HEAT AND MASS TRANSFER IN NUCLEATE BOILING REGIME OF HE I IN A NATURAL CIRCULATION LOOP

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ABSTRACT

This paper is devoted to the experimental study of He I natural circulation loop under nucleate boiling conditions, which simulates the cooling system of the 4 Tesla superconducting solenoid CMS under construction at CERN for the LHC. The test section consists of an electrically heated copper tube of 0.10-m ID and 0.95-m long. Uniform heat fluxes in the range of 0-2000 W/m^2 were employed. All data were generated near atmospheric pressure. Reported are results of the boiling curves and the effect of heat flux on the heat transfer coefficient under boiling. An attempt is carried out to predict the boiling incipience and to correlate the heat transfer coefficient based on the combining effect of forced convection and nucleate boiling by a power-type asymptotic model.

KEYWORDS: He I, nucleate boiling, heat transfer coefficient, boiling incipience
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INTRODUCTION

Two-phase natural circulation loops commonly called thermosyphons are thermo-fluid-dynamic systems mainly used to the refrigeration of a heat source by means of buoyancy driven motion of a fluid in a loop, instead of mechanical pumping. They are able to generate larger circulation rates compared to single-phase loops and therefore capable of larger heat transfer rates. In view of this, thermosyphons have large industrial applications in energy plants as nuclear reactor, electrical machines and superconducting magnets.

The present study deals with heat and mass transfer of a two-phase thermosyphon flow in liquid helium I (4.2 K), which is the cooling method for a high-energy physics particles detector, the solenoid CMS under construction at CERN, Geneva.

In most of industrial applications, a subcooled liquid enters at the bottom of the heated section and receives the sensible heat as it moves upward. Since the wall temperature, although higher than the saturation temperature, is below the value required for bubble nucleation, the heat is removed by a liquid single phase convection mechanism. When, the wall temperature reaches a superheat high enough to initiate nucleation, boiling sets in at the surface even if the bulk liquid is still subcooled. The liquid temperature continues to increase until the saturation; the saturated nucleate boiling regime begins with the existing of a net vapor generation which increases with the tube high; resulting in a bubbly to annular flow regime. The point of appearance of two-phase flow is called the point of incipience of nucleate boiling regime. It divides the heated tube into a single phase and a two-phase zone, each characterized by different mode of heat transfer. Consequently, it is of primary importance in the design of thermosiphon based cooling system, to predict the point of the onset of nucleate boiling and the heat transfer coefficient associated with each flow regime.

The literature review reveals that many investigations of two-phase natural flow, mainly for water, refrigerants, and organic fluids, have been performed [1].

Baudouy was the first to investigate a two-phase heat transfer coefficient in a He I thermosyphon loop [2]. He proposes a correlation based on the Martinelli method developed for annular flow pattern under forced flow conditions. This correlation considers the two-phase convective effect and neglects the nucleate boiling contribution which enhances significantly the heat transfer coefficient. Thus, the present paper is aiming to provide a correlation for the two-phase heat transfer coefficient in boiling flow thermosyphon loop under steady state conditions based on the superposition method coupling the action of forced convection and the wall nucleate boiling.

REVIEW OF HEAT TRANSFER COEFFICIENT MODELS

Three distinct regions are found in boiling forced-convection curve according to the *$q/\Delta T$* slope variation. At low heat flux, the heat transfer is governed by single phase forced convection laws. At moderate heat flux the heat transfer is determined by the combined effects of forced convection and surface boiling. At high heat flux, all nucleation sites on the heated surface are activated, the effect of forced convection disappears, and the heat transfer is transmitted only by nucleate boiling.

Empirical relationships developed to estimate the heat transfer coefficient in convective boiling are an attempt to account the simultaneous effect of macro-convection associated to the bulk mass flow and nucleate boiling considering the liquid motion (microconvective agitation) behind a departing bubble from the wall. These models can be classified by how the nucleate boiling and forced convection coefficients are combined to obtain the two-phase heat transfer coefficient h_{TP}. The general power law is of the form:

$$h_{TP}=(h_{CV}^{n}+h_{EN}^{n})^{1/n} \text{ or } h_{TP}=((F.h_{CV,fo})^{n}+(S.h_{pool})^{n})^{1/n} \qquad (1)$$

where h_{CV} and $h_{CV,fo}$ are respectively the forced convection heat transfer coefficient based on the total mass flow rate and the liquid mass flow rate, h_{EN} and h_{pool} are respectively the nucleate boiling heat transfer coefficient associated to nucleate boiling flow and pool boiling configuration, F is the amplification coefficient to express the increase of convective turbulence due to the presence of vapor phase, and S is the suppression coefficient to reflect the fact that nucleation conditions in forced convection is lower compared to pool boiling conditions, due to a thinner boundary layer.

A number of flow boiling correlations published are only variations of Equation (1) such as that proposed by Rohsenow [3], Chen [4], Shah [5], Winterton and co-workers [6, 7] and Kandlikar [8].

Most of them are only reliable for system conditions very close to the experiments from where they originate. Consequently, a general correlation of boiling data does not seem possible because the strong influence of parameters and properties affecting heat transfer in boiling, which are not readily controlled, is not taking in account.

Recently, an effort was carried out by Steiner *et al.* to derive a universal correlation reviewing an extensive data base (water, hydrocarbons, refrigerants, and cryogens) [9]. They attempt to obtain a general distribution of the data bank over the whole range of boiling conditions (reduced pressures, quality, flow rates ...), that is why, it has been considered the best one available.

PROPOSED MODEL

The model proposed in this paper assumes that both nucleation and convective mechanisms occur to some degree over the entire boiling curve and the contribution of each one is made by:

$$h_{TP}=(h_{CV}^3+h_{EN}^3)^{1/3} \tag{2}$$

The exponent 3 in Equation (2) reflects that $h_{TP} \rightarrow h_{CV}$ when h_{CV} is the dominant term (single phase none boiling region) and $h_{TP} \rightarrow h_{EN}$ when h_{EN} is the preponderant term (fully developed boiling region).

The convective component h_{CV} has been calculated using Petit and Taine's correlation in order to take account of the fact that the flow in our configuration is under development hydrodynamically and thermally:

$$h_{CV} = 0.023 \mathrm{Re}_f^{\ 0.8} \mathrm{Pr}_f^{\ 0.4} \left(\frac{\lambda_f}{D}\right)\left(1 + 6\frac{D}{z}\right) \tag{3}$$

where D is the tube diameter, z is the channel height, λ_f is the liquid thermal conductivity, Pr_f is the liquid Prandtl number, Re_f is the liquid Reynolds number evaluated using the total mass flow rate [10].

The nucleate boiling heat transfer coefficient h_{EN} was determined; either from our nucleate boiling flow data correlation or by applying Steiner's nucleate boiling correlation.

Proposed Nucleate Boiling Correlation

In the fully developed nucleate boiling region, it might be expected that the main flow velocity would have a little effect on the rate of heat transfer because the dominant mechanism is the high local velocities induced by bubble mixing near the wall [11, 12]. The relation between heat flux and temperature can be expressed in a similar manner to that in pool boiling (Rohsenow [13] or Kutateladze [14]), A typical form used here, is

$$q_{EN} = \psi.(T_w - T_{sat})^m \tag{4}$$

where T_w is the wall temperature, T_{sat} the saturation temperature, and ψ is a parameter containing the effect of pressure, physical properties and the wetting characteristics of surface-fluid combination. m is ranging from 2 to 4 in various published correlations. In this study, the best fit according to Equation (4) for our fully developed nucleate boiling data were obtained with m=3 and ψ=82000 within the accuracy of 10%. From Equation (4), we have

$$h_{EN} = \psi^3 q^{\frac{2}{3}} \Leftrightarrow h_{EN} = Cq^{0.66} \qquad (5)$$

