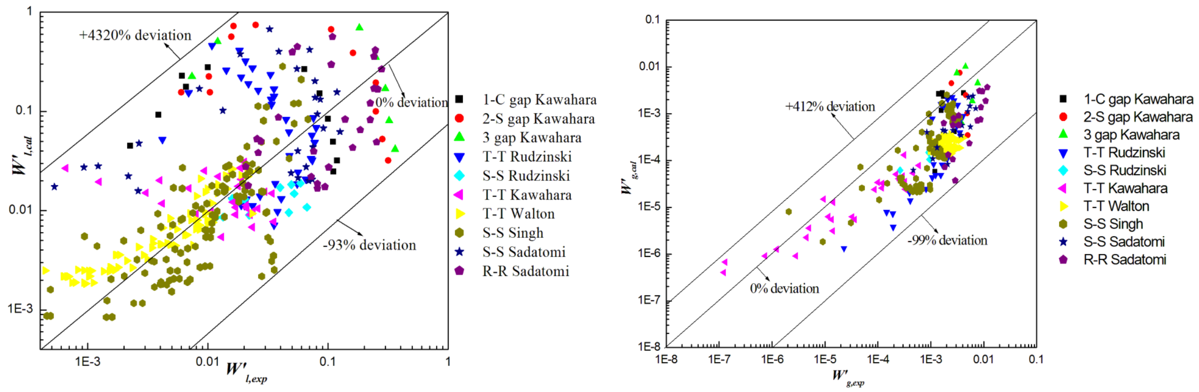
In Carlucci *et al.* [11] model, the calculated liquid and gas turbulent mixing rate shows large discrepancy, when compared against measured liquid and gas phase mixing rate as seen in **Figure 4(a)** and **Figure 4(b)** respectively.

2.5. Insights from Previous Models

In this paper the liquid and gas phase mixing rate in two phase flow have been predicted using the models of Bues [8], Kazimi and Kelly [9] and Carlucci *et al.* [11]. All these models consider all the flow regimes. Only Kawahara *et al.* [10] model considered models for different flow regimes. The assessment of these models shows that there is large discrepancy between models and experimental data which is shown in **Table 3**.

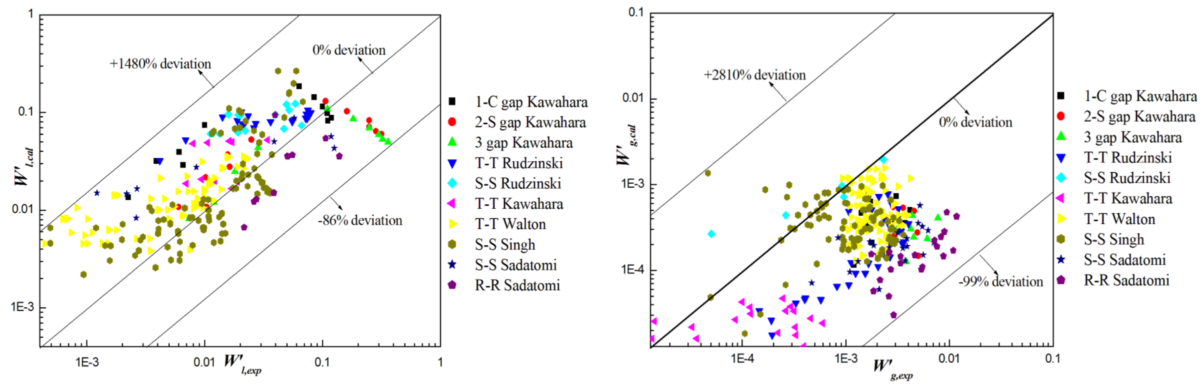
Assessment of these models provide important shortcoming which are as follows.

a) Array effect: In all these models except Kawahara *et al.* [10] model, the array effect like Square-Square,



