Pressure drops: scaling, research prioritization and validation-consistency

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ABSTRACT

Pressure drop is an important parameter in nuclear T-H (thermal-hydraulics) as well as in nuclear safety analysis. In this paper, a methodology has been proposed for assessing the impact of friction and acceleration pressure drop in reactors through the integration of the scope among Prioritization, V&V&C (Verification & Validation & Consistency), Scaling and Against Annapolis 1996 Specialists Meeting, This paper provides a preliminary analysis of the errors in pressure drop calculations in both single-phase and two-phase simulations with system T-H code of RELAP5 within consideration of V&V&C. The paper suggests considering pressure drop as a significant evaluation parameter in the scaling assessment framework, advocating for additional thermal-hydraulic experiments and model developments. Future research will involve further computational comparisons of benchmark pressure drop experiments and methodological studies on pressure drop assessment.

Keywords: *Thermal hydraulics; System code; Pressure drop; V&V&C.*

1. INTRODUCTION

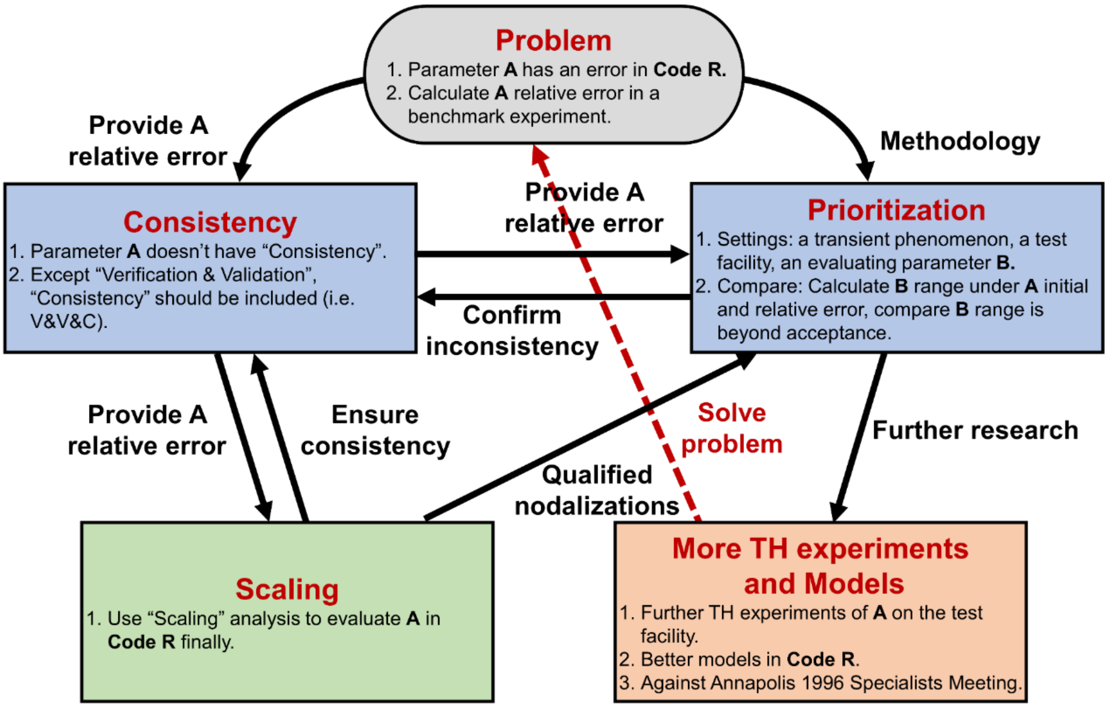

Figure 1 Methodology and route to solve the evaluation problem

System codes are extensively utilized in nuclear safety analysis. Given the evolving demands for new reactor designs and the inherent imperfections of existing models, there is a continuous need for model improvements. In light of this, D'Auria has introduced a methodology to determine the necessity for enhancements in specified models (D'Auria 2018). In this study, this methodology is coupled with scaling and the V&V&C (Verification, Validation, and Consistency) approach to facilitate model development and assessment, as illustrated in Figure 1.

When significant discrepancies are observed in parameter A between computational codes and experimental results, D'Auria's prioritization methodology can be employed to assess the criticality of A. The process involves selecting a classical transient phenomenon in the reactor, a corresponding test facility, and parameter B to evaluate this phenomenon. Subsequent steps include verifying the initial value and relative error of parameter A under the chosen phenomenon, calculating the range of parameter B using code R based on these values, and comparing whether the results fall within acceptable limits. If the range of parameter B exceeds accepted thresholds, several conclusions can be drawn: 1) Parameter A is crucial and should be integrated into the evaluation system; 2) A distinct error exists in code R concerning parameter A, significantly impacting the accuracy of critical transient phenomena calculations; 3) Additional thermal-hydraulic (T-H) experiments are warranted at the test facility to refine the models in code R.

This approach not only addresses the evaluation of new parameters but also supports the assertion that future research should concentrate on rectifying deficiencies in well-recognized models, which is against the Annapolis 1996 Specialists meeting (Aksan et al. 2024). Moreover, deviations in the range of parameter B underscore the lack of "Consistency" concerning parameter A, advocating for the inclusion of "Consistency" as an integral part of the V&V&C framework in the evaluation system (D'Auria and Lanfredini 2019). Additionally, performing scaling analysis both before initiating Prioritization and after refining models is vital (D’Auria and Galassi 2010). Scaling is crucial in system code evaluation as it aims to assess accuracy, which measures discrepancies between T-H codes and experiments, making scaling a fundamental element within the licensing processes of Nuclear Power Plants (NPP). Scaling techniques also help ascertain the applicability of models and experimental data to full-scale nuclear reactors, a key characteristic for successful implementation of Best Estimate Plus Uncertainty (BEPU) approaches (D'Auria 2019).

Moreover, while T-H phenomena generally depend on geometric scale, the accuracy in scaling should be regarded as a non-dimensional, scale-independent statistical parameter (D’Auria and Galassi 2010). If a new parameter indicates that the geometric scale significantly influences code accuracy in a T-H phenomenon, this can be considered evidence of a modeling deficiency concerning parameter A that requires rectification. For instance, previous research has underscored the critical role of pressure drop (PD) in the experimental design and modeling of nuclear reactor system thermal-hydraulics, vital for ensuring nuclear safety and enhancing system performance (Cai et al. 2022). It is therefore imperative to prioritize the development and investment in experimental and simulation studies of PD in nuclear reactor thermal-hydraulics. This study specifically focuses on the reliability and consistency of the PD model within one of the Best Estimate Codes, RELAP5. It analyzed the simulation results under different operating conditions within the reactor, compared the relative errors between the model and the data used in the code, and drew preliminary conclusions.

2. METHODOLOGY

In nuclear reactor thermal-hydraulics, pressure drops primarily include friction pressure drop (FPD), acceleration pressure drop (APD), gravitational pressure drop, and local pressure drops. Given that the calculation of gravitational pressure drops is straightforward, and local pressure drops are challenging to compute manually, this paper focuses on the reliability of the FPD and APD models within the code. The formula for calculating FPD is:

$$\Delta p = -\frac{f \rho L |u| u}{2D} \tag{1}$$

Where f represents the friction factor, L is the length, D denotes the hydraulic diameter, ρ is the density, and u is the velocity. For two-phase flow, the code utilizes the Lockhart-Martinelli correlation based on separated flow theory:

$$\left(\frac{\mathrm{dP}}{\mathrm{dL}}\right)_{2\phi} = \phi_{\mathrm{f}}^2 \left(\frac{\mathrm{dP}}{\mathrm{dL}}\right)_{\mathrm{f}} = \phi_{\mathrm{g}}^2 \left(\frac{\mathrm{dP}}{\mathrm{dL}}\right)_{\mathrm{g}} = \frac{1}{2\mathrm{D}} \left\{ \begin{aligned} & f_{\mathrm{f}}\rho_{\mathrm{f}}\left(\alpha_{\mathrm{f}}\mathrm{u}_{\mathrm{f}}\right)^2 + f_{\mathrm{g}}\rho_{\mathrm{g}}\left(\alpha_{\mathrm{g}}\mathrm{u}_{\mathrm{g}}\right)^2 + \\ & \mathrm{C}\left[f_{\mathrm{f}}\rho_{\mathrm{f}}\left(\alpha_{\mathrm{f}}\mathrm{u}_{\mathrm{f}}\right)^2 f_{\mathrm{g}}\rho_{\mathrm{g}}\left(\alpha_{\mathrm{g}}\mathrm{u}_{\mathrm{g}}\right)^2 \right]^{1/2} \end{aligned} \right\}$$

$$C = -2 + \left(28 - 0.3\sqrt{\mathrm{G}}\right)\left[\exp\left(-\frac{\left(\log_{10}\Lambda + 2.5\right)^2}{2.4 - \mathrm{G}\left(10^{-4}\right)}\right)\right],\ \Lambda = \frac{\rho_g}{\rho_f}\left(\frac{\mu_f}{\mu_g}\right)^{0.2} \tag{2}$$

Where ϕ^2 represents the two-phase friction multiplier, α is the component fraction, G denotes the mass flux, and μ is the dynamic viscosity. This model is widely applied across various thermal-hydraulic codes(Sun et al. 2024, Wu et al. 2022). For APD, it can be directly calculated from the difference in momentum between the inlet and outlet:

$$A\Delta P_{\mathrm{acc}} = m_{f,out}u_{f,out} + m_{g,out}u_{g,out} - m_{f,in}u_{f,in} - m_{g,in}u_{g,in} \tag{3}$$

Where A represents area, m is mass flow rate. When performing manual calculations (MCs), steady-state results output by the code are substituted into the above formula. The results are then compared with the PDs calculated by the code using the following equation:

$$RE\left(Relative\ error\right)=\frac{\Delta P_{RELAP}-\left(\Delta P_{\text{Manual, Friction}}+\Delta P_{\text{Manual, Acceleration}}\right)}{\Delta P_{RELAP}} \tag{4}$$

Theoretically, manual calculations employ the exact same formulas as those used in the code's calculations, utilizing the steady-state data output by the code. Thus, the results should be nearly identical. However, in practice, the outcomes significantly deviate from expectations.

3. 1-PHASE CALCULATIONS

Improving the accuracy of frictional pressure drops hinges on having a robust single-phase model. In RELAP5 mod3.2, the Zigrang-Sylvester 1985 formula is employed to determine the friction factor (Colebrook et al. 1939). It's worth noting that the friction factor not only plays a dominant role in influencing single-phase distributed pressure drops but also represents the primary source of uncertainty in single-phase frictional pressure drops, particularly due to roughness.

Moreover, it is essential to recognize that all friction factors developed so far are explicit forms derived from the Colebrook equation (which is implicit). Transitioning from an implicit to an explicit scheme entails certain consequences, such as the addition of an integration domain, increased computational complexity, and the introduction of an error compared to the implicit scheme. For instance, the Zigrang-Sylvester explicit formula used in RELAP5 mod3.2 has an error of 0.5% when referenced against the Colebrook equation (Zigrang and Sylvester 1985). The results and analysis of the single-phase calculations will be published in a separate article soon.

While one might argue that this error is negligible for single-phase cases, it could be significantly larger for two-phase cases. Therefore, one of the primary aims of this paper is to underscore the need for further experimental research on two-phase pressure drops.

4. 2-PHASE CALCULATIONS

For all two-phase calculation cases, the modeling in RELAP5 is as depicted in Figure 2. The model's inlet and outlet consist of two time-dependent control volumes, maintaining constant set values for pressure and thermodynamic equilibrium quality. The midsection comprises a horizontal pipe, 20 meter in length, which is segmented into 20 control volumes. For all cases, the pipe roughness is consistently set at 0.0004m. The five PDs of interest are between the second and third, sixth and seventh, tenth and eleventh, fourteenth and fifteenth, as well as the eighteenth and nineteenth control volumes, respectively noted as P_2-P_3, P_6-P_7, etc. The inlet junction control volume immediately preceding the pipe manages the two-phase mass flow rate, which is set to a constant value. The distinction between different cases is solely based on varying initial conditions.

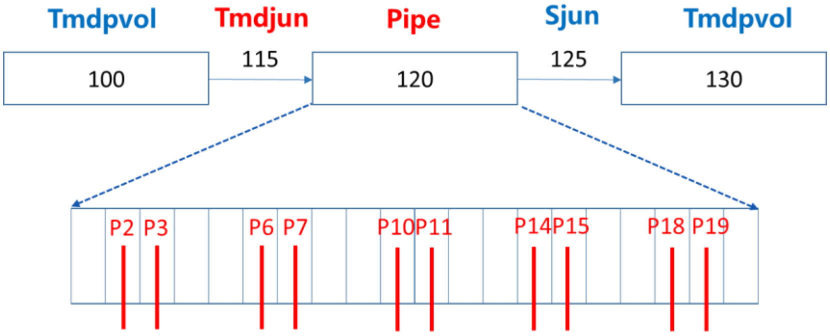

Figure 2 Schematic representation of the RELAP5 modeling setup for two-phase flow analysis

4.1. Effect of diameter

Taking consistency into account, nineteen different diameter cases ranging from 0.01 meters to 1 meter have been considered, essentially encompassing all pipe diameters that could be encountered in a nuclear reactor. Figure 3 displays the relative error in PD at various locations along pipes of different diameters. It is observed that the relative error near the center does not exceed 5% across all pipe diameters, whereas the relative error near the inlet and outlet increases significantly with larger diameters. Notably, the relative error at the outlet progressively increases with diameters beyond 0.1 meters, and the maximum relative error at the inlet occurs at a diameter of 0.2 meters—an anomaly that warrants attention. Additionally, within the laminar–turbulent transition, where the Reynolds number ranges from 2200 to 3000, there is a marked increase in the relative error at both the inlet and outlet as the pipe diameter grows.

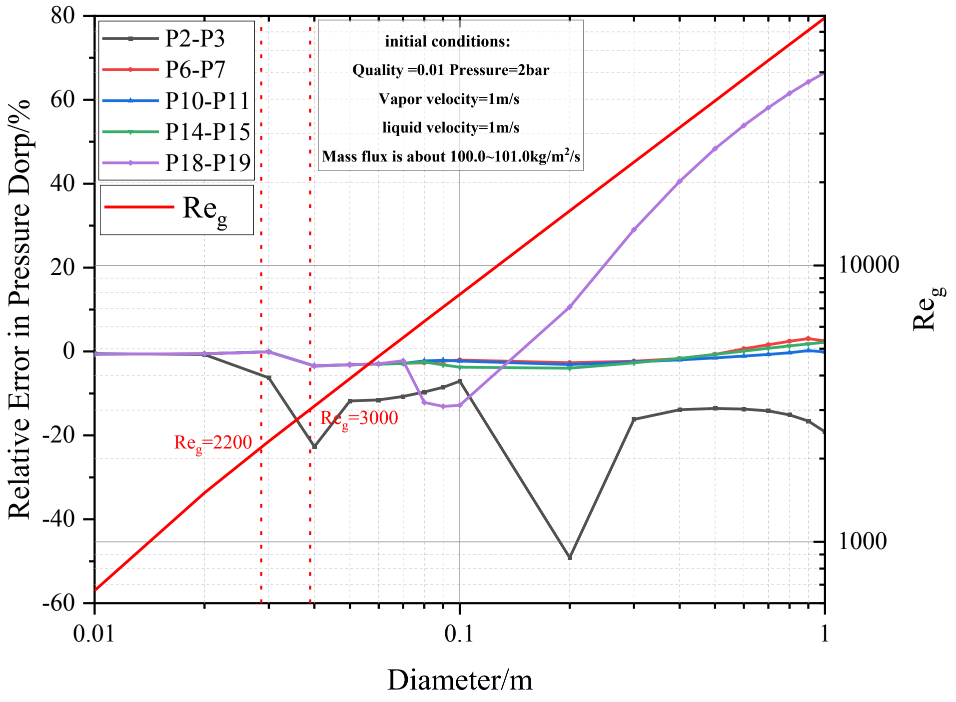

Figure 3 Relative error between the pressure drop calculated by RELAP5 and manual calculations across different pipe

diameters

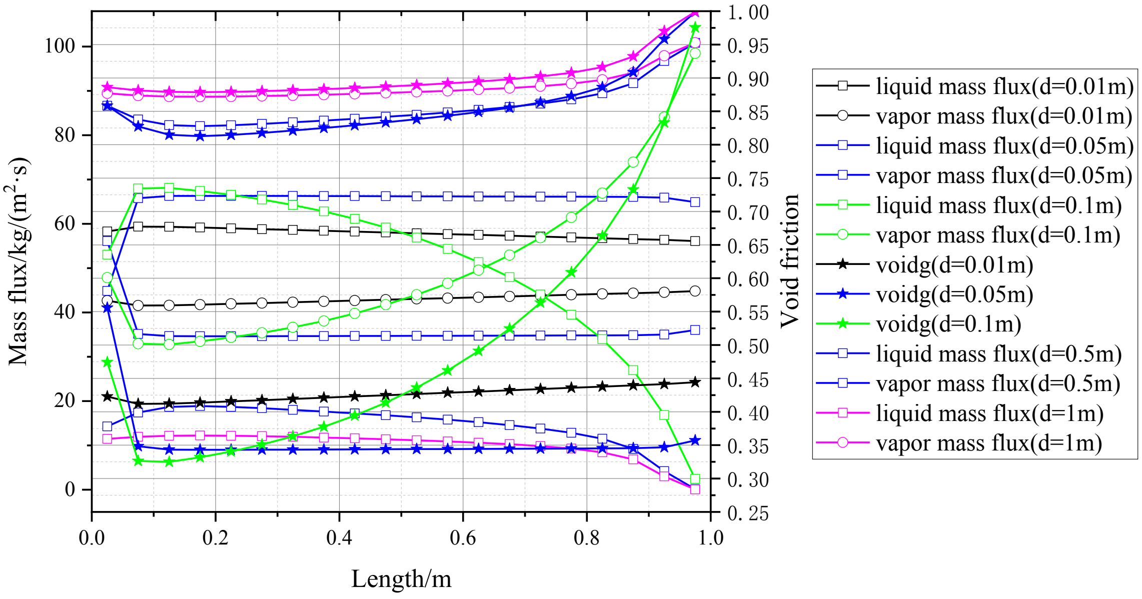

Figure 4 Variation of liquid mass flux, vapor mass flux, and void fraction along the pipe length for different pipe diameters

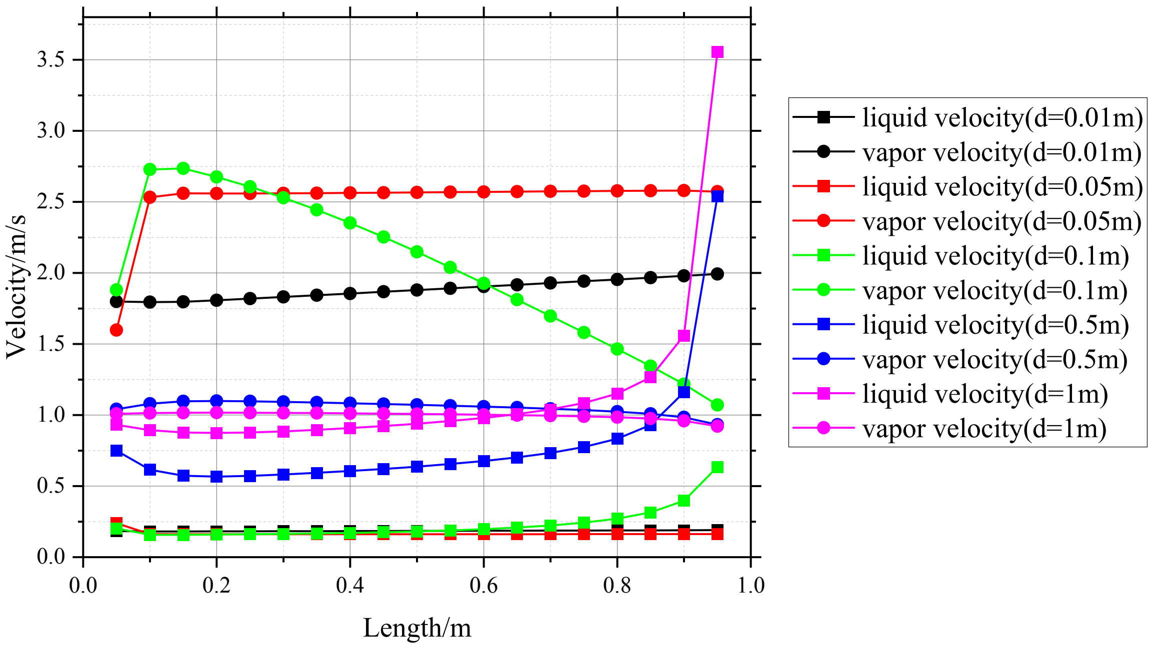

Figure 5 Variation of liquid velocity and vapor velocity along the pipe length for different pipe diameters

Figure 4 and Figure 5 present the variations of mass flux and velocity along the pipe length for different diameters, respectively. In Figure 4, it is evident that due to the constant pressure maintained at the outlet and the highest pressure observed in the first control volume at the inlet for smaller diameters, the void fraction for the smallest diameters at the inlet is minimized. Additionally, the vapor mass flux and void fraction increase progressively along the flow, indicating an ongoing vaporization process. Notably, for a diameter of 0.1 meters, the mass flux and void fraction exhibit the most significant changes along the flow direction, while the relative error in pressure drop is small. The connection between these observations remains unclear.

Similarly, in Figure 5, a substantial decrease in vapor velocity is observed for the diameter of 0.1 meters, likely due to the pronounced vaporization process at this diameter. Furthermore, abrupt changes in mass flux between the first and second control volumes and in velocity between the 19th and 20th control volumes can be seen. Consequently, the results for the first and 20th control volumes were excluded from this study.

4.2. Effect of vapor velocity(VV)

Generally, the vapor phase velocity is always greater than or equal to the liquid phase velocity. Thus, we fixed the liquid velocity at 1m/s and set five different conditions for the vapor phase velocity, ranging from 1m/s to 5m/s. Figure 6 presents the relative error of PDs at various positions along the pipe with diameters of 0.1 meters and 1 meter under different flow velocities. It can be observed that in most conditions, the relative error (in absolute value) decreases as the vapor velocity increases. It is particularly noteworthy that at a diameter of 1 meter, the error at the inlet and outlet can reach as high as 63%. Moreover, this value (considering sign) decreases with increasing vapor velocity. To further analyze the source of error, we plotted the code-calculated PDs and the manually calculated vapor phase acceleration, liquid phase acceleration, and FPDs for the five conditions with a diameter of 1m in Figure 7. From Figure 7Figure 6, we can discern that the vapor APD is almost zero and can be neglected. The FPD is nearly the same at different positions along the pipe, thus it is not the cause of the substantial variation in PDs along the pipe. Conversely, the liquid APD shows significant variation at different pipe positions, and this trend aligns with that of the total PD. Therefore, we can preliminarily conclude that the observed relative error is primarily due to the discrepancy between the liquid APD and the total PD calculated by the code. To determine the root cause of these discrepancies, it is essential to conduct an in-depth study of the code's algorithms and two-phase flow models in the future.

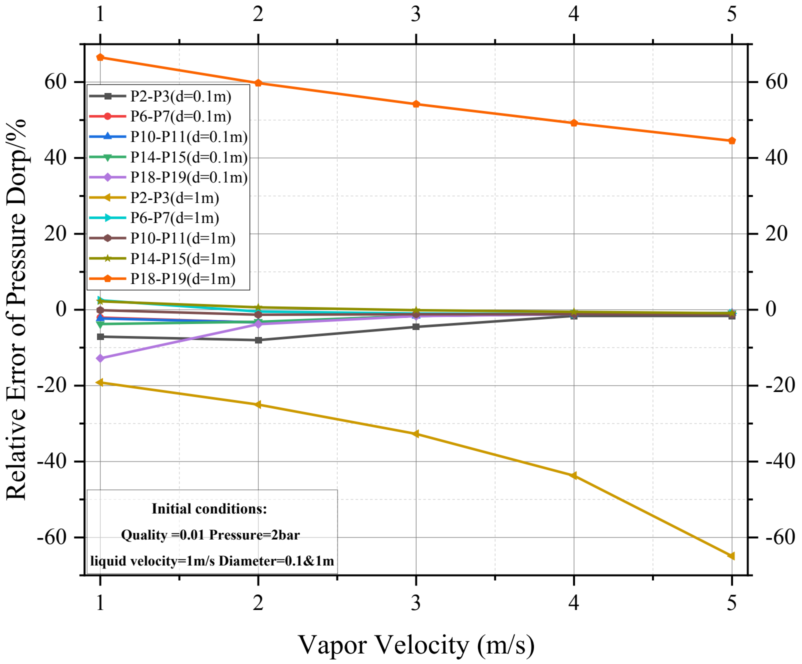

Figure 6 Relative error between the pressure drop calculated by RELAP5 and manual calculations at various vapor velocities

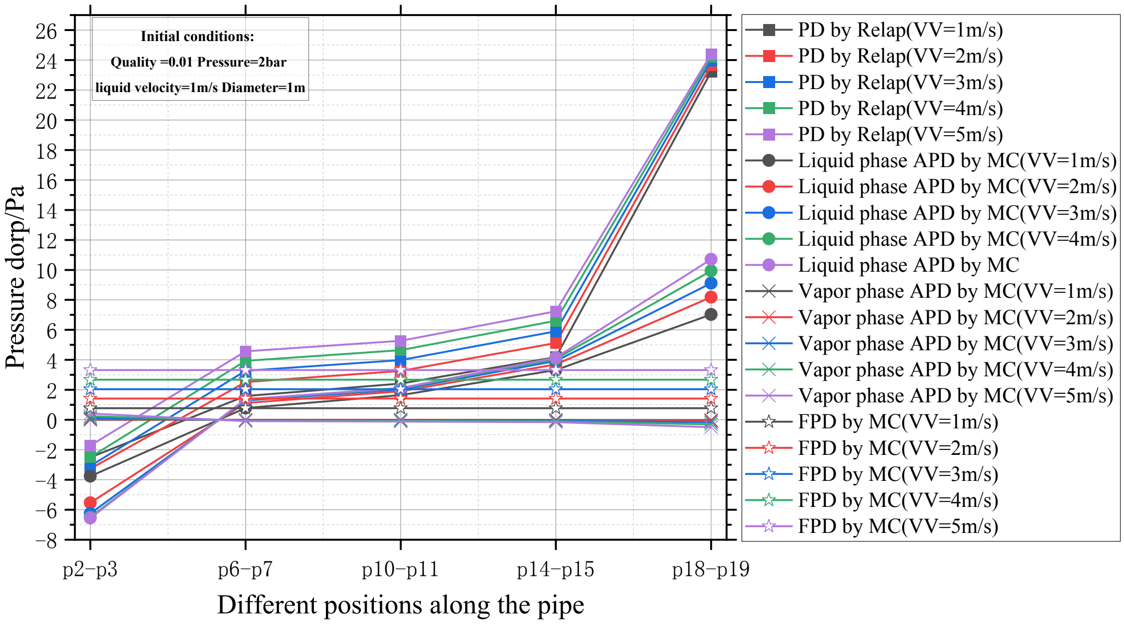

Figure 7 Comparison curves of pressure drops calculated by RELAP5 versus manual calculations of liquid phase acceleration pressure drops, vapor phase acceleration pressure drops, and friction pressure drops at various positions along the pipe

5. CONCLUSION

This study simulated and analyzed pressure drop in horizontal pipes. We compared the relative errors between model predictions and the data used in the RELAP5 code. Several preliminary conclusions were drawn from this analysis.

- The observed relative errors are primarily attributed to discrepancies between the liquid APD and the total PD calculated by the code. This is evident from the significant variations in liquid APD at different pipe positions, which align with the trends in the total pressure drop. Notably, the FPD remained relatively consistent and was not the main source of substantial error variation.
- The study highlighted specific conditions where the relative error increased significantly, such as with larger pipe diameters and during the laminar-turbulent transition. This anomaly, particularly the increased error at the inlet and outlet for pipe diameters exceeding 0.1 meters, warrants further investigation. It also indicates that the diameter fails to follow consistency checks.

To address these discrepancies and improve model accuracy, future research should not only involve a detailed examination of the code's algorithms and two-phase flow models but also increase experimental and simulation studies on pressure drop. Furthermore, it is crucial to re-evaluate the prioritization of pressure drop. By integrating the concepts of Verification, Validation, and Consistency, we can enhance the reliability and accuracy of the models while maintaining consistency across various scenarios.

These efforts will ultimately contribute to safer and more efficient nuclear reactor designs by improving the reliability and consistency of thermal-hydraulic simulations.

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