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ONE-DIMENSIONAL TWO-PHASE HOMOGENEOUS FLOW MODEL FOR A VERTICAL HEATED PIPE

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Abstract.
This work presents the implementation of a one-dimensional numerical simulation code developed to model a two-phase Natural Circulation Loop (NCL). The code is based on the homogeneous flow model, which treats the two-phase vapor-liquid mixture as a pseudo-fluid and consists of governing equations for mixture continuity, vapor continuity, mixture momentum, and mixture energy. This work employs the steady state version of the mixture continuity, mixture momentum and mixture energy. The vapor density and void fraction fields are calculated through constitutive equations. The objective is to obtain the axial properties along a two-phase NCL. The numerical results were compared against theoretical and experimental data from the literature for a two-phase natural circulation test facility. Finally, the validity and limitations of applying the one-dimensional homogeneous flow model to two-phase natural circulation loops are discussed.

Keywords: *two-phase flows, natural circulation loops, one-dimensional homogeneous flow model, staggered grid, reactor coolant system*

1. INTRODUCTION

Passive Cooling Systems (PCSs) are devices designed to remove heat without relying on active components that require external power input, such as pumps or fans. A primary example of passive cooling systems are natural circulation loops (NCLs), which are of high relevance in the nuclear power industry due to their application as passive safety features. Modelling two-phase flow natural circulation loops is of special interest for some specific reactor designs, such as the ESBWR (El-Genk, 2008) or the REX-10 Small Modular Reactor (Lee and Park, 2013), both show in fig. 1. A key challenge in studying natural circulation loops is accurately modelling two-phase flow phenomena, especially predicting axial void fraction profiles. For one-dimensional formulations of two-phase natural circulation loops, more comprehensive mathematical models are necessary to offset the limitations of the reduced dimensionality of the model. Mixture models that consider the vapor-liquid two-phase flow as a single combined mixture were proposed by the literature as a solution to address these modeling requirements.

Two-phase NCL modelling has been a subject of extensive research over the past decades. Particular emphasis has been placed on accurately modeling the thermal-hydraulic phenomena present in the coolant circuit of Boiling Water Reactors (BWRs). This focus has led to the development of several reactor safety system analysis codes, such as RELAP5, designed to predict the transient response of these systems (Idaho National Engineering Laboratory, 1995).

A significant area of interest within this field is the modelling of flow instabilities distinctive of two-phase flow systems. These instabilities are present during reactor transients, such as startup, and they are caused by phase changes in the system (Prasad *et al.*, 2007). Numerous studies have explored these phenomena using the four-equation drift-flux model. Paniagua *et al.* (1999) modelled the geysering instabilities during startup in a two-phase NCL using a momentum integral

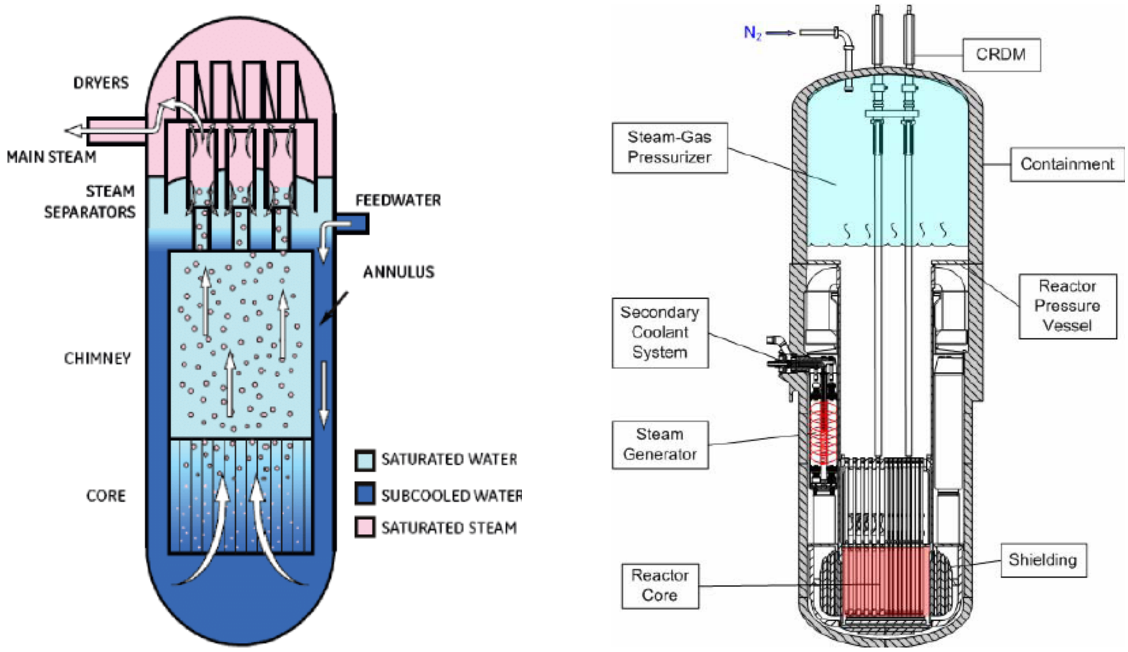

Figure 1: On the left: Economic Simplified Boiling Water Reactor (ESBWR), from GE-Hitachi; on the right: REX-10 Small Modular Reactor.

formulation. Manera *et al.* (2005) simulated flashing-induced instabilities using the nuclear reactor code FLOCAL. Lee and Park (2013) developed TAPINS, a thermal-hydraulic system code for REX-10, a fully passive integral PWR. Other works include that of Chen *et al.* (2015), where a three-equation homogeneous flow model was used to study flow oscillations present during sub-cooled boiling. More recently, Zou *et al.* (2016) applied the Jacobian-Free Newton-Krylov method to solve the drift-flux balance equations.

This work presents the implementation of a one-dimensional numerical simulation code developed to model a two-phase natural circulation loop, based on the four-equation homogeneous flow model (Ishii and Hibiki, 2011). This model treats the two-phase vapor-liquid mixture as a pseudo-fluid and consists of governing equations for mixture continuity, vapor continuity, mixture momentum, and mixture energy. In the present work, however, the model is employed to provide the steady state flow fields, so only three equations are used – mixture continuity, momentum and energy.

The paper of Gartia *et al.* (2006) was adopted as a reference for evaluation of the results produced by the model. In their work, a generalized correlation is proposed for two-phase NCLs and compared against nuclear system codes and experimental data. The model employed in the present work was included in this set of comparisons. This work of Gartia *et al.* (2006) was produced by one of the most prominent research groups in the field of NCLs, the Bhabha Atomic Research Centre. They have also proposed a correlation for single-phase NCLs in Vijayan and Austregesilo (1994), establishing a function between Reynolds and a modified Grashof number. Therefore, the results provided by Gartia *et al.* (2006) were taken as a solid reference for evaluation of the present model. Section 4presents more details about the NCL that has been modeled and the results obtained. Before section 4, section 3described the mathematical model and the solution strategy. The paper closes with the conclusions.

2. FUNDAMENTALS OF TWO-PHASE NATURAL CIRCULATION LOOPS

Figure 2 shows a schematic representation of a two-phase NCL. The heater, located in the lower part of the loop, has the function of transferring heat into the system. Depending on the operating and geometrical parameters, the working fluid enters the heater with some level of sub-cooling. So the heater initially transfers sensible heat to the fluid until the saturation temperature is reached. After that, phase change takes place. In any NCL – single or two-phase – the change on the fluid density generates buoyancy, which drives the fluid upwards after the heater. In a two-phase NCL, the change in density is much stronger, promoting high mass fluxes, which posed an advantage of such systems in comparison to the single-phase ones.

The system parameters, mainly the power input, will determine the amount of steam that is produced in the heater. However, as the mixture flows upwards, the hydrostatic pressure decreases, which generates an additional amount of steam.

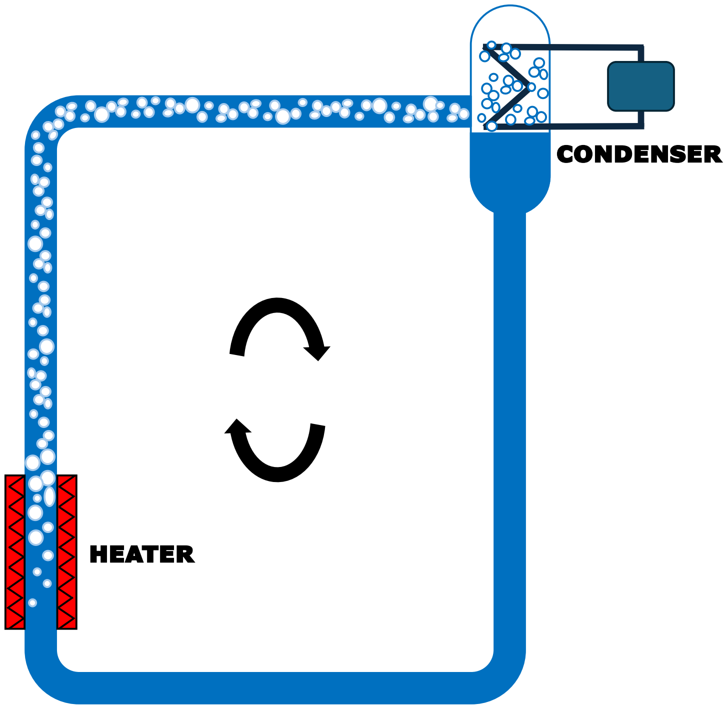

Figure 2: Schematic drawing of a two-phase NCL.

The mixture then flows to the condenser, which is responsible to transfer the absorbed power to a heat sink. The system connected to the condenser is the secondary circuit. In the condenser, saturated water is produced. This condensate flows downwards and then reaches heater again, closing the cycle. As in any natural convection system, the equilibrium is achieved when the buoyancy forces compensate the friction losses. And depending in this equilibrium, the system might develop instabilities, which is of high interest in the analysis of reactor system dynamics. More information on hydrodynamic stability of NCLs can be found on Prasad *et al.* (2007) and Boure *et al.* (1973).

Real NCLs are equipped with several auxiliary components, such as safety valves, control valves in the secondary circuit, filling valve, a power controller, and so on. The paper of Ooi *et al.* (2019) presents an interesting description of the design and operation of an experimental two-phase natural convection loop.

3. MATHEMATICAL MODEL AND NUMERICAL METHOD

As described int the introduction, the model consists of a reduced steady state version of the four equation homogeneous flow model proposed by Ishii and Hibiki (2011).

The variable s is chosen as the longitudinal axial direction of the pipe. Thus, the simplified equations for the conservation of mass, momentum, and energy (enthalpy) of the mixture variables are expressed as follows, respectively:

$$\frac{d}{ds}\left(\rho_m\, v_m\right) = 0, \tag{1}$$

$$v_m \frac{dv_m}{ds} = -\frac{1}{\rho_m}\frac{dp_m}{ds} - \frac{f}{2D}v_m^2 - g, \tag{2}$$

$$\frac{d}{ds}\left(\rho_m v_m\, h_m\right) = v_m \frac{dp_m}{ds} + S_h, \tag{3}$$

where ρ_m is the mixture specific mass, v_m is the mixture flow velocity, p_m is the pressure field, and h_m is the mixture specific enthalpy. f is the wall friction factor, g is the gravity acceleration, D is the pipe inner diameter, and S_h is the energy source term.

In the homogeneous flow model, both the liquid and gas phases share the same homogeneous flow velocity, v_m. In this context, the wall friction factor, denoted by f, is calculated using the correlation for single-phase flow proposed by

Churchill (1977) which is applicable for all regimes. This correlation is expressed as:

$$f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + (f_1+f_2)^{-1.5}\right]^{1/12}, \tag{4}$$

where $\mathrm{Re} = \rho_m\, v_m\, D/\mu_m$ is the flow Reynolds number with the mixture dynamic viscosity μ_m. f_1 and f_2 are, respectively:

$$f_1 = \left\{-2.457\ln\left[\left(\frac{7}{\mathrm{Re}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]\right\}^{16}, \qquad f_2 = \left(\frac{37530}{\mathrm{Re}}\right)^{16}. \tag{5}$$

In the equation for f_1, the ε represents the roughness height, *i.e.*, ε/D gives the relative roughness of the pipe.

The specific energy source term S_h is positive along the heater, which has a length L_h, negative along the condenser with a length L_c, and zero other parts of the pipe. Thus, the specific energy source term along the heater is:

$$S_h = \frac{Q_h}{AL_h}, \tag{6}$$

where Q_h is the power supplied by the heater and A is the cross-sectional area of the pipe; along the condenser is:

$$S_h = -\frac{Q_c}{AL_c}, \tag{7}$$

where Q_c is the power removed by the condenser.

The specific mass of the mixture is determined using the properties of water and steam as a function of the mixture pressure and specific enthalpy, as follows:

$$\rho_m = \hat{f}(p_m, h_m). \tag{8}$$

Similarly, the vapor or void fraction α is also expressed as a function of the mixture pressure and specific enthalpy, as follows:

$$\alpha = \hat{g}(p_m, h_m). \tag{9}$$

In this work, the water/vapor properties are computed using `X Steam` (Holmgren, 2024), which is based on the "International Association for Properties of Water and Steam Industrial Formulation 1997" (IAPWS IF-97, 1997).

The conservation equations (1)-(3) are discretized using the finite difference method, with first order upwind scheme. The discretized equations are solved using the fixed point iteration method.

The geometry is considered to be a closed-loop system with a rectangular form. As it is presented in the results section, the actual geometry of the loop considered for validation is trapezoidal shaped loop. However, it can be represented by an equivalent rectangular loop, as long as it preserves the pressure losses of the real geometry.

4. RESULTS

The output produced by the model was evaluated using the data provided by Gartia *et al.* (2006), which include theoretical data from a general correlation, results from nuclear system codes and experiments.

The objective of Gartia *et al.* (2006) is to propose a correlation which is able to characterize the steady state regime of any two-phase NCL. Basically they developed expressions for the mass flow, Reynolds and Grashof numbers and a non-dimensional geometrical parameter.

The authors then tested the proposed correlation against nuclear system codes and an in-house experimental loop with three different diameters. Figure 3 presents an schematic view of the experimental loops, which have the same geometry except for the diameter, for which there are three variants: 9.1 mm, 15.74 mm and 19.86 mm.

The loop dimensions are shown in fig. 3. The heater is vertically oriented and receives heat form an electrical source. The steam then produced flows upward until it reaches the top tube, which is slightly inclined (8° of inclination) to prevent bubbles from being retained in the piping. The top tube leads to the condenser section, which communicates to a secondary circuit that absorbs the heat in the condensation process. The condensate formed flows downwards until it reaches the bottom horizontal tube, which then takes the fluid to the heater again, closing the cycle.

4.1 Results for a single case

Figure 4 shows the profiles of flow velocity, void fraction, pressure, and enthalpy along the loop, obtained by the simulation using the developed model for a specified set of operational conditions. From left to right, the red circles indicate heater inlet, heater outlet, condenser inlet and condenser outlet. This figure does not show comparisons with the reference paper. It can be observed that, as the enthalpy h increases in the heater, the void fraction α and the velocity $\mathbf{v}$ increase, as expected. The mass flow obtained is 0.0319 kg/s.

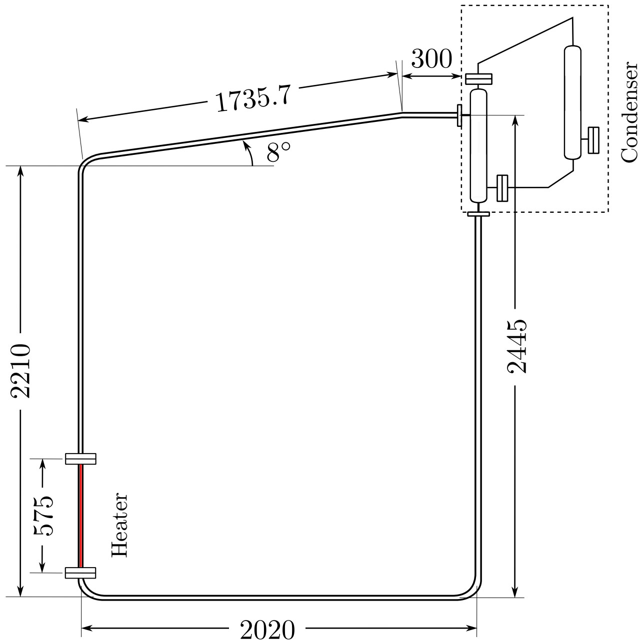

Figure 3: Natural Convection Loop of Gartia *et al.* (2006).

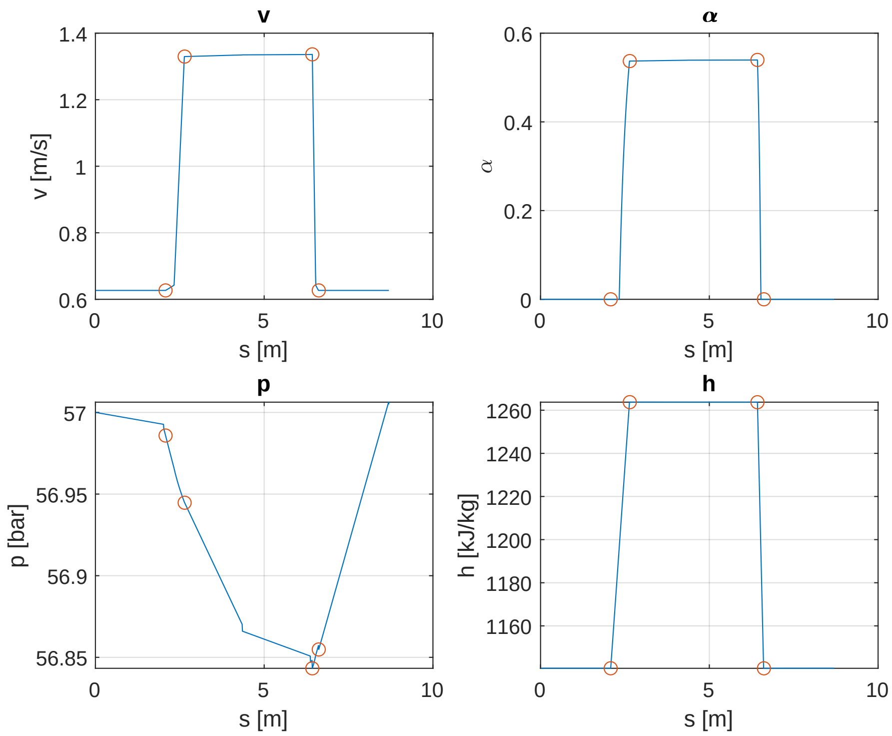

Figure 4: Field profiles for inlet pressure of 56.98 bar, sub-cooling of 11.12 K and power input of 4 kW. From left to right, the red circles indicate heater inlet, heater outlet, condenser inlet and condenser outlet.

4.2 Code validation

Figure 5 presents a comparison of the results produced by the present model with experimental and computational results for the experimental loop of 9.1 mm inside diameter. The system codes employed in the validation were RELAP5/MOD 3.2 and TINFLO-S. Results were also compared against the correlation proposed by the authors of the reference paper to calculate the steady state mass flow rate based on the geometric and operating parameters. Summarizing, results from the the following references were compared with the present model:

- Experiment
- RELAP5/MOD 3.2
- TINFLO-S
- mass flow correlation proposed by Gartia *et al.* (2006)

More details regarding these codes can be found in the reference paper. In this comparison, the variation of mass flow rate with the power input was observed, for an operating pressure around 57 bar and a heater inlet sub-cooling of about 12 K.

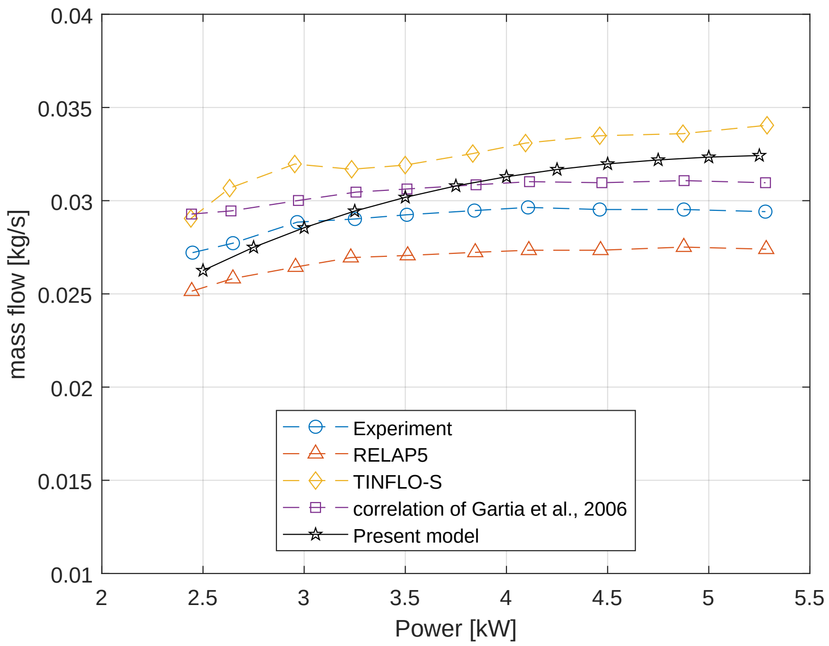

Figure 5: Results for mass flow as function of power input; comparison between data provided by Gartia *et al.* (2006) and the present model.

It can be observed from fig. 5 that the present model presents higher sensibility of the mass flow to the power input in comparison to the reference data. It has considerably good agreement with the experiment between 2.5 kW and 3.5 kW. Afterwards, it over predicts the experimental results. However, it still presents better agreement if compared to the TINFLO-S code. The high sensibility of the mass flow to the power input can be associated to an incapacity of the present model to correctly predict the friction losses as the void fraction increases.

A second comparison was made employing the relation $\mathrm{Re} \times \mathrm{Gr} \,/\, \mathrm{Ng}$ proposed by Gartia *et al.* (2006), expressed by eq. 10. In this case, the three different loops (which differ only in the internal diameter – 9.1 mm, 15.74 mm and 19.86 mm) were simulated. Figure 6 shows the comparisons.

It can be seen that the results produced by the present model closely follows the experimental data, scattering around the correlation proposed by Gartia *et al.* (2006).

Here, Reynolds is calculated according to the scaling laws presented by authors, in which Reynolds, for turbulent regimes, is defined as

$$\mathrm{Re} = 1.9561 \left[\frac{\mathrm{Gr}}{\mathrm{Ng}}\right]^{0.36364} \tag{10}$$

where Gr is a modified Grashof number and Ng is a geometric parameter. Please refer to Gartia *et al.* (2006) for the definitions of Gr and Ng.

The results of the present model show a different behavior than that characterized by the correlation, which can also be related to the differences between the friction losses that are taken into account in the model and the actual friction losses. It is also noticeable that are specific values of $\mathrm{Gr} \,/\, \mathrm{Ng}$ beyond which the trend changes, following the inclination of the correlation. Anyhow, the results produced by the present model fall inside a range of +40% and -40% from the correlation, as proposed by Gartia *et al.* (2006).

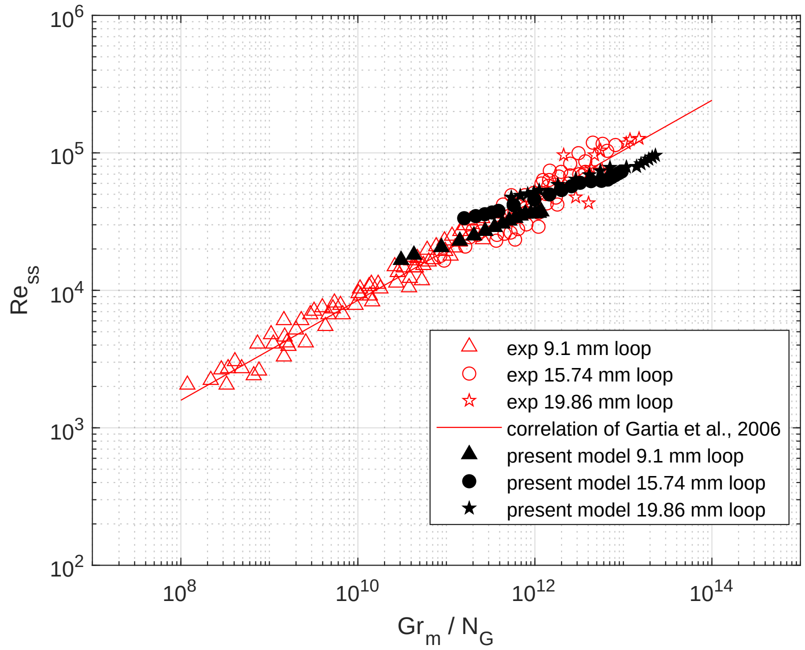

Figure 6: Comparison of experiments and the present model for the three loops – 9.1 mm, 15.74 mm and 19.86.

5. CONCLUSION

In this work, a one-dimensional code to model two-phase natural circulation loop using the homogeneous flow model was successfully implemented. The model was developed for calculation of the steady-state regime, with the vapor specific mass and void fraction fields calculated through constitutive equations.

It can be concluded form the results that the model produces qualitatively good agreement with experimental and theoretical data. However, it can be observed that, depending on the input power, the model overestimates the mass flow. This can be link to an incapacity of the model to properly calculate the friction losses as the void fraction increases. Further investigations, employing a more adequate correlation and/or the implementation of a drift flux model are necessary to evaluate the capacity of the present model.

Overall, the authors conclude that this study highlights the potential and applicability of the one-dimensional homogeneous flow model for simulating two-phase natural circulation loops, providing a valuable tool for engineers and researchers in the field of thermal-hydraulics.

6. ACKNOWLEDGEMENTS

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