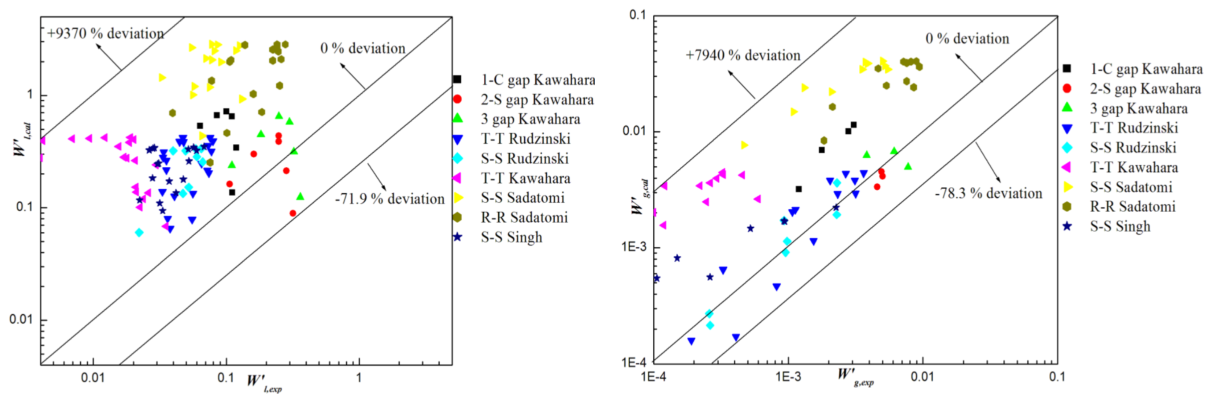
(a) (b)

Figure 1. Comparison of the predictability of Bues [8] model model against subchannels experiments for liquid and gas phase turbulent mixing rate in two phase flow.



(a) (b)

Figure 2. Comparison of the predictability of Kazimi and Kelly's [9] model model against subchannels experiments for liquid and gas phase turbulent mixing rate in two phase flow.

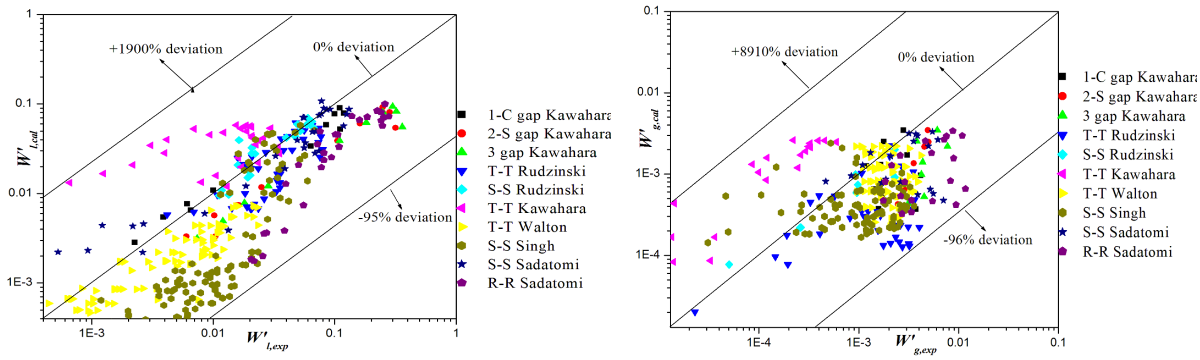


(a) (b)

Figure 3. Comparison of the predictability of Kawahara *et al.* [10] model model against subchannels experiments for liquid and gas phase turbulent mixing rate in two phase flow.

Rectangular-Rectangular, and Triangular-Triangular subchannel array has not been considered.

b) Subchannel size effect: Carlucci [11] model doesn't predict well, when area of subchannel is very small, which is shown by large error in Triangular-Triangular subchannel experiment of Kawahara [7] where area of subchannel is very less (~16.6 mm^2).



(a) (b)

Figure 4. Comparison of the predictability of Carlucci *et al.* [11] model against subchannels experiments for liquid and gas phase turbulent mixing rate in two phase flow.

Table 3. Error analysis between calculated liquid turbulent mixing and measured liquid turbulent mixing rate in two phase flow.

Model	Liquid mixing rate			Gas mixing rate		
	Max error %	Min error %	Average error %	Max error %	Min error %	Average error %
Bues [8]	+4320	−93	+515.4	+412	−93	−52.1
Kazimi and Kelly [9]	+1480	−86	+153.2	+2810	−99	−41.8
Kawahara [10]	+9370	−71.9	+1200	+7940	−78.3	+637
Carlucci [11]	+1900	−95	−15.6	+8910	−96	+104

c) Gap size effect: Models of Bues [8], Kazimi and Kelly [9] and Carlucci *et al.* [11], doesn't predict well, when the gap between subchannels is more than 2.1 mm.

d) Pressure effect: In Kawahara *et al.* [10] model, the effect of pressure has not been considered.

3. Model Developments

Since previous models have large errors, there is need to develop a new turbulent mixing model which can predict well for various subchannel geometries. A slug-churn flow model is proposed to predict liquid and gas phase mixing rate. The model has been tested against low pressure and temperature (ambient) air-water and high pressure and temperature steam-water experimental data found that it shows good agreement with available experimental data.

From the insights of previous experiments and models of two phase turbulent mixing rate, it can be inferred that the two phase turbulent mixing depends strongly on the subchannel quality, mass flux, pressure and subchannels geometry. Thus the liquid turbulent mixing number for two phase flow in subchannels can be expressed as

$$N_{l,\text{mix}} = C_l \times \left(\text{Re}_{\text{mix}}\right)^{a_l} \tag{5}$$

where

$$\text{Re}_{\text{mix}} = \frac{G \times D}{\mu_{\text{hom}}} \tag{6}$$

$$N_{l,\text{mix}} = \left(\frac{W'_{l,\text{mix}} \times D^2}{A \times \mu_{\text{hom}}}\right) \tag{7}$$

$$\mu_{\text{hom}} = \left(\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right)^{-1} \tag{8}$$

The coefficient (C_l) and exponent (a_l) were obtained by fitting the test data of Rudzinski [3], Kawahara *et al.* [5], and Kawahara *et al.* [7] plotted on dimensionless liquid mixing number against mixture Reynolds number as shown in **Figure 5**.

The equation so obtained is given by relationship

$$W'_{l,\mathrm{mix}} = \frac{0.00104 \times A \times \mu_{\mathrm{hom}} \times (\mathrm{Re}_{\mathrm{mix}})^{1.80}}{D_h^2} \tag{9}$$

The equation for gas phase turbulent mixing rate in two phase flow can be written as follows

$$N_{g,\mathrm{mix}} = C_g \times \left(\beta_{gas} \times \ln\left(\mathrm{Re}_{\mathrm{mix}}\right)\right)^{a_g} \tag{10}$$

where

$$\mathrm{Re}_{\mathrm{mix}} = \frac{G \times D}{\mu_{\mathrm{hom}}} \tag{11}$$

$$\beta_{gas} = \frac{J_g}{J_g + J_l} \tag{12}$$

$$N_{g,\mathrm{mix}} = \left(\frac{W'_{g,\mathrm{mix}} \times D^2}{A \times \mu_{\mathrm{hom}}}\right) \tag{13}$$

The coefficient (C_g) and exponent (a_g) were obtained from the test data of subchannel experiments of Rudzinski [3], Kawahara *et al.* [5], and Kawahara *et al.* [7] plotted on dimensionless gas mixing number against combined volumetric gas fraction and mixture Reynolds number as shown in **Figure 6**.

The equation so obtained is given by relationship

$$W'_{g,\mathrm{mix}} = \frac{0.0000749 \times A \times \mu_{\mathrm{hom}} \times \left(\beta_{gas} \times \ln\left(\mathrm{Re}_{\mathrm{mix}}\right)\right)^{5.1436}}{D^2} \tag{14}$$

3.1. Modeling of Geometrical Influence of Subchannel

Incorporation of Gap and Centroidal Distance between Subchannels

The two phase turbulent mixing is affected by various parameters such as subchannels geometry, spacer and gap

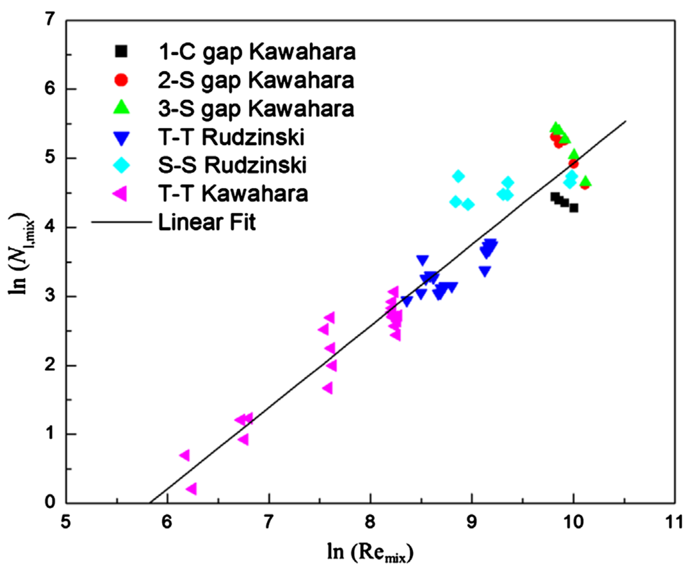


Figure 5. Liquid mixing rate.

spacing between subchannels. Previous models like Carlucci [11] model considers gap to rod diameter ratio, Kawahara *et al.* [10] model considers pitch to rod diameter ratio, Bues [8] model and Kazimi and Kelly [9] model considers gap to hydraulic diameter ratio. In the present model, the gap spacing to centroidal distance ratio of subchannels (**Figure 7**) is considered. The spacer effect is not considered in present model.

The equation for liquid mixing number in two phase flow can be represented by

$$N_{l,\mathrm{mix}} = F_{l,gc} \times K_l \tag{15}$$

where

$$K_l = C_l \left[\mathrm{Re}_{\mathrm{mix}} \right]^{a_l} \tag{16}$$

The equation of gap to centroid factor for liquid mixing rate can be expressed as best fit by

$$F_{l,gc} = \left(N_{l,\mathrm{mix}} / K_l \right) = C_1 \left[\left(\beta_{liq} \right) \left(\frac{S}{\delta} \right) \right]^{a_1} \tag{17}$$

where

$$\beta_{liq} = \frac{J_l}{J_g + J_l} \tag{18}$$

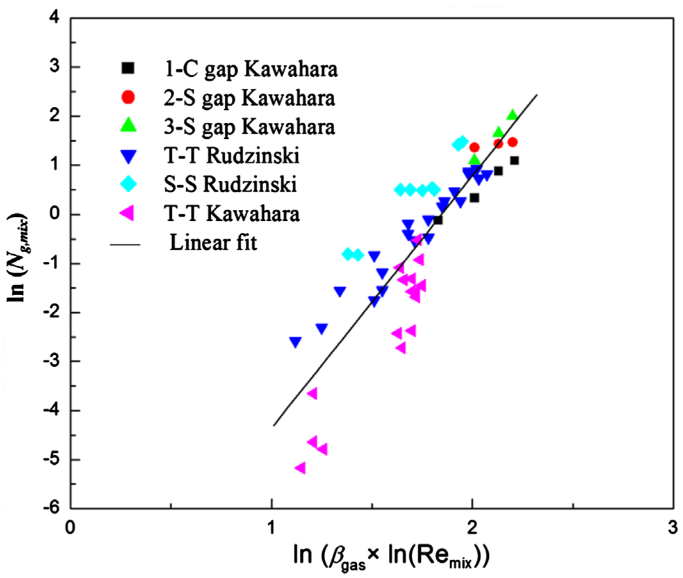


Figure 6. Gas mixing rate.

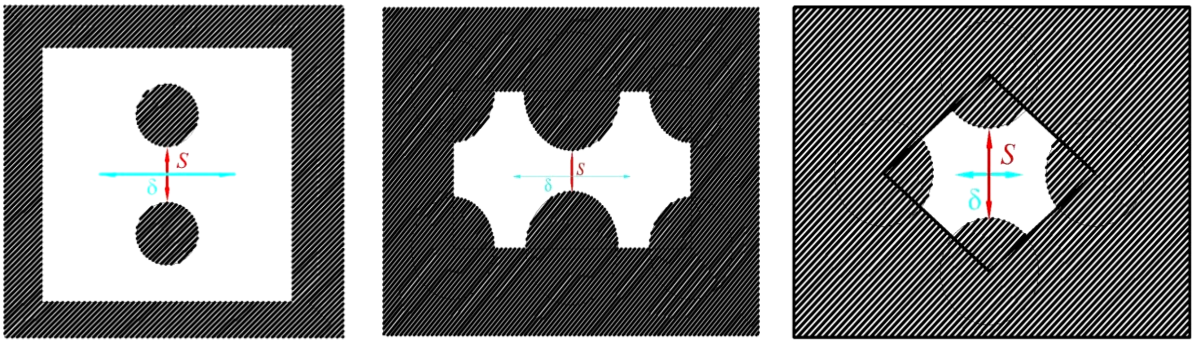


Figure 7. Representation of geometrical parameter in R-R, S-S and T-T subchannel array.

The coefficient (C_1) and exponent (a_1) were obtained by the test data of subchannel experiments of Rudzinski [3], Kawahara *et al.* [5], and Kawahara *et al.* [7] plotted on dimensionless gap to centroid factor against combined gap to centroidal distance ratio and volumetric liquid fraction against combined gap to centroidal distance ratio and volumetric liquid fraction of individual subchannel geometries (R-R, T-T, and S-S) as shown in **Figures 8(a)-(c)**.

The equation for gas phase can be represented by

$$N_{g,\text{mix}} = F_{g,gc} \times K_g \tag{19}$$

where

$$K_g = C_g \left[\beta_{gas} \times \ln\left(\text{Re}_{\text{mix}}\right)\right]^{a_g} \tag{20}$$

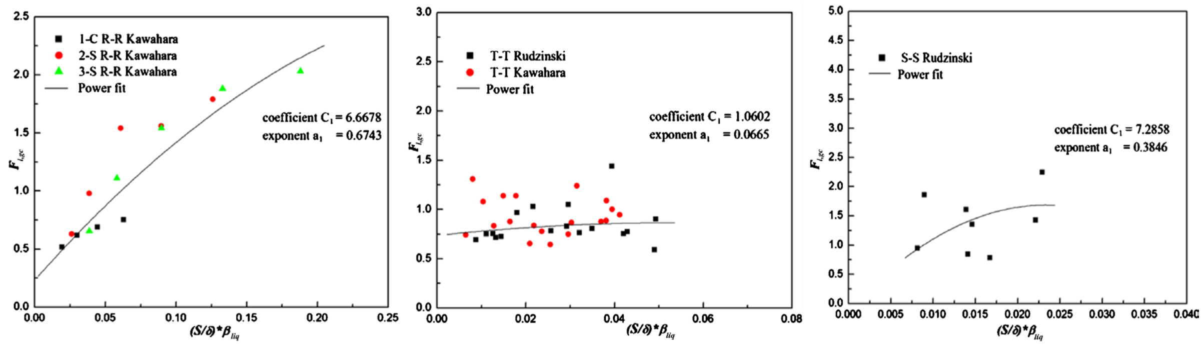
The equation of gap to centroid factor for gas mixing rate can be expressed as best fit by

$$F_{g,gc} = \left(N_{g,\text{mix}} / K_g\right) = C_1 \times \mathrm{e}^{a_1 \times (\beta_{liq})\left(\frac{S}{\delta}\right)} \tag{21}$$

The coefficient (C_1) and exponent (a_1) were obtained by the test data of subchannel experiments of Rudzinski [3], Kawahara *et al.* [5], and Kawahara *et al.* [7] plotted on dimensionless gap to centroid factor against combined gap to centroidal distance ratio and volumetric liquid fraction of individual subchannel geometries (R-R, T-T, and S-S) as shown in **Figures 9(a)-(c)**.