Steiner Nucleate Boiling Correlation

Owing to his analysis, Steiner identifies explicitly the influence of the heat flux q, vapor quality x, tube diameter D, saturation pressure and surface roughness R_w upon nucleate boiling heat transfer coefficient [15]. He proposed the following correlation:

$$h_{EN} = h_0 \left\{ c_F \left(\frac{q}{q_0} \right)^{0.7-0.13\times10^{0.48p^*}} \left[1.66p^{*0.45} + \left(2 + \frac{1}{1-p^{*7}} \right) p^{*3.7} \right] \left(\frac{D_0}{D} \right)^{0.4} \left(\frac{R_w}{R_{w0}} \right)^{0.13} \right\} \qquad (6)$$

where: $c_F = 0.35M^{0.24}$ (c_F = 0.57 for helium);

$p^* = \dfrac{p}{p_c}$ is the reduced pressure;

q_0, D_0, h_0, and R_{w0} are the nucleate flow boiling coefficients at a reference state [15].

EXPERIMENTAL SET-UP

The experimental facility used for the study has been described in detail in [2]. The main unit is composed of two vertical tubes joined in a U shape with the upper ends connected to the vapor-liquid separator forming a thermosyphon loop. The test section used for this study is constructed from copper tube of 0.10 m in diameter and is uniformly heated. 2 mm diameter holes for static pressure taps were drilled into the tube at either end of the heated length. Germanium thermometers were used to measure local inside-wall temperature of the tube and to deduce the local heat transfer coefficient ($h=q/\Delta T$).

RESULTS AND DISCUSSION

Nucleate Boiling Curve

FIGURE 1 presents typical boiling curves, which are the variation of heat flux q with the wall superheat *i.e.* the temperature difference between the heated surface T_w and the fluid, T_f, at different tube heights, noted z. Three heat transfer regimes can be identified. In the first zone AB, heat flux rises linearly with wall superheat and no bubbles are formed, the heat is removed by single-phase liquid (SPL) forced convection. At B the wall temperature reaches a superheat high enough to initiate nucleation and the temperature difference would suddenly decrease due to liquid mixing near the wall induced by bubble detachment. More investigations are needed to conclude whether our measurements exhibit such behavior. In the knee zone BC, the heat flux rises at a fast rate with ΔT indicating the

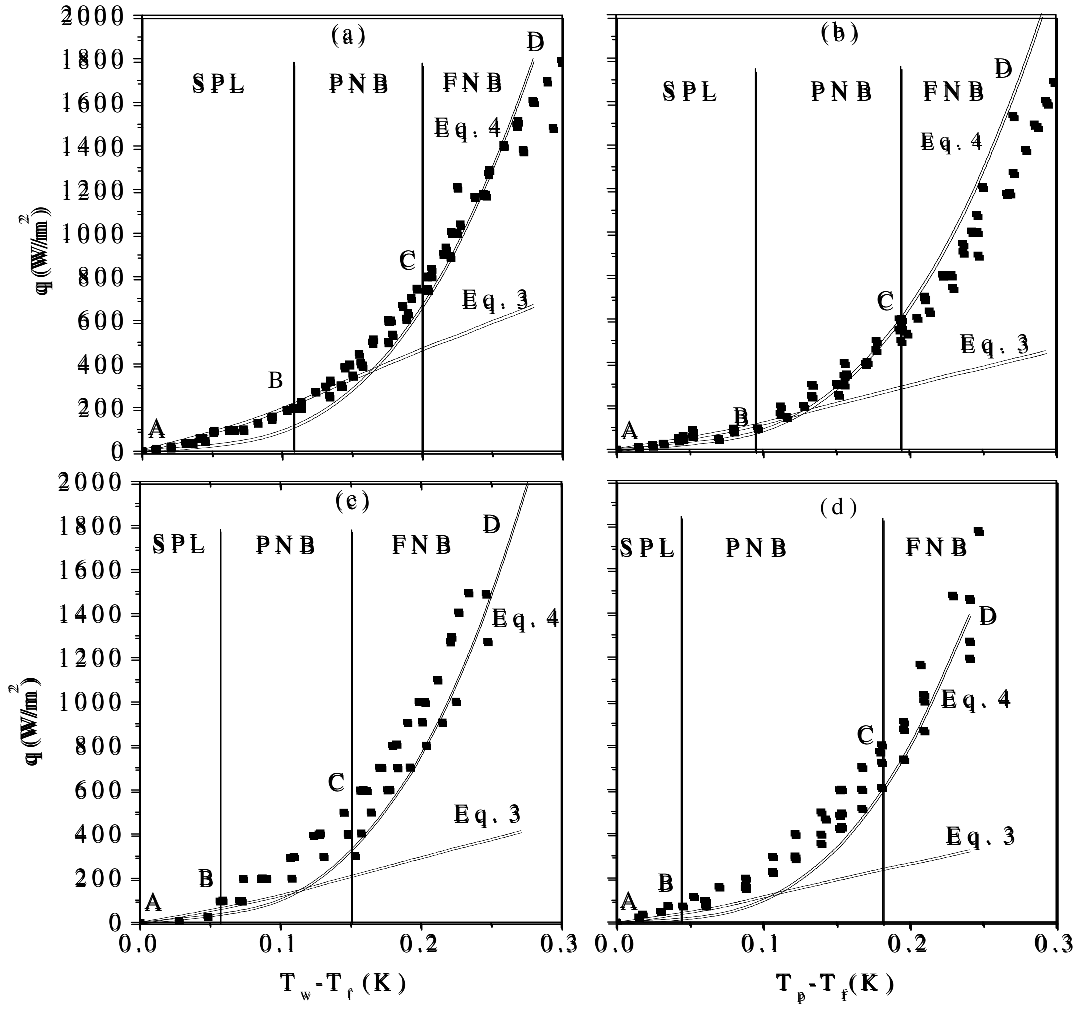

FIGURE 1. Boiling curves at (a) z=0.07 m, (b) z=0.3 m, z=0.76 m, and (c) z=0.9 m channel height.

onset of partial nucleate boiling region (PNB) where a fraction of the heated surface is covered by bubbles and the other part is still subjected to convective heat transfer. Along the path CD, more and more nucleation sites are activated and the heat flux steeply increases with the wall temperature difference representing the fully developed nucleate boiling region (FNB). Here, the wall is completely covered by bubbles and the heat transfer will be entirely governed by nucleate boiling.

Nucleate Boiling Incipience

The point of onset of nucleate boiling is determined readily from the slope change between the two first regions (SPL) and (PNB). As it can be seen from FIGURE 1, nucleation occurs first towards the exit of the heated section and while increasing heat flux, the point of boiling incipience shifts towards tube inlet. In our experiments, the wall superheat corresponds to the point B which is around 0.11 K for z=0.07 m, 0.08 K for z=0.3 m, 0.06 K for z=0.76 m, and 0.049 K for z=0.9 m. These values are much higher than those predicted by Graham and Hsu [16]. This is presumably because the process of bubble nucleation is suppressed by the induced flow as it will be discussed below.

Theoretical analysis developed in literature to predict the incipient point of boiling are based on the Gibb's equilibrium theory of bubble in the uniformly superheated liquid and a one dimensional steady or transient heat conduction equation. It was postulated that in the liquid film adjacent to the heating surface, the superheated layer, δ, must attain a threshold

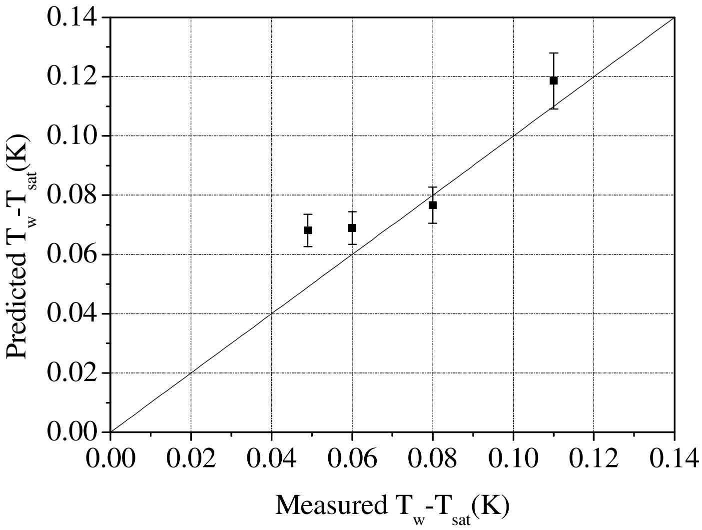

FIGURE 2. Wall superheat needed to onset nucleate boiling predicted by Equation (8) compared to our results

value so that the critical bubble nuclei with radius r_c can further grow to the point of detachment. Hence, the superheat required for nucleation is given by:

$$T_w - T_{sat} = \sqrt{\frac{8\sigma T_{sat} q}{k_l \rho_v h_{fg}}} \tag{7}$$

where T_{sat}, σ, k_l, h_{fg}, ρ_v are respectively the saturation temperature, surface tension, liquid thermal conductivity, latent heat of vaporization, and the vapor density.

Boiling incipience depends strongly on forced convection. With increasing mass flow rate, thermal boundary layer becomes thinner and linear temperature gradient within it is not sufficient to allow bubble formation, thus nucleation is delayed. Recently, investigations have been carried out by Kamil *et al.* to identify the experimental conditions of boiling incipience in natural circulation loop using water and organics fluids [17]. They correlate them to relevant parameters such as heat flux, subcooling, and liquid submergence. The liquid submergence is the ratio of the liquid level in the cold part of the loop (down flow pipe + phase separator) to the length of the test section expressed in percentage value. They pointed out that the driving head available in the downcomer tube is influenced by the liquid submergence. So, the circulation rate depends upon liquid submergence in addition to heat flux, inlet liquid subcooling, vapor quality, and frictional resistance. At a given heat flux, they found that degree of superheat needed to onset nucleate boiling increases with increasing liquid submergence. Therefore, it is important to include the effect of submergence in the prediction of wall superheat required to nucleation. Kamil *et al.* have proposed the following correlation:

$$T_w - T_{sat} = \sqrt{\frac{8\sigma T_{sat} q}{k_l \rho_v h_{fg}}} S^{0.67} \tag{8}$$

In our case, experiments were conducted with S=95%. FIGURE 2 depicts the wall superheat calculated by Equation (8) against the measured one at different channel heights. It predicts our experimental values with a mean error of 16%.

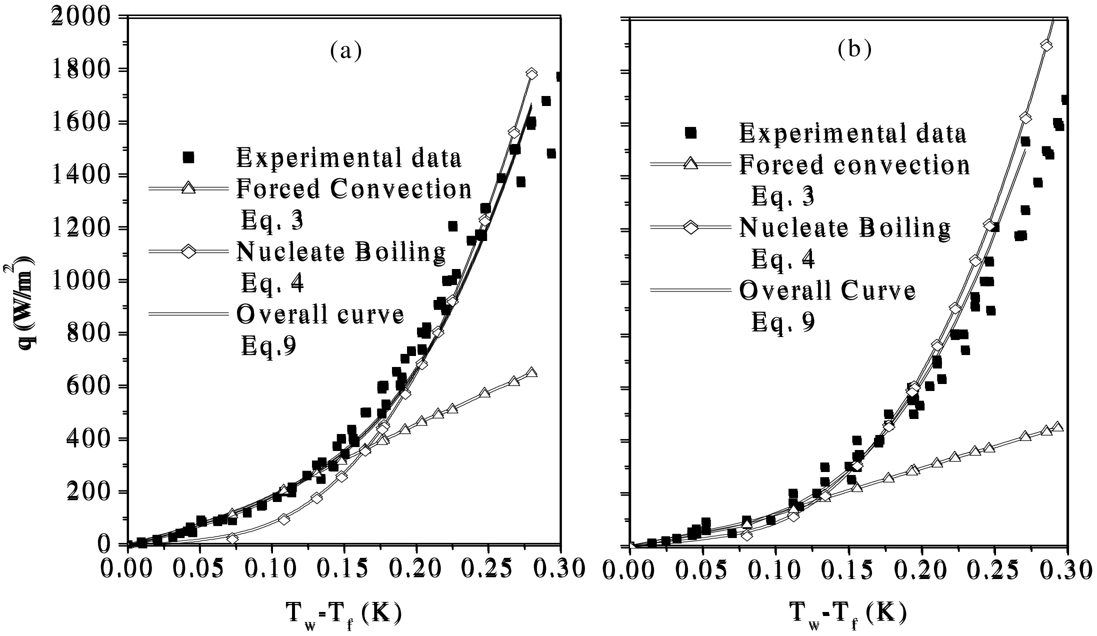

FIGURE 3. Boiling Curves at (a) z=0.07 m and (b) z=0.3 m channel height predicted by the proposed model using our nucleate boiling flow data.

FIGURE 3 shows boiling curves at z=0.07 m and z=0.3 m predicted by the proposed model using our nucleate boiling data correlation for h_{EN}. The total heat transfer flux is given by a combined effect of the heat flux due to the bubble motion and forced convection following a power law:

$$q = \left(q_{CV}{}^{3} + q_{EN}{}^{3}\right)^{1/3} \tag{9}$$

One can see that boiling curves predicted by Equation (9) merge with the forced convection curve at low wall superheat and with the fully developed boiling curve at relatively high wall superheat. The transition region is fitted within 15% accuracy.

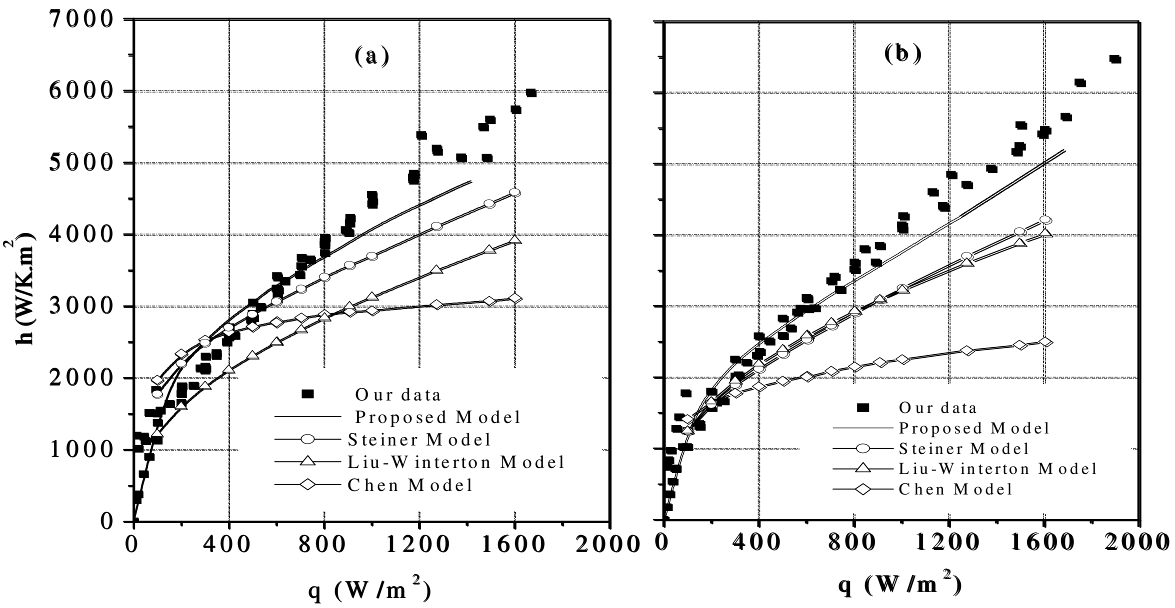

FIGURE 4. Comparison of prediction heat transfer coefficient with correlations in [4], [7], and [9] at (a) z=0.07 m and (b) z=0.3 m channel height.

Comparison of Existing Correlations with the Proposed Model

Three kinds of heat transfer correlations for saturated boiling flow are widely used in literature, one by Chen, using addition of two components corresponding to the two mechanisms (forced convection and nucleate boiling) with the introduction of an amplification factor F and a suppression factor S, one by Liu-Winterton who pointed out deficiencies of Chen's correlation, and developed a new approach following Equation (1) with n=2, and another one by Steiner-Taboreck applying Equation (1) with n=3. Here a comparison is made with our model using Equation (3) for h_{CV} and Equation (6) for h_{EN}. The comparison results are reported in FIGURE 4. In average our proposed model gives the best predictive accuracy of 18% among the tested correlations. The second is the Steiner-Taboreck model with 25% followed by the Liu-Winterton model with 28% and the Chen model with 40% finally. It can be noted that the tested correlations, originally developed in forced flow, underestimate our heat transfer coefficient data. This is due to the fact that flow in circulation loop is always under development, as it was noted in [2].

CONCLUSION

The present paper investigates experimentally heat and mass transfer of He I in a natural circulation loop under nucleate boiling conditions. The boiling curves demonstrate clearly the existence of three heat transfer regions: single phase forced convection region, partial nucleate boiling region and fully developed nucleate boiling region. They were examined in detail to predict heat transfer coefficient along the whole boiling curve by a power type asymptotic model combining the effect of forced convection and nucleate boiling heat transfer. The proposed model tends to a single phase forced convection model in low wall superheat region and to a fully developed nucleate boiling model in high wall superheat region. In the transition region both forced convection and nucleate boiling coexist and contribute to the heat exchange. Besides, an attempt was carried out to predict the point of onset of nucleate boiling using Kamil *et al*. correlation developed in the case of natural circulation loop. It predicts our results within 16% average error.

REFERENCES

1. Zvirin, Y., *Nuclear Engineering and Design*, **67**, 203-225, (1981).
2. Baudouy, B., "Heat and mass transfer in two-phase He I Thermosiphon flow", *in Advances in Cryogenic Engineering* 47B, edited by S. Breon, AIP, 2001, pp. 1514-1521.
3. Rohsenow, W.M., *Heat transfer,* University of Michigan Press, 1953.
4. Chen, J. C., *Ind Engng Chem. Proc. Des. Dev*, **5**, pp. 322-329, (1966).
5. Shah, M. M., ASHRAE *Trans*., **82(2)**, pp 66-86, (1976).
6. Gungor, K. E., Winterton, R.H.S., *Int. J. Heat Mass Transfer*, **29**, pp 351-358, (1986).
7. Liu, Z., Winterton, R.H.S., *Int. J. Heat Mass Transfer*, **34**, pp. 2759-2766, (1991).
8. Kandlikar, S.G., *J. Heat Transfer*, **112**, pp 219-228, (1990).
9. Steiner, D., Taborek, J., Heat transfer Engng, **13(2)**, pp. 43-69, (1992).
10. Taine, J., Petit, J.-P., Transferts thermiques – Mécanique des fluides anisothermes, Dunod, (1989).
11. Collier, J.G., Thome, J.R., *Convective boiling and condensation*, 3rd Ed. Oxford University Press, 1994.
12. Tong, L.S., Tang, Y.S., *Boiling heat transfer and two-phase flow,* 2nd Ed. Taylor & Francis, 1997.
13. Rohsenow, W.M., *Trans. ASME*, **74**, pp 669-976, (1952).
14. Kutateladze, S. S., *Int. J. Heat Mass Transfer*, **4**, pp. 3-45.
15. Steiner, D., *Cryogenics*, **26**, pp. 309-318, (1986).
16. Hsu, Y.-Y., Graham, R. W., Transport processes in boiling and two phase systems: including near-critical fluids, U.S.A.: American Nuclear Society, 1986.
17. Kamil, M., Alam, S.S., Ali, H., *Int. J. Heat Mass Transfer*, **(38) 4**, pp. 745-748, (1995).