Comparative Study of Drift-Flux Void Fraction Correlations Covering All Flow Regimes for Predicting Pipe Wall Thinning in Two-Phase Flow

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1. Introduction

In the secondary system of nuclear power plants, steam–water two-phase flow is a key phenomenon. Accurate prediction of the void fraction—defined as the ratio of gas-phase volume to total volume—is essential for maintaining thermal margin, ensuring safe operation, and preserving piping integrity. Since it directly governs degradation mechanisms such as corrosion and erosion, accurate void fraction estimation provides actionable insight for preventing pipe wall thinning.

At plant scale, the secondary system forms a large, complex piping network; accordingly, this industry commonly uses one-dimensional computational fluid dynamics(1-D CFD) network analysis that solves mass, momentum, and energy equations along links and junctions as a practical, scalable framework for system-level thermal-hydraulic evaluation.

Although many two-phase models exist, most target specific flow regimes or geometries. To address this, empirical and mechanistic approaches have been proposed; among them, the drift-flux model is widely accepted. Using two key parameters—the distribution parameter and the drift velocity—it represents the two-phase velocity field and estimates the corresponding void fraction across diverse conditions, including complex geometries [1,2].

Embedded as the void-fraction closure in 1-D CFD network solvers, the drift-flux formulation replaces separate phase-momentum equations with a mixture-momentum equation plus slip representation(via the distribution parameter and drift velocity), thereby reducing the number of unknowns, improving global convergence on plant-scale problems, and achieving plant-level turnaround times at realistic computational cost without sacrificing key two-phase physics.

Accurate void fraction and related flow parameters are especially important for assessing severe degradation such as Flow-Accelerated Corrosion (FAC) and Erosion, which frequently occur in steam–water systems under high shear and large velocity gradients [3]. FAC involves flow induced oxidation and dissolution that progressively remove metal from pipe walls, whereas Erosion arises from high-velocity particle or droplet impingement combined with turbulence; both are highly sensitive to local hydrodynamics.

This study evaluates the predictive performance of a homogeneous model and two representative drift-flux correlations. The evaluation is conducted using experimental data obtained under two-phase flow conditions. The objective is to determine their applicability in predicting flow characteristics relevant to pipe wall thinning phenomena, including FAC and Erosion, within the secondary system of pressurized water reactors(PWRs).

2. Methodology

2.1 Drift-flux model

The drift-flux model was first proposed by Zuber and Findlay in 1965. It simplifies the complexity of heterogeneous two-phase flow by decomposing the average mixture velocity into two parameters: the distribution parameter(C_0), and the drift velocity(u_{gj}), as shown in the equation below:

$$\alpha = \frac{\beta}{C_0 + \overline{u_{gj}}} \tag{1}$$

Where, α is the void fraction, β denotes the volumetric void fraction, $\overline{u_{gj}}$ is the mean drift velocity. The parameter C_0 accounts for the non-uniform distribution of phases in the cross-section and will be further described in the following correlations.

This model is widely implemented in major thermal-hydraulic system analysis codes such as RELAP5-MOD3, TRACE-M, and MARS-KS due to its low computational demand and robust structure[4]. It does not track individual phase velocities but instead models the relative motion of the phases through simple algebraic expressions

2.2 Drift-flux Void fraction correlations

To compute the Zuber and Findlay void fraction, appropriate correlations for C_0 and $\overline{u_{gj}}$ must be employed. The representative correlations used in system codes are Chexal et al(1997) and Bhagwat et al(2014)[5,6]. These correlations are applicable across the entire range of flow regimes and offer several advantages:

- *Independence from flow pattern classification*
- *Wide spectrum of operating conditions*

- The applicability to various fluid types
- Continuity in the void fraction function

As these correlations are not expressed in a closed-form solution, the void fraction was numerically solved using and iterative method, specifically the Newton-Raphson method , which iteratively refines estimates by using the derivative of a function to find its roots.

The representative correlations used in system codes are shown in the equations below:

· Chexal et al(1997):

$$C_0 = \frac{L}{K_0 + (1 - K_0)\langle\alpha\rangle^r} \quad (2)$$

$$\overline{u_{gj}} = 1.41\left[\frac{(\rho_f - \rho_g)\sigma g}{{\rho_f}^2}\right]^{0.25} C_{t,Chexal} \quad (3)$$

· Bhagwat et al(2014):

$$\begin{aligned} C_0 &= \left\{2 - \left(\frac{\rho_g}{\rho_f}\right)^2\right\} \Big/ \left\{1 + \left(\frac{Re_{tp}}{1000}\right)^2\right\} \\ &+ \frac{\left\{\left[1 + \left(\frac{\rho_g}{\rho_f}\right)^2 \cos\theta_h\right] / (1 + \cos\theta_h)\right\}^{\frac{1-\langle\alpha\rangle}{5}}}{1 + (Re_{tp}/1000)^2} \\ &+ \frac{C_{0,1}}{1 + (Re_{tp}/1000)^2} \end{aligned} \quad (4)$$

$$\begin{aligned} \overline{u_{gj}} &= (0.35\sin\theta_h + 0.45\cos\theta_h)\sqrt{\frac{\Delta\rho g D_h}{\rho_f}} \\ &\cdot (1 - \langle\alpha\rangle)^{0.5} C_{t,Bhagwat} \end{aligned} \quad (5)$$

In the given equations, L is Chexal correlation fluid parameter, K_0 and r are correlation fitting parameters. ρ_g and ρ_f denote the gas and liquid densities, σ is surface tension, and g is gravitational acceleration. Respectively, while Re_{tp} is the two-phase mixture Reynolds number and θ_h is the pipe orientation angle measured from the horizontal axis. D_h refers to the hydraulic diameter. C_t and $C_{0,1}$ are empirical coefficient.

2.3 Experimental data description

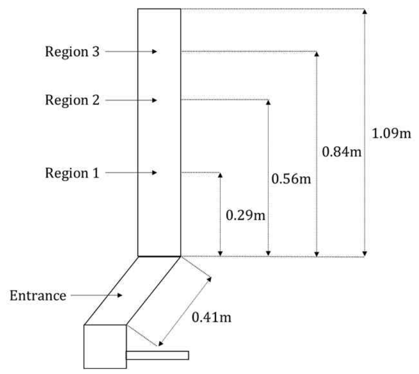


Fig. 1. Schematic of the test section(Hall et al., 1988)[7]

Table 1. Test section measurement details[7]

Parameter	Description
Fluid System	Steam-water
Pipe Diameter($D = D_h$)	0.171[m]
Test Section Length(L)	1.09[m]
Measurement Locations	Region1, Region2, Region3
Operating Condition	Pressure = 640[psig] Temperature = 529[K]
Measured Parameters	Volume-averaged

The experimental data utilized in this study are based on tests conducted at NRC-Purdue University facilities, with steam-water flow under pressurized conditions[7]. Steam was injected through a nozzle into a vertical test section, creating two-phase mixing that was measured at multiple axial locations.

Detailed of the test section are shown in Fig. 1 and Table 2. The measurement section consists of three regions: Bottom section(Region 1: 0.29m), Mid-section(Region 2: 0.56m), and Top section(Region 3: 0.84m), with the void fraction sensors installed at each point. Superheated steam was supplied through the entrance nozzle, and local densities were estimated using known flow rates and pressure-temperature conditions. These experimental void fraction data are used to benchmark and validate the drift-flux models under evaluation.

3. Results and discussion

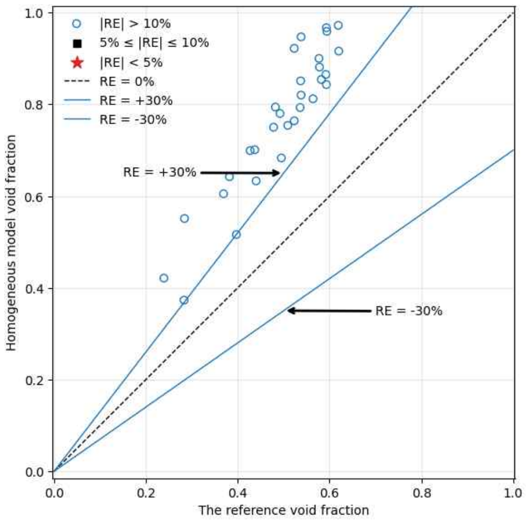
3.1 Void fraction prediction results

Fig. 2~4 present cross-plots of the reference void fraction(α_{means}) versus the model predictions for the Chexal and Bhagwat correlations, as well as a homogeneous model for comparison in Regions 1-3(L/D_h=1.68, 3.26, 4.94). In each plot, red stars denote $|RE| < 5\%$, black square denote $5\% \leq |RE| \leq 10\%$, and blue circles $|RE| > 10\%$. The dashed 45°line marks perfect agreement (RE=0), while the solid lines show $\pm 30\%$ relative-error bounds.

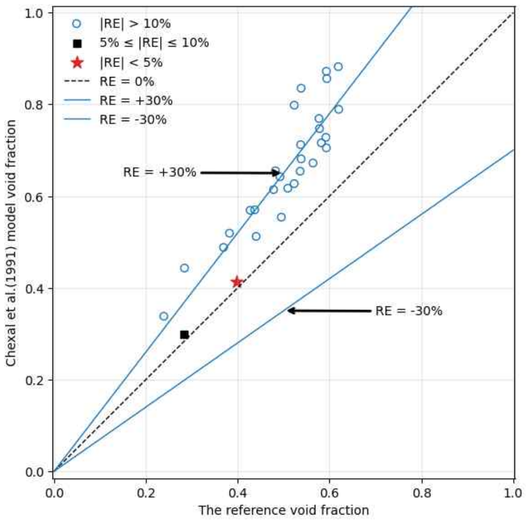
Region 1 in Fig. 2: Only the Chexal model produced any data points with relative error below 5% and had the highest fraction of predictions within the $\pm 30\%$ relative error band. In contrast, other correlations exhibited lower overall reliability in this region.

Region 2 in Fig. 3: Both the Chexal and Bhagwat models yielded data points with errors under 5%, whereas the homogeneous model still failed to achieve the $\pm 30\%$ relative error band. Notably, the Chexal model maintained the largest proportion of predictions within the acceptable error range.

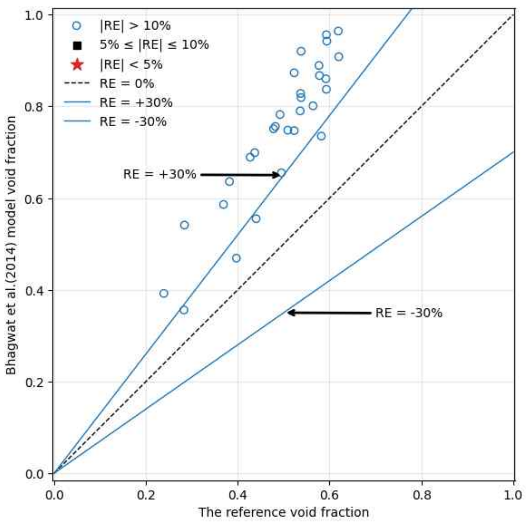
Region 3 in Fig. 4: All models showed improved reliability in the high void fraction regime($\alpha > 0.8$), while predictions for $\alpha < 0.8$ exhibited increased error rates.



(a) Homogenous model

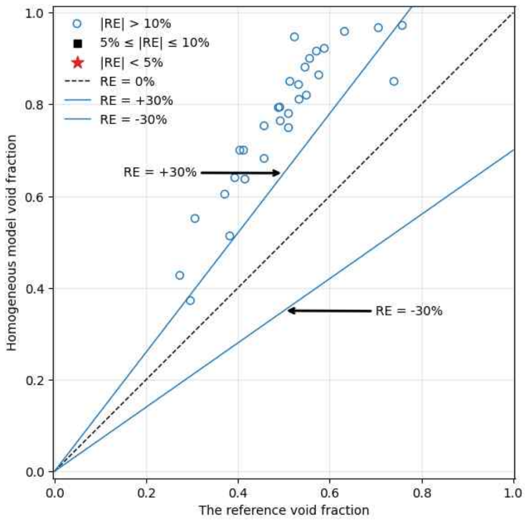


(b) Chexal et al.(1997) model

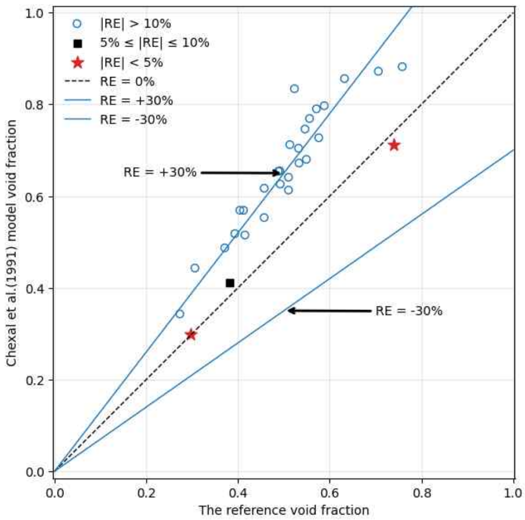


(c) Bhagwat et al.(2014) model

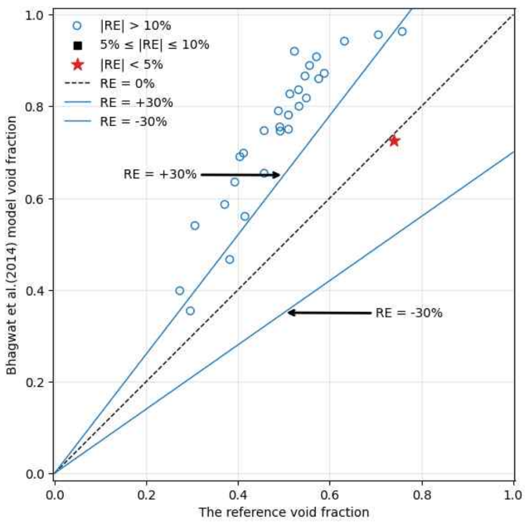
Fig. 2. Relative error analysis of different models in Region 1



(a) Homogenous model

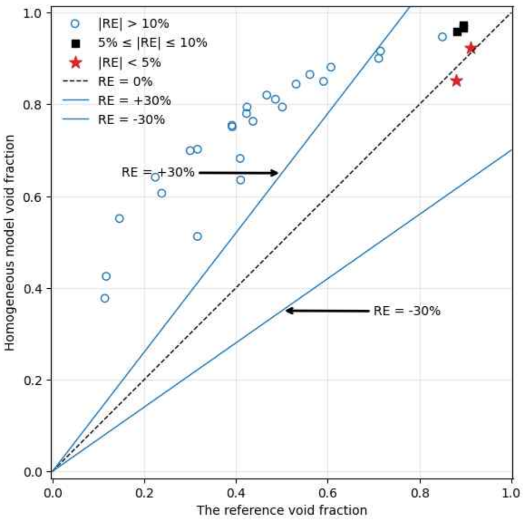


(b) Chexal et al.(1997) model

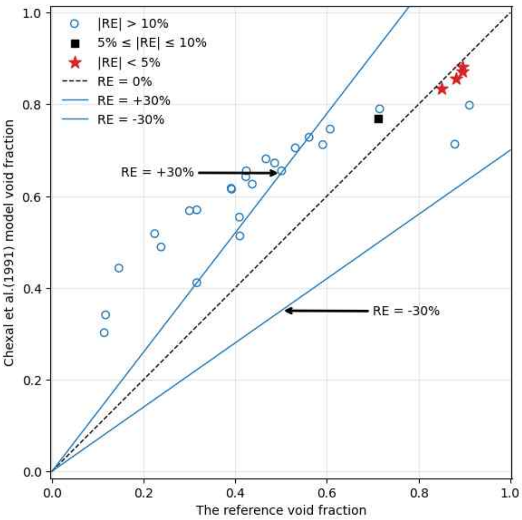


(c) Bhagwat et al.(2014) model

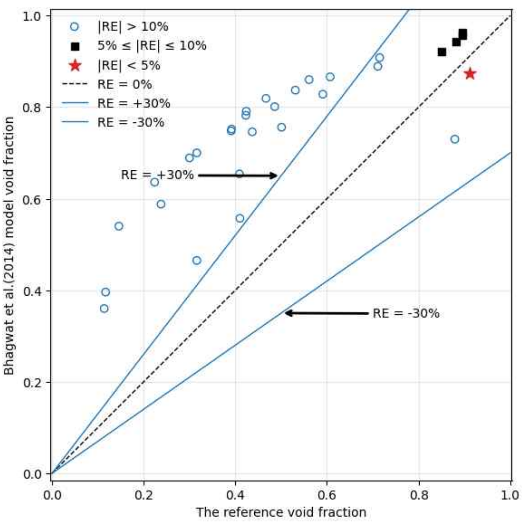
Fig. 3. Relative error analysis of different models in Region 2



(a) Homogenous model



(b) Chexal et al.(1997) model



(c) Bhagwat et al.(2014) model

Fig. 4. Relative error analysis of different models in Region 3

3.2 Model performance comparison

Table 2. Model comparison for Void fraction prediction

Region	Metric	Homo.	C. et al.	B. et al.
1	RMSE	0.028	0.016	0.026
	AARE	55.74%	29.99%	51.29%
	R^2	-6.65	-1.61	-5.71
2	RMSE	0.028	0.016	0.026
	AARE	54.70%	29.21%	50.48%
	R^2	-4.52	-0.80	-3.9
3	RMSE	0.029	0.018	0.028
	AARE	82.68%	53.35%	78.73%
	R^2	-0.43	0.43	0.33

To quantitatively evaluate the predictive accuracy of each model, three statistical metrics including RMSE(Root Mean Square Error), AARE(Average Absolute Relative Error), and R^2 (the coefficient of determination) were computed for each region as summarized in Table 2.