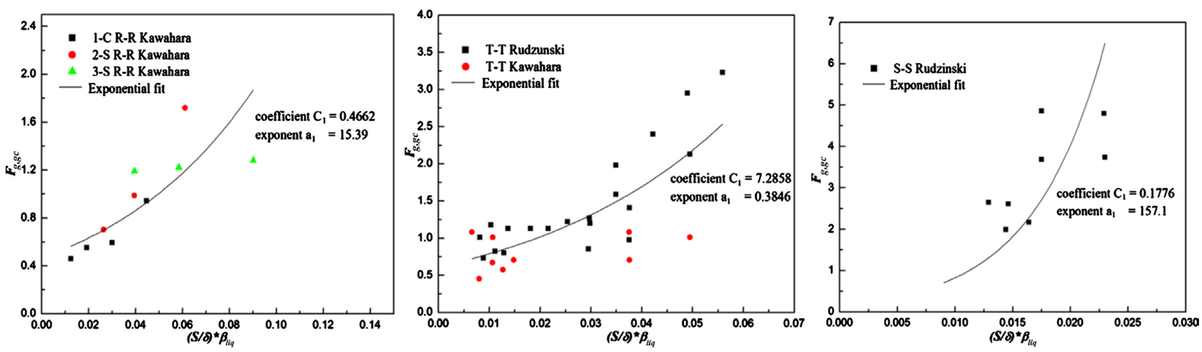
3.2. Modeling of Pressure Effect

Carlucci [11] is the only model which considers pressure effect in terms of bubble diameter, which changes with change in pressure. However, bubble diameter is difficult to predict in two phase flow since the size of bubble



(a) (b) (c)

Figure 8. The coefficient C_1 and exponent a_1 for various subchannel geometry in liquid phase mixing rate.



(a) (b) (c)

Figure 9. The coefficient C_1 and exponent a_1 for various subchannel geometry in gas phase mixing rate.

does not have a single value for a particular operating condition. However, the bubble diameter which has strong effect on void fraction depends on the surface tension of fluid. Hence present model considers the surface tension of fluid to model the effect of pressure.

Thus the effect of pressure is represented by the following expression

$$F_p = \left(\frac{\sigma_{H.T.}}{\sigma_{R.T.}}\right)^n \tag{22}$$

where $n = 2$ is the best fit for pressure correction factor

$\sigma_{H.T.} =$ surface tension at high temperature,

$\sigma_{R..T.} =$ surface tension at reference temperature *i.e.* ambient temperature

The correlation so obtained by Equation (9) and Equation (14) are modified by introducing gap to centroid factor and pressure dependent factor. The modified equation for liquid and gas phase are as follows

$$W'_{l,\text{mix}} = F_{l,gc} \times F_p \times \frac{0.00104 \times A \times \mu_{\text{hom}} \times \left(\text{Re}_{\text{mix}}\right)^{1.80}}{D_h^2} \tag{23}$$

$$W'_{g,\text{mix}} = F_{g,gc} \times F_p \times \frac{0.0000749 \times A \times \mu_{\text{hom}} \times \left(\beta_{gas} \times \ln\left(\text{Re}_{\text{mix}}\right)\right)^{5.1436}}{D_h^2} \tag{24}$$

4. Model Evaluation

In this chapter, the model proposed 3 is evaluated by comparing the prediction from present model with experimental data in a two phase slug churn flow regime

4.1. Test against Low Pressure and Temperature (Ambient) Air-Water Experimental Data

We performed error analysis for liquid and gas phase turbulent mixing rate and found that max error, min error and gross mean error for liquid phase mixing rate considering all subchannel geometry is about +91.7%, −54.3% and −4.27% respectively. The error analysis for individual geometry is shown in **Table 4**. Comparison between calculated and measured liquid turbulent mixing rate in two phase flow is shown in **Figure 10**.

The max error, min error and gross average error for gas phase mixing rate considering all subchannels geometry is about +66.2%, −55.7% and −3.29% respectively. The error analysis for individual subchannels geometry is shown in **Table 5**. Comparison between calculated and measured gas phase turbulent mixing rate in two phase flow is shown in **Figure 11**.

However considering the case of triangular-triangular subchannel experiment (Kawahara [7]), some of data points (yellow symbol in **Figure 11**) in gas mixing rate showing more error between calculated and measured mixing rate. The gross mean error is about 1380%. The reason behind showing more error is not yet perfectly understood.

4.2. Test against High Pressure and Temperature Steam-Water Experimental Data

The error analysis has been performed against high pressure and temperature steam-water experiment (Rowe and angel [12]) of 52 bar, 255˚C and 28 bar, 215˚C with mass flux 1356.8 and 2712.5 kg/m^{2}s for total turbulent mixing rate and found that max error, min error and gross average error for total mixing rate considering square-square subchannel geometry ($S = 2.1$ mm and $S = 0.5$ mm) is about +79.3%, −45.4% and +9.94%. Comparison between calculated and measured liquid turbulent mixing rate in two phase flow is shown in **Figure 12**.

4.3. Limitations of Proposed Model

In the present model, the geometrical and pressure effect has considered. However proposed model have following limitation

a) The spacer effect is not considered in present model.

b) This model is only valid for slug churn flow regime

Table 4. Error analysis between calculated liquid turbulent mixing and measured liquid turbulent mixing rate in two phase flow.

Subchannels geometry	Max error	Min error	Average error %
1-C gap Kawahara	+37	−10.2	+11.5
2-S gap Kawahara	−8.01	−34.5	−18.5
3 gap Kawahara	+13.6	−14.9	−3.05
T-T Rudzinski	+46.09	−40.6	+0.08
S-S Rudzinski	+91.7	−51.4	+4.35
T-T Kawahara	+28.4	−54.3	−12.3

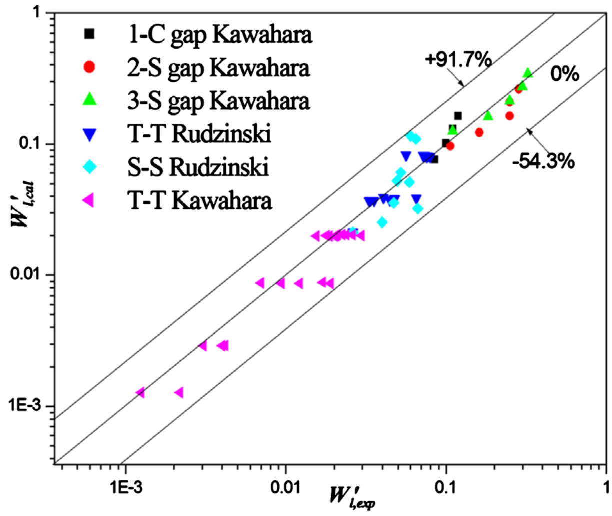


Figure 10. Comparison of the predictability of present model against subchannels experiment for liquid phase turbulent mixing rate in two phase flow.

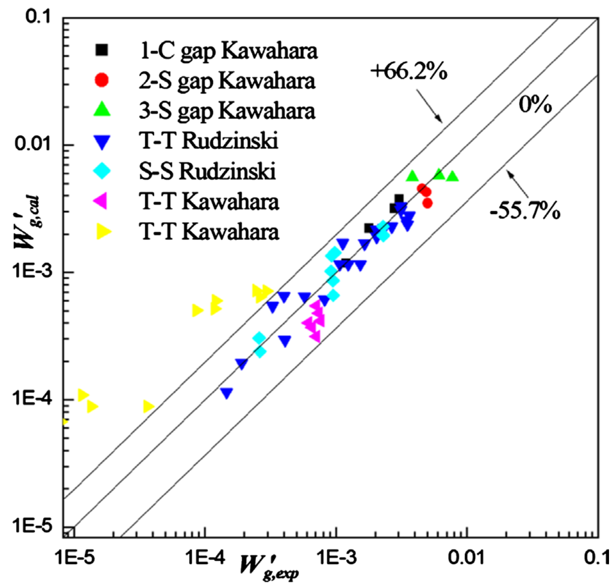


Figure 11. Comparison of the predictability of present model against subchannels experiment for Gas phase turbulent mixing rate in two phase flow.

Table 5. Error analysis between calculated gasturbulent mixing and measured gas turbulent mixing rate in two phase flow.

Subchannels geometry	Max error	Min error	Average error %
1-C gap Kawahara	+24.7	−16.7	+14.8
2-S gap Kawahara	−65.8	−30.5	−14.9
3 gap Kawahara	+46.3	−28.2	+4.08
T-T Rudzinski	+66.2	−32.4	+0.015
S-S Rudzinski	+45.8	−30.9	+6.24
T-T Kawahara	−22.7	−55.7	−39.6

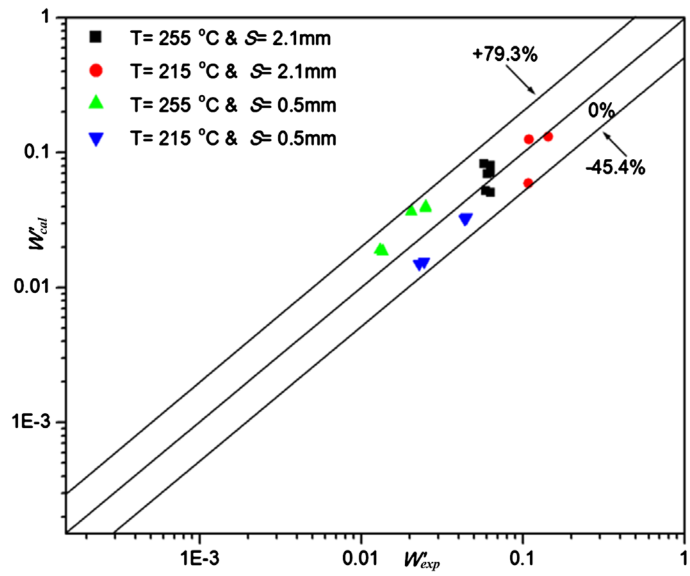


Figure 12. Comparison of the predictability of present model against subchannel experiment for total turbulent mixing rate in two phase flow.

5. Conclusions

An assessment has been done for turbulent mixing models against the experimental data available in literature and found that there are large discrepancies between predicted turbulent mixing rate models and experimental data. These models are semi-empirical in nature and applicable only for a particular geometry and operating condition. Hence this requires to development of a new model, which predicts well for different subchannel geometries and operating conditions.

In the view if this, a model for slug churn flow regime is proposed in this paper to predict the liquid and gas phase turbulent mixing rate between adjacent subchannels. In this paper, we have defined new dimensionless parameters *i.e.* liquid mixing number and gas mixing number for two phase turbulent mixing The liquid phase mixing number is a function of mixture Reynolds number whereas the gas phase mixing number is a function of both mixture Reynolds number and volumetric fraction of gas. The effect of gap to centroid spacing between subchannels and subchannel array *i.e.* square, triangular and rectangular subchannel is also included in present model. The pressure effect is modeled by considering surface tension of the fluid.

To evaluate present model, we tested present model against low pressure and temperature (ambient) air-water experiment of Rudzinski [3], Kawahara *et al.* [5] and Kawahara *et al.* [7] and high pressure and temperature steam-water experiment of Rowe and angel [12]. In case of low pressure and temperature air-water experiment, the max error, min error and gross average error for liquid phase mixing rate is about +91.7%, −54.3% and −4.27% respectively whereas the max error, min error and gross average error for gas phase mixing rate is about +66.2%, −55.7% and −3.29% respectively. In case high pressure and temperature steam-water experiment, the max error, min error and gross mean error for total mixing rate is about +79.3%, −45.4% and +9.94%. Present model showed good agreement with measured mixing rate under low pressure and high pressure condition as compared to earlier model.

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