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A UNIFIED APPROACH TO CALCULATE STEADY STATE FLOW RATE IN SINGLE-PHASE, TWO-PHASE AND ADIABATIC NATURAL CIRCULATION LOOPS

M.R. Gartia
Bhabha Atomic Research Centre
Reactor Engineering Division,
Trombay, Mumbai 400085
Phone: +91-22-25592598
Email: manas_gartia@yahoo.co.in

P.K. Vijayan
Bhabha Atomic Research Centre
Reactor Engineering Division,
Trombay, Mumbai 400085
Phone: +91-22-25595157
Email: vijayanp@barc.gov.in

D.S. Pilkhwal
Bhabha Atomic Research Centre
Reactor Engineering Division,
Trombay, Mumbai 400085
Phone: +91-22-25591509
Email: pilkhwal@barc.gov.in

D. Saha
Bhabha Atomic Research Centre
Reactor Engineering Division,
Trombay, Mumbai 400085
Phone: +91-22-25593836
Email: dsaha@barc.gov.in

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ABSTRACT

Derivation of a steady state flow correlation valid for both single- and two-phase natural circulation systems has been presented earlier by the authors. In the present paper, we present an exact analytical expression for the steady state flow rate in an adiabatic natural circulation loop based on the same methodology followed for single-phase and two-phase loops. Then the nondimensionalization procedure followed is extended to adiabatic loops to obtain an explicit correlation for the flow rate as the function of a single dimensionless parameter and having the same form as that for single-phase and two-phase natural circulation loops (NCLs). Subsequently, experimental data compiled from literature were compared with the theoretical correlations for steady state flow rate. The paper presents the details of the nondimensional correlations derived, the experimental data used for the assessment of the correlations and the results obtained.

1. INTRODUCTION

The applications of natural circulation loops are widespread. Both single-phase and two-phase natural circulation systems are important for nuclear industry. Single-phase NC is used for decay heat removal in PWRs, VVERs and PHWRs during upset conditions like pumping power failure. Compared to single-phase systems, two-phase systems are capable of generating larger buoyancy force and hence larger flow rates. Typical industrial applications of two-phase systems are Natural Circulation Boiling Water Reactors (NCBWRs), Natural Circulation Boilers (NCBs) in fossil fuelled power plants, Natural Circulation Steam Generators (NCSG) in PWRs & PHWRs and thermosyphon reboilers in chemical process industries. Recently the gas driven circulation enhancement has gained momentum due to its use in the design of a hybrid nuclear reactor based on the accelerator driven subcritical system (ADSS) which is innovative and inherently safe and having the added advantage of ability to transmute the nuclear waste of present commercial nuclear plants, leading to significant reduction of the amount of radiotoxicity.

The primary function of a natural circulation loop is to transport heat from a source to a sink. Generally, the heat sink is above the heat source to enhance the circulation rates. The circulation is passive in nature and can continue as long as the heat source and heat sink are maintained without the use of any moving parts (in case of gravitational body force). Due to this, NCLs find application in many industrial fields. General reviews on single-phase NCLs have been given by Japikse (1973), Zvirin (1981), Mertol and Greif (1985) and Greif (1988). The heat transport capability of natural circulation loops is directly proportional to the flow rate it can generate. Hence reliable prediction of the flow rate is essential for the design and performance evaluation of natural circulation loops. Generally the prediction methods are available in dimensionless groups form (or scaling parameters) which are not loop specific. Such dimensionless groups are useful in comparing the performances of different loops and to extend data from small scale loops to the prototype.

2. REVIEW OF SCALING LAWS

2.1 Single-phase natural circulation loops

Considerable work has already been done in this field previously by Welander (1967), Creveling et al. (1975), Chen (1983), Bau and Torrance (1981), Huang and Zelaya (1988), Vijayan et al. (1992) for uniform diameter loops. By testing against data Vijayan and Austregesilo (1994) has shown that the dimensionless groups proposed hold good for uniform diameter loops. Most practical applications of NCLs, however, employ loops of non-uniform diameter. Hence, the non-dimensionalisation procedure described in Vijayan and Austregesilo (1994) was extended to non-uniform diameter loops (Vijayan (2002)). Vijayan (2002) showed that simulation of steady state flow rate in single-phase NCLs (uniform or non-uniform) can be achieved by simulating just one non-dimensional parameter.

2.2 Two-phase natural circulation loops

Pioneering work in the field of scaling laws for two-phase natural circulation systems have been carried out by Nahavandi et al. (1979), Zuber (1980), Heisler (1982), Ishii and Kataoka (1984), Kocamustafaogullari and Ishii (1987), Schwartzbeck and Kocamustafaogullari (1989), Yadigaroglu and Zeller (1994), Reyes Jr. (1994) and Vijayan et al. (1999). Further non-linear analysis of two-phase NCLs to obtain the flow rate using homogeneous model has been done by Lin and Chin Pan (1994) and by Jeng and Chin Pan (1999) using drift-flux model. With many of the reported nondimensionalization procedures, the resulting dimensionless groups are too many and it is not possible to explicitly obtain the flow rate as a function of the different dimensionless groups. The authors were successful in explicitly expressing the flow rate in two-phase loops as a function of a single dimensionless group (Vijayan et al. (2000)). Later Gartia et al. (2006) presented an exact analytical expression for the two-phase flow rate based on the same methodology followed for single-phase loops and having the same form as that for single-phase NCLs.

2.3 Adiabatic natural circulation loops

A rather simple and low cost method to get a high flow rate in a pool type system without a mechanical pump consists of gas injection into a liquid flowing up inside some risers. The circulation of the fluid is similar to the fluid dynamic process of chemical high-recirculation airlift reactors that is adopted in some chemical and biotechnological industry to carry out slow reactions like oxidations, chlorinations, wastewater treatment and can also be applied to the generation of secondary flow in heat transfer equipment inside a water pond. The fluid circulation is driven by the density difference between a riser, where a two-phase flow occurs (typically with a bubble flow pattern), and a downcomer. These facilities are characterized by a simple loop construction with no moving parts and low (pneumatic) energy supply. The magnitude of liquid circulation for a given gas flow rate is one of the most important design parameters for such systems. Though many experiments related to such adiabatic natural circulation loops have been performed in recent times (Ambrosini et al. (2004, 2005), Salve et al. (2004) and Rao et al. (1999)), to the authors' knowledge, explicit dimensional correlations for steady state flow are still not available.

In the present paper, we present an exact analytical expression for the flow rate in an adiabatic natural circulation loop based on the same methodology followed for single-phase and two-phase loops. Then the nondimensionalization procedure followed is extended to adiabatic loops to obtain an explicit correlation for the flow rate as the function of a single dimensionless parameter and having the same form as that for single-phase and two-phase NCLs. