Development of TPNCIRC code for Evaluation of Two-Phase Natural Circulation Flow Performance under External Reactor Vessel Cooling Conditions

A-Reum Choi*, Hyuk-Jin Song, Jong-Woon Park
Dongguk univ., 707, Seokjang-Dong, Gyeong Ju, South Korea
**Corresponding author: areum4219@gmail.com*

1. Introduction

During a severe accident, corium is relocated to the lower head of the nuclear reactor pressure vessel (RPV). Design concept of retaining the corium inside a nuclear reactor pressure vessel (RPV) through external cooling under hypothetical core melting accidents is called external reactor vessel cooling (ERVC) [1].

The natural circulation flow path under the ERVC condition is illustrated in Fig. 1. In order to efficiently cool the exterior surface of an RPV, nuclear boiling of the two-phase natural circulation flow through the annular gap between the reactor vessel exterior surface and insulation should be sufficiently maintained. In this respect, validated two-phase natural circulation flow (TPNC) model is necessary to determine the adequacy of the ERVC design and operating conditions such as inlet area, form losses, gap distance, riser length and coolant conditions.

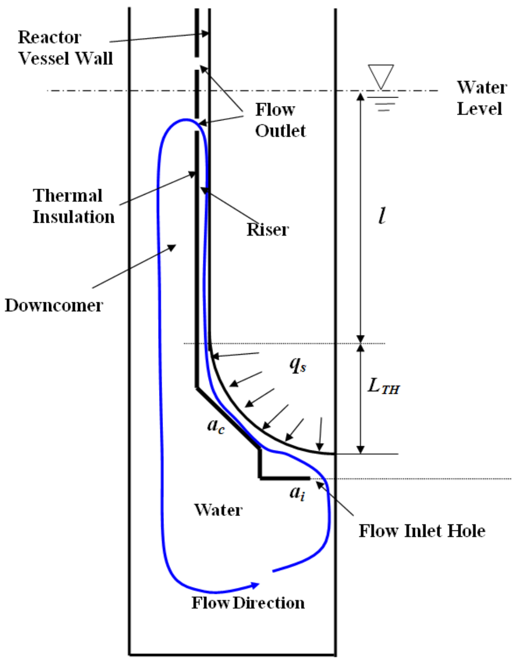


Fig. 1. Schematic of natural circulation flow path under ERVC condition.

The most important model generally characterizing the TPNC are void fraction and two-phase friction factors. Typical experimental and analytical studies to be referred to on two-phase circulation flow characteristics are those by Reyes [2], Gartia et al. [3] based on Vijayan et al. [4], Nayak et al. [5] and Dubey et al. [6]

In the present paper, two-phase natural circulation (TPNC) flow characteristics under external reactor vessel cooling (ERVC) conditions are studied using two existing TPNC flow models of Reyes [2] and Gartia et al. [3] incorporating more improved void fraction and two-phase friction models. These models and correlations are integrated into a computer program, TPNCIRC, which can handle candidate ERVC design parameters, such as inlet, riser and downcomer flow lengths and areas, gap size between reactor vessel and surrounding insulations, minor loss factors and operating parameters of decay power, pressure and subcooling. Accuracy of the TPNCIRC program is investigated with respect to the flow rate and void fractions for existing measured data from a general experiment [6] and ULPU specifically designed for the AP1000 in-vessel retention [7]. Also, the effect of some important design parameters are examined for the experimental and plant conditions.

2. Analytical Model and Method

Present study is basically based on existing TPNC models of Reyes [2] and Gartia et al. [3]. However, these models originally used simple void fraction and two-phase frictional pressure drop models and thus present paper improved these models by incorporating drift flux void fraction model.

The TPNC models of Reyes and Gartia et al. are briefly described as follows:

2.1. Two-phase flow model

2.1.1. Reyes model.

Reyes [2] developed a cubic equation to predict the flow velocity, u_c, in a steady-state, two-phase fluid thermosyphon for both subcooled and saturated flow conditions:

$$u_c^3 + \phi_a u_c^2 + \phi_b u_c - \phi_c = 0 \quad (1)$$

where ϕ_a, ϕ_b and ϕ_c are the coefficients that are given by a function of thermal power, thermo-physical properties and friction and form losses, as illustrated in the following:

Nomenclature

a	cross- sectional area, m^2
α	void fraction
A	flow area, m^2
β_{tp}	two-phase thermal expansion coefficient, kg/J
D	dimensionless hydraulic diameter, m
F	friction coefficient
g	gravitational acceleration, m/sec^2
h	enthalpy, J/kg
H	loop height, m
l	dimensionless length, m
L	length, m
L_{TH}	heated length, m
N_G	dimensionless parameter defined by Eq. (4)
p	constant
q_s	heat generation density, W/m^3
Q	total heat input rate, W
u	velocity, m/sec
W	mass flow rate, kg/sec
x	quality
X	Lockhart-Martinelli parameter
ϕ^2_{LO}	two-phase friction multiplier
ρ	density, kg/m^3
$\bar{\rho}$	average density, kg/m^3
μ	dynamic viscosity, Ns/ m^2

Superscripts

b	constant
he	heater exit
t	total

Subscripts

c	corium(molten core)
eff	effective
g	vapor
gs	saturated vapor
l	liquid
in	inlet
ls	saturated liquid
LO	liquid only
r	reference value
ss	steady state
SP	single phase
sub	subcooled
TP	two-phase

$$\phi_a = \frac{\dot{q}_s\Delta\rho}{a_c\rho_{ls}}\left[\frac{(1+F_{TP})\rho_{gs}h_{ls}-2\Delta\rho F_{TP}h_{sub}}{F_T\rho_{gs}^2h_{ls}^2-(1+F_{TP})\rho_{gs}h_{lg}h_{sub}\Delta\rho+F_{TP}(\Delta\rho)^2h_{sub}^2}\right] \quad (2a)$$

$$\phi_b = \frac{\Delta\rho}{a_c^2\rho_{ls}^2}\left[\frac{\Delta\rho(F_{TP})q_s^2+2L_{TH}g\rho_c^2a_c^2h_{sub}\rho_{gs}h_{lg}}{F_T\rho_{gs}^2h_{ls}^2-(1+F_{TP})\rho_{gs}h_{lg}h_{sub}\Delta\rho+F_{TP}(\Delta\rho)^2h_{sub}^2}\right] \quad (2b)$$

$$\phi_c = \frac{1}{a_c\rho_{ls}}\left[\frac{2L_{TH}gq_s\Delta\rho\rho_{gs}h_{lg}}{F_T\rho_{gs}^2h_{ls}^2-(1+F_{TP})\rho_{gs}h_{lg}h_{sub}\Delta\rho+F_{TP}(\Delta\rho)^2h_{sub}^2}\right] \quad (2c)$$

2.1.2. Gartia model.

Gartia et al. [3] proposed a generalized correlation to estimate two-phase natural circulation flow rate: equations of continuity, energy and momentum equations were used to obtain a dimensionless two-phase flow rate. At steady state, explicit equation for the mass flow rate in the two-phase natural circulation loops is given by:

$$W_{ss} = \left[\frac{2}{p}\frac{g\rho_r\beta_{tp}HQD_r^bA_r^{2-b}\rho_l}{\mu_r^bN_G}\right]^{1/3-b} \quad (3)$$

In Eq. (3), N_G is the dimensionless parameter and in the case of a uniform diameter loop and is given by

$$N_G = \frac{L_t}{D_r}\left[(l_{eff})_{SP} + \bar{\phi}^2_{LO}(l_{eff})^{he}_{SP} + \phi^2_{LO}(l_{eff})^t_{he}\right] \quad (4)$$

Also, Gartia et al. [3] applied a new parameter β_{tp} which is the expansion coefficient expressed as follows:

$$\beta_{tp} = \frac{\rho_{in}-\rho_{exit}}{((\rho_{exit}+\rho_{in})/2)\Delta h} \quad (5)$$

2.2. Two-phase friction factor multiplier

The two-phase friction multiplier is one of the important parameters for the estimation of two-phase natural circulation flow rate. Gartia et al. [3] used homogeneous equilibrium model for the two frictional pressure loss. Two-phase friction factor multipliers, ϕ^2_{LO} and $\bar{\phi}^2_{LO}$, are applied for the heated two-phase section and adiabatic two-phase section, respectively, and they are defined by the following equations [3]:

$$\phi^2_{LO} = \frac{\rho_l}{\rho_{exit}}\left[\frac{1}{1+x((\mu_l/\mu_g)-1)}\right]^b \quad (6)$$

$$\bar{\phi}^2_{LO} = \frac{\rho_l}{\bar{\rho}_{exit}}\left[\frac{1}{1+(x/2)((\mu_l/\mu_g)-1)}\right]^b \quad (7)$$

Equation (6) and (7) were based on rather old McAdams viscosity effect model [8]. However, this model has a limitation in that quality is linear according to power. Therefore, in the present study, widely used two-phase frictional multiplier developed by Chisholm model [9] is applied to the present TPNCIRC code:

$$\phi^2_{LO} = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (8)$$

where C is the Chisholm parameter which has different value according to flow types: C=20 for turbulent liquid-turbulent gas is used in the present work.

2.3. Void fraction model

Void fraction is also an important parameter for the estimation of two-phase pressure drop and flow rate and is generally represented as a function of mass quality, x, and combinations of various properties [10]. The most widely known void fraction models are as follows:

1. Homogeneous equilibrium model (HEM)
2. Slip ratio
3. Drift flux model

Among these models, the drift flux model is a type of averaged separated flow model with relatively simple formulation than the rigorous two-fluid model, taking into account the effect of non-uniform two-phase characteristic velocities in the channel and the void fraction profile as well as the local relative velocity. Void fraction can be obtained from the drift flux model as follows:

$$\alpha = \frac{x}{\rho_g}\left[C_o\left(\frac{x}{\rho_g}+\frac{1-x}{\rho_l}\right)+\frac{V_{gj}}{G}\right]^{-1} \quad (9)$$

where C_o is the distribution parameter, V_{gj} is the drift flux and G is the mass flux.

For C_o and V_{gj} in Eq. (8), Ishii's correlations [11] are applied in the present study as follows:

$$C_0 = 1.2 - 0.2\sqrt{\rho_g/\rho_l} \quad (10)$$

Ishii [11] suggested diverse correlations for the drift flux velocity depending on flow conditions such as bubbly, slug and churn-turbulent flow.

$$V_{gj} = \sqrt{2}\left(\frac{\sigma g \Delta\rho}{\rho_l^2}\right)^{\frac{1}{4}}(1-\langle\alpha\rangle)^{1.75} \quad (11a)$$

$$V_{gj} = 0.35\sqrt{\frac{g D_H \Delta\rho}{\rho_l}} \quad (11b)$$

$$V_{gj} = \sqrt{2}\left(\frac{\sigma g \Delta\rho}{\rho_l^2}\right)^{\frac{1}{4}} \quad (11c)$$

2.4. Solution procedure

The two-phase natural circulation flow rate is calculated by integrating the flow rate or velocity model of Reyes [2] and Gartia et al. [3], three types of void fraction models and Chisolm two-phase frictional pressure drop model [9] described in the previous section.

In the calculation, the natural circulation flow rate or velocity cannot be obtained in a straightforward way, i.e., we need global iterations by initially assuming unknown flow rate or velocity and obtain void fraction and two-phase pressure drop, updating the flow rate or velocity until converged. Fig. 2 shows the entire calculation procedure of the TPNCIRC.

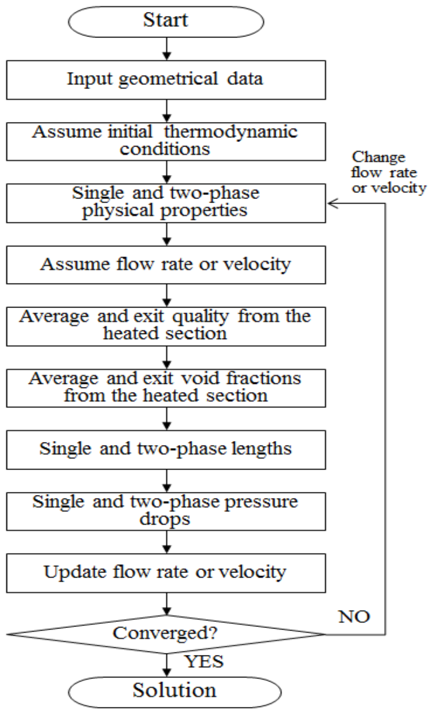


Fig. 2. Flow of calculation in the TPNCIRC.

3. Results and discussion

3.1. Comparison of predictions and measured data

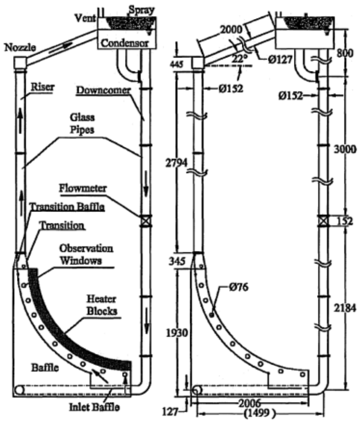
Accuracy of the TPNCIRC code is investigated with respect to the flow rate, exit quality and void fractions by comparing with existing measured data from a general natural circulation experiment of Dubey et al. [6] and the ULPU test loops specifically designed for the AP1000 reactor [7].

The schematic of the two experimental loops are presented in Fig. 3. For the ULPU tests, there are three kinds of configurations, III, IV and V and each dimensions are presented in Table 1.

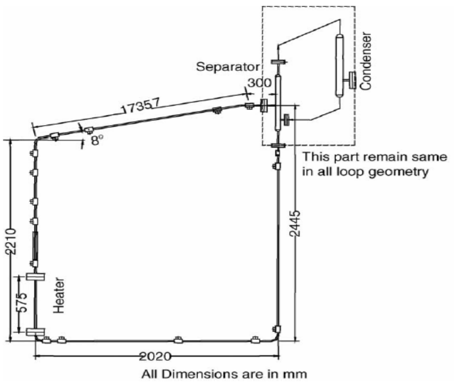
3.1.1. Analysis for the ULPU data [7].

Figure 4 shows the predictions of two-phase flow rates for the three ULPU conditions [7] by using the two models of Reyes [2] and Gartia et al. [3] with newly incorporating the drift flux void fraction model and Chisolm two-phase frictional pressure drop correlation in the present work. It can be recognized from Fig. 4 that the measured flow rates are well predicted by the two modified models for subcooling to 6 K.

The values of volumetric flow rates are distributed between 10 and 15 liter/sec. For smaller gaps (between the baffle and the heated section, see Fig. 3), the predictions are reasonably good for lower heat fluxes but for larger gaps the predictions are good for higher heat fluxes. The measured two-phase flow rates from the ULPU for the gaps less than or equal to 6 inch are not very sensitive to the heat flux variations. However, the reason of this is not available from the literature [7]. This needs further investigation.



(a) ULPU Configuration V [7]



(b) Dubey's loop [6]

Fig. 3. Experimental facilities for two-phase natural circulation flow.

Table 1: Design parameters in ULPU test [7]

Parameter (Unit)	ULPU III Config. III	ULPU IV Config. IV	ULPU V Config. V
Thermal Power (MW)	0.502	0.502	0.502
Average heat flux on the wall (kW/m^2)	800	800	800
Riser length (m)	4.00	4.00	4.00
Riser diameter (m)	0.152	0.152	0.152
Radius of curvature of the heater (m)	2.00	2.00	2.00
Baffle shape	Straight baffle	Curved baffle	Curved baffle
Slice depth (m)	0.2	0.2	0.2.
Annular gap clearance (m)	0.064 - 0.23	0.23	0.076/0.152
Environment pressure (atm)	1	1	1

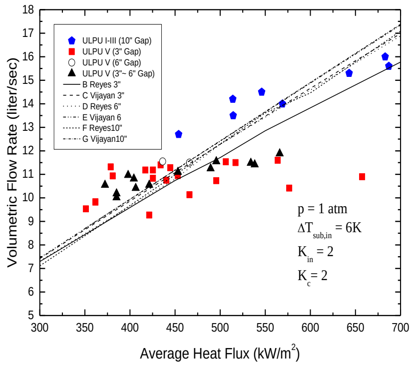
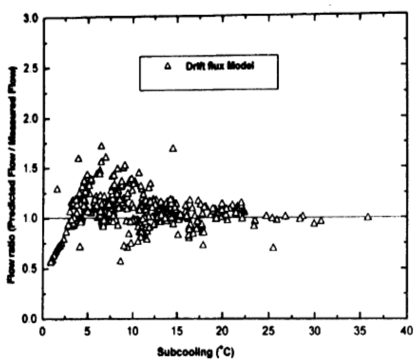


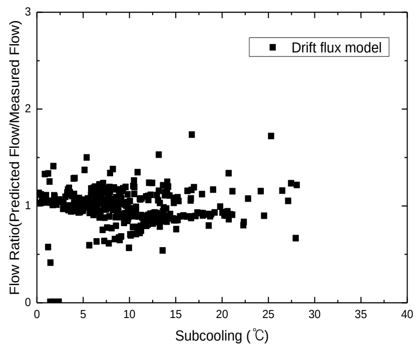
Fig. 4. Comparison of analytical predictions with the ULPU data.

3.1.2. Analysis for the Dubey data [6].

Figure 5 shows the ratio of predicted vs. measured two-phase flow rates obtained from the original Dubey's prediction and the present upgraded model. The ratios are presented according to subcooling. As shown in Fig. 5, the flow rate ratios from the present model is more close to 1.0 which means that the two values are the same. Presnt predictions are in better agreement with the experimental data and are much improved for lower subcooling.

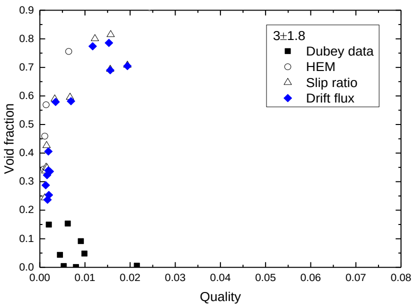


(a) Dubey's prediction [6]

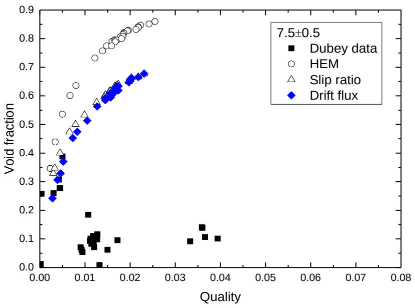


(b) Present prediction

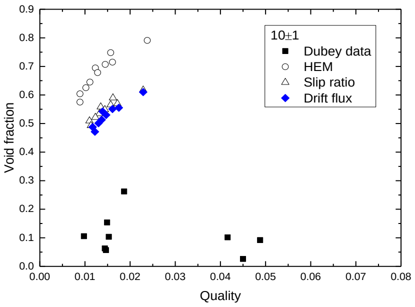
Fig. 5. Ratio of predicted vs. measured two-phase flow rates.



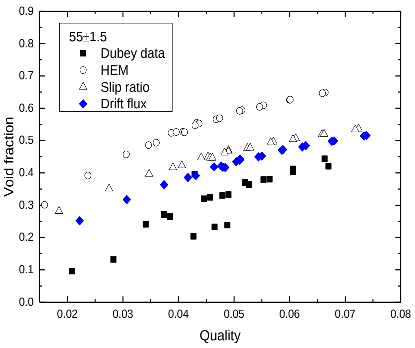
(a) At 3 bar



(b) At 7.5 bar



(c) At 10 bar



(d) At 55 bar

Fig. 6. Void fractions vs. quality for Dubey data [6].

Predictions of the void fractions by using the modified Gartia TPNC model by using three void fraction models such as HEM, slip and drift flux are obtained for the diverse pressure conditions of the general experiment of Dubey et al. [6]. The results are shown in Fig. 6. The pressure conditions are 3, 7.5, 10 and 55 bar. Compared with the reasonable predictions of the two-phase flow rates, the performance of void fraction predictions are quite different for each pressure conditions. The void fractions are overpredicted for low pressure conditions as shown in Fig. 6(a) to 6(c) but it is much better for higher pressure as shown in Fig. 6(d).

Also, as generally expected, HEM void model is most overpredicting. However, the drift flux model is in best agreement with the experimental data for higher pressure. The slip ratio and drift flux void models show nearly similar performances.

3.2. Parametric study on the ERVC parameters

3.2.1. ULPU Geometry.

The two TPNC models are applied to a parametric study on natural circulation flow rate for the ULPU geometry by varying ERVC related design parameters in Fig. 1 such as riser length, annular gap and inlet subcooling with the other parameters are fixed. The ranges of parameter values considered are presented in Table 2.

Table 2: ERVC related design parameter ranges considered

Parameter (Unit)	Values
Environment pressure (atm)	1.0
Riser diameter (m)	0.152
Heated length (m)	3.14
Riser length (m)	2~6
Annular gap clearance (m)	0.15~3
Inlet subcooling (K)	3.0~10.0

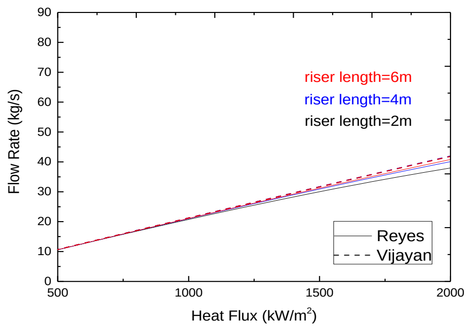


Fig. 7. Comparison of the two models with riser length as a parameter.

The calculation results are presented in Figs. 7-9 for the variation of the three design parameters. It can be observed from these figures that for heat flux lower than 2MW, predictions by using the two TPNC models are very close to each other. For heat flux larger than 2MW, a slight difference between the two predictions is observed except for a little larger discrepancy for low subcooling as shown in Fig. 9: in case of lower subcooling, the flow rate from the Reyes model is smaller than that from the Gartia model. This is clearly due to differences of void fractions predicted by the two models. However, it seems that there is no problem in applying the two models because the average heat flux estimated for a nuclear power plant is usually less than 1500kW/m^2 and the inlet subcooling is expected more than 7 K.

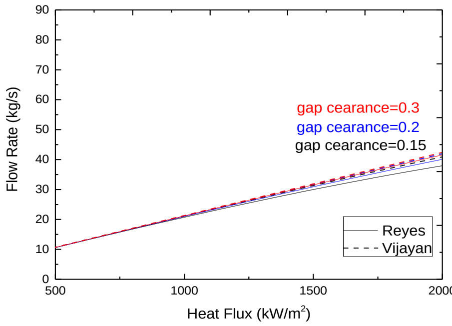


Fig. 8. Comparison of the two models with gap as a parameter.

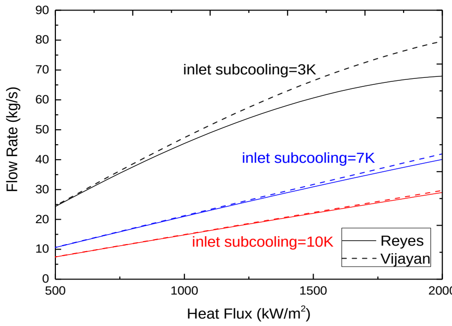


Fig. 9. Comparison of the two models with subcooling as a parameter.

3.2.2. Application to a plant scale.

As shown in Fig. 1, in the reactor conditions of the OPR1000 and APR1400, there is an abrupt change in the flow areas from the reactor cavity to the inlet hole and this may retard the flow due to minor loss. Also, the annular gap between reactor vessel and the thermal insulation is limited due to a constraint of short distance from the reactor vessel to the cavity wall.

Therefore, the effects of the minor loss at the flow inlet hole and the annular gap on the natural circulation flow are examined for the APR1400 geometrical conditions using the modified Reyes model. Reference 2 can be referred to for the dimensions and thermal conditions used.

Figure 10 shows that the flow rate decreases as the inlet form loss increases. For lower inlet flow subcooling (less than 10 K), the effect of the loss coefficient is dominant. For higher subcooling (greater than 10 K), however, the effect is small. In order to obtain large natural circulation flow, high subcooling should be obtained with deep water in the cavity or a design to minimize inlet form loss.

Figure 11 shows that the natural circulation flow rate increases as the gap clearance between the reactor and the insulation increases for subcooling less than approximately 3 K. However, for higher subcooling (greater than 5 K), the flow rate is loosely dependent on gap size for subcooling greater than 5 K. The gap clearance may not be a critical factor for high subcooling.

Also, Figs. 10 and 11 show that for low subcooling, the flow rate decreases due to increased two-phase pressure drop.

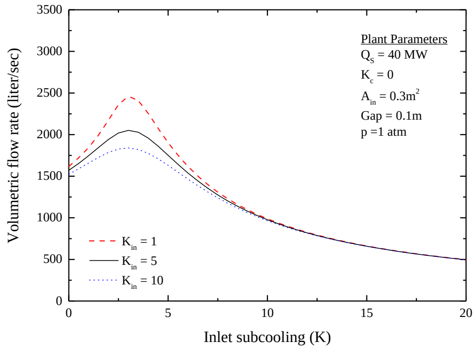


Fig. 10. Effect of the inlet loss coefficient on the volumetric flow rate.

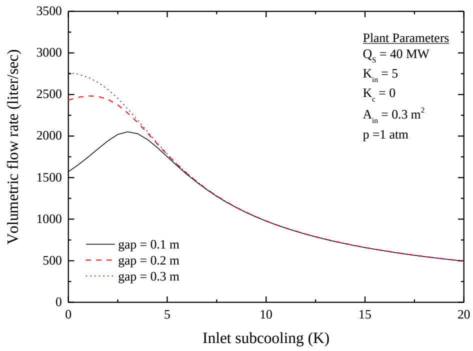


Fig. 11. Effect of the annular gap clearance on the volumetric flow rate.

4. Conclusion

Using the flow models and correlations are integrated into a computer program, TPNCIRC, a number of correlations have been examined. The results of the circulation were similar for design parameters such as riser length, gap. In case of subcooling is 3K, however, Reyes model is smaller than that from Gartia model. This seems coming from the differences of void fractions predicted by the two models. The Two TPNC models incorporating drift flux void model gives the best agreement with experimental data. Generally, the circulation results show that reasonable agreement.

REFERENCES

[1] J. W. Park, Analytical evaluation of two-phase natural circulation flow characteristics under external reactor vessel cooling, Annals of Nuclear Energy 36, pp. 1668-1675, 2009.

[2] J. N. Reyes, Scaling single-phase variable catastrophe functions: an application to two-phase natural circulation. Nuclear Engineering and Design, 151, pp. 41-48, 1994.

[3] M. R. Gartia, P. K. Vijayan, D. S. Pilkhwa, A generalized flow correlation for two-phase natural circulation loops. Nuclear Engineering and Design, 236, pp. 1800–1809, 2006.

[4] P. K. Vijayan, M. R. Gartia, G. S. S. P. Rao, D. S. Pilkhwal, D. Saha, Steady state behavior of single-phase and two-phase natural circulation loops, 2nd RCM on the IAEA CRP on Natural circulation phenomena, modeling and reliability of passive systems that utilize natural circulation, Corvallis, USA , 2005.

[5] A. K. Nayak, P. Dubey, D. N. Chavan, P. K. Vijayan, Study on the stability behaviour of two-phase natural circulation systems using a four-equation drift flux model, Nuclear Engineering and Design 237, pp. 386-398, 2007.

[6] P. Dubey, G. S. S. P. Rao, D. S. Pilkhwal, P. K. Vijayan, D. Saha, Analysis of experimental data on two-phase natural circulation from the flow pattern transition instability facility at Apsara reactor, BARC/2004/E/031.

[7] T. N. Dinh, J. P. Tu, T. Salmassi, T. G. Theofanous, Limits of coolability in the AP 1000-related ULPU-2400 configuration V facility, University of California, Santa Barbara 6740 Cortona Drive, Goleta CA 93117, CRSS-03/06, 2003.

[8] W. H. McAdams,W.K. Wood, R. L. Bryan, Vaporization inside horizontal tubes II-benzene–oil mixtures. Trans. ASME 66, 671–684, 1942.

[9] D. Chisholm, A theoretical basis for the Lockhart-Martinelli correlation for two-phase flow, Int. J. Heat Transfer, Vol.10, pp. 1767-1778, 1967.

[10] C. K. Rice, The effect of void fraction correlation and heat flux assumption on refrigerant change inventory predictions, ASHRAE transactions, Volume 93, No.3035, 1987.

[11] M. Ishii, One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes. ANL-77-47, USA, 1977.