Across all regions, the homogeneous model in Fig. 2(a) ~ 4(a) consistently showed the poorest performance, with the highest RMSE and AARE values and strongly negative R^2 values. In Region 1, for example, the homogeneous model yielded an RMSE of 0.028 and an AARE of 55.74%, with an R^2 of -6.65, including significantly worse predictive capability than a simple mean-based estimate. This trend continued in Region 2 and Region 3, where similar levels of discrepancy were observed. These results highlight the inherent limitations of the homogeneous assumption when applied to complex two-phase flow regimes, where interfacial dynamics play a critical role.

In contrast, the Chexal model in Fig. 2(b)~4(b) demonstrated the most accurate prediction in terms of absolute error metrics, achieving the lowest RMSE and AARE values across all regions(e.g., RMSE = 0.016 and AARE = 29.99% in Region 1). However, its R^2 values remained negative in Region 1 and 2(-1.61 and -0.80, respectively), indicating that the model did not sufficiently capture the variance in the data.

The Bhagwat model in Fig. 2(c)~4(c) exhibited intermediate predictive performance among the compared models. This model showed a trend broadly similar to the homogeneous model. However, unlike the Chexal model, which employs an implicit formulation requiring numerical iteration, the Bhagwat model uses an explicit analytical solution based on the drift-flux formulation. This explicit method removes the need for iterative solvers and enables faster computation.

3.3 Discussion

The comparative analysis of three void fraction models revealed significant differences in predictive accuracy across varying flow regions. The homogeneous model consistently exhibited poor agreement with experimental data, as indicated by high RMSE and AARE values, as well as strongly negative R^2 values.

These results highlight the limitations of assuming uniform phase distribution in steam-water two-phase flows, particularly near the mixing-dominated entrance region.

Between the two drift-flux models, the correlation proposed by Chexal et al. exhibited the lowest RMSE and AARE values across all test sections, indicating superior performance in terms of absolute error magnitude. However, its negative R^2 values in Region 1 and 2 suggest limited capability in explaining variance under developing two-phase flow conditions. In contrast, the Bhagwat model showed intermediate performance, with slightly larger absolute errors and no clear advantage in variance prediction. This model employs a formulation that permits an explicit analytical solution for the void fraction. This explicit formation eliminates the need for iterative numerical solvers, thereby improving computational efficiency.

4. Conclusion

This study evaluated the performance of three void fraction prediction models under steam-water two-phase flow conditions using experimental data obtained at multiple axial locations. The results showed that the homogeneous model is inadequate for accurately capturing local void distributions in complex flow regimes, as evidenced by its large errors and highly negative R^2 values. Among the drift-flux models, the Chexal model achieved the lowest RMSE and AARE values across all regions, making it suitable for calculating the appropriate void fraction where minimizing absolute error is the primary objective. In contrast, the Bhagwat model exhibited slightly larger absolute errors and offered no consistent advantage in variance predictions. Its primary strength lies in its explicit analytical formulation for void fraction, which removes the need for iterative numerical solvers and significantly improves computational efficiency. However, this efficiency gain did not translate into predictive accuracy comparable to the Chexal model.

These findings indicate that the Chexal model can efficiently predict the void fraction without explicitly classifying flow regimes. Therefore, it is suitable for application in large-scale one dimensional thermal-hydraulic analysis, such as complex piping networks in the nuclear power plant secondary system. Such application can improve the reliability of thermal-hydraulic calculation in two-phase flow regions and, in turn, enhance the predictive accuracy of wall thinning prediction models. Future work should extend the applicability of the Chexal model to each range of flow conditions and piping geometries to further strengthen its reliability and versatility in plant-scale simulations. In addition, expanding the analysis to include comparisons between predicted and measured wear rates would provide proactive support for secondary-side piping wall thinning management in nuclear plant.

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