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Assessment of Two-Phase Frictional Pressure Drop Correlation in THALES Code

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1. Introduction

THALES[1] is a subchannel analysis code developed by KEPCO Nuclear Fuel Co. Ltd.(KNF), utilized in the thermal hydraulic design of nuclear power plant reactor cores. The THALES code calculates three-dimensional flow and heat distributions within the reactor core by solving the governing equations for two-phase mass, momentum, and energy in each subchannel. In the axial momentum equation, axial pressure drops within the fuel assembly are mainly attributed to frictional losses from fuel rod surface and form losses associated with the mixing vane spacer grid. In two-phase flow, frictional pressure drop of mixture is defined as follows.

$$\left(-\frac{\partial P}{\partial z}\right)_{fr} = \phi_{LO}^2 \left(-\frac{\partial P}{\partial z}\right)_{fr,LO} \quad (1)$$

ϕ_{LO}^2 represents the two-phase friction multiplier, defined as the ratio of the frictional pressure drop of the two-phase mixture to that of the liquid-only flow. In the THALES code, the two-phase friction multiplier is calculated using an embedded correlation. This paper compares the prediction of axial pressure drop in two-phase flow within the critical heat flux test sections as calculated by the THALES code, with various two-phase frictional pressure drop correlations.

2. Methodology

The concept of the two-phase friction multiplier was first introduced by Lockhart and Martinelli in 1949[2]. Initially, the multiplier was developed based on a simple separated flow model, as a function of inlet mass flux, quality, and other fluid properties. Chisholm(1967)[3] later introduced the Lockhart-Martinelli correlation in the following form.

$$\phi_{LO}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (2)$$
$$\phi_{GO}^2 = 1 + CX + X^2 \quad (3)$$

ϕ_{GO}^2 is two-phase friction multiplier analogous to ϕ_{LO}^2, but defined for vapor-only flow. C is a constant specific to each flow regime and X is the Martinelli parameter, defined as the ratio of the pressure drop in liquid flow to the pressure drop in vapor flow.

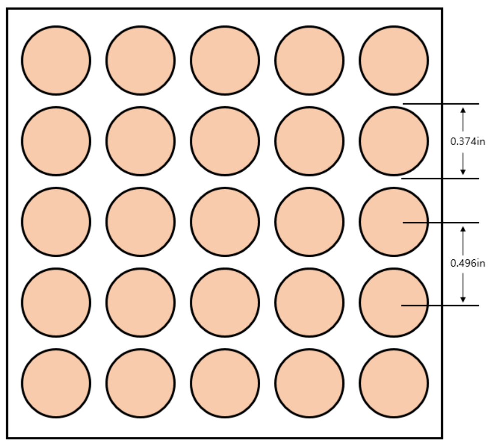
Following the development of the Lockhart-Martinelli correlation, numerous correlations have been established for various flow conditions, based on experimental data. In this paper, several of these correlations[4] were selected to evaluate the Sher-Green & modified Martinelli-Nelson Correlation[1], which is the THALES two-phase frictional pressure drop correlation. These correlations are summarized in Table 1.

Table 1. Two-phase frictional pressure drop correlations[1, 4]

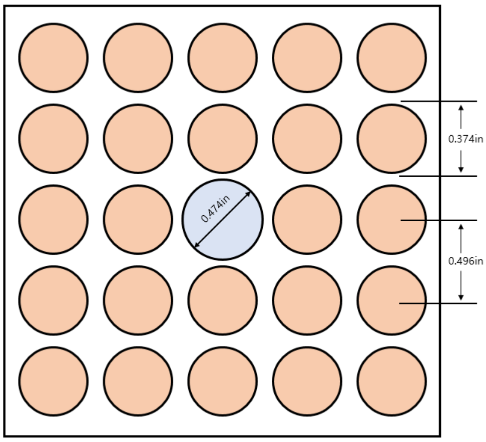
Index	Correlation	Year Developed
1	Modified Armand	1960
2	Friedel	1979
3	Müller-Steinhagen&Heck	1986
4	Jung-Radermacher	1989
5	Tran	1999
6	Sun-Mishima	2009
7	Kim-Mudawar	2012

The test data used for evaluating pressure drop predictions are derived from the critical heat flux tests conducted for development of KNF-X correlation[5]. The test section comprises a 5x5 rod arrays with a mixing vane spacer grid. Two types of test sections were used: typical and thimble. The typical section consisted of 25 fuel rods, while the thimble section comprised 24 fuel rods and one thimble tube positioned at the center of the bundle. The configurations of the typical and thimble test sections are illustrated in Fig. 1.

The test sections were simulated using the THALES code, and axial pressure losses were calculated for each test case. For each test case, THALES simulations were conducted using eight different two-phase frictional pressure drop correlations, including the THALES embedded correlation. The calculated pressure losses were then compared with the test data. Modified Martinelli-Nelson void fraction model[1] was selected for THALES calculation.



a) Typical Section



b) Thimble Section

Fig. 1. Test sections used in the critical heat flux test

3. Results

A total of 1,054 test cases were compared with the THALES calculations. The comparison was conducted using two different parameters, as detailed below.

$$\text{Error\%(noabs)} = \sum_{i=1}^{n}\left[\frac{(\Delta P)_P - (\Delta P)_M}{(\Delta P)_M}\right]/n \quad (4)$$

$$\text{Error\%(abs)} = \sum_{i=1}^{n}\left|\frac{(\Delta P)_P - (\Delta P)_M}{(\Delta P)_M}\right|/n \quad (5)$$

$(\Delta P)_P$ represents the axial pressure drop within the test section as calculated by the THALES code, while $(\Delta P)_M$ denotes the measured pressure drop. Error%(noabs) indicates the direction of the error, whereas Error%(abs) reflects the average prediction accuracy across the different correlations.

The maximum inlet mass flux among test cases was 3.74 Mlbm/hr-ft^2, while the minimum inlet mass flux was 0.75 Mlbm/hr-ft^2. Fig. 2 presents the distribution of inlet mass flux across all test cases.

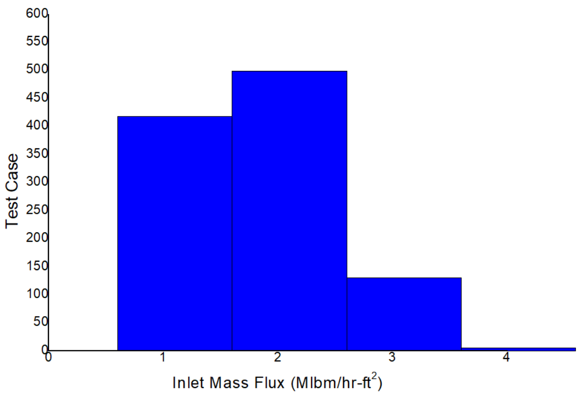


Fig. 2. Distribution of inlet mass flux across test cases

Figure 3 through 6 present the comparison of pressure drop predictions for each correlations, categorized by inlet mass flux. Errors are expressed in percentage terms.

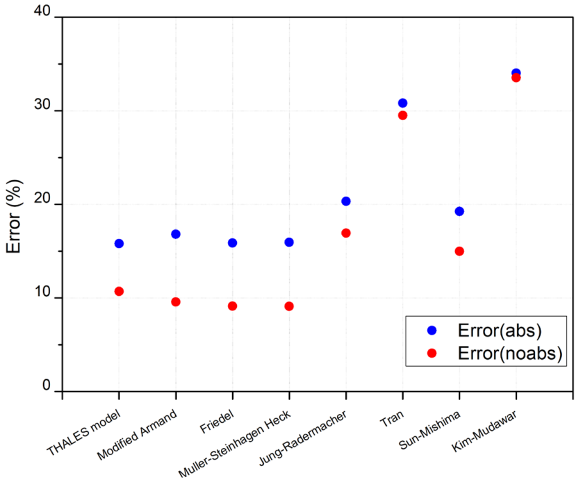


Fig. 3. Prediction of pressure drop at all test data

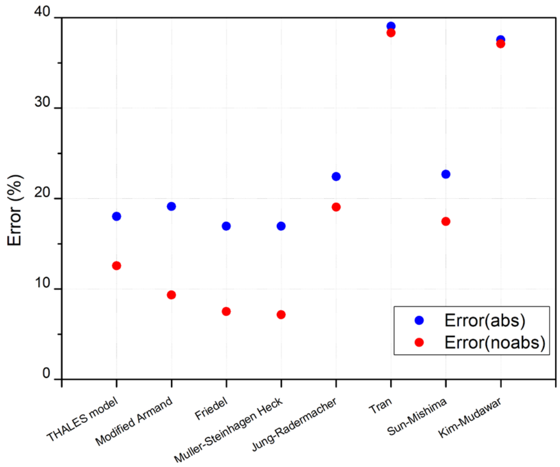


Fig. 4. Prediction of pressure drop at low inlet mass flux (mass flux ≤ 1.5 Mlbm/hr-ft^2)

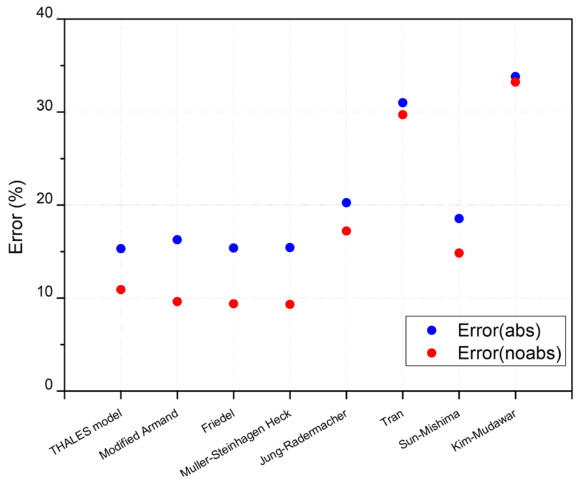


Fig. 5. Prediction of pressure drop at intermediate inlet mass flux (1.5 Mlbm/hr-ft^2 < mass flux ≤ 2.5 Mlbm/hr-ft^2)

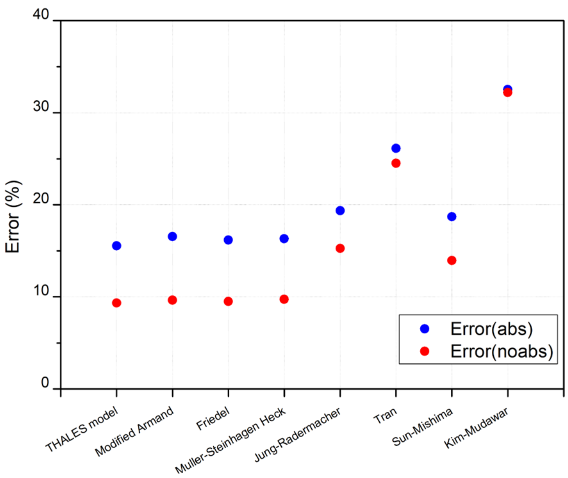


Fig. 6. Prediction of pressure drop at high inlet mass flux (2.5 Mlbm/hr-ft^2 < mass flux)

As a result, the THALES correlation predicted the pressure drop with greater accuracy or comparably to other correlations. The THALES correlation, along with modified Armand, Friedel and Müller-Steinhagen&Heck correlations, provided the most reliable predictions across all mass flux ranges. These correlations are defined as functions of quality. The THALES correlation and modified Armand correlation are defined with different formulations depending on the quality range. In contrast, the Jung-Radermacher, Tran, Kim-Mudawar and Sun-Mishima correlations are based on Lockhart-Martinelli correlation, as represented by equations (2) and (3). Those correlations are functions of the Martinelli parameter, which varies depending on the flow regimes. In the thermal hydraulic analysis of nuclear reactor cores, defining the flow regime is challenging due to the influence of the mixing vane spacer grids on lateral flow. Additionally, most correlations were developed using data from low-pressure, low-temperature and low-mass flux conditions, in contrast to the critical heat flux test data employed in this study. This suggests that correlations based on quality are recommended for predicting pressure drop in two-phase flow near critical heat flux conditions.

4. Conclusions

In this paper, we compared the pressure drop predictions for various two-phase frictional pressure drop correlations, using the THALES code. The results indicates that, the THALES correlation for two-phase frictional pressure drop accurately predicted the pressure drop in critical heat flux test data, performing comparably of better than other correlations. Additionally, correlations based on Martinelli parameter tend to overpredict the pressure drop more than those defined as functions of quality when applied to the test data. The predictive performance was independent of inlet mass flux conditions.

These findings demonstrate that two-phase frictional pressure drop correlation in the THALES code, which is currently used in the core thermal hydraulic design of operating nuclear power plants, can also be applied to the core thermal hydraulic design of i-SMRs for pressure drop prediction. Further studies should aim to produce more critical heat flux test data to facilitate the evaluation and development of two-phase frictional pressure drop correlations.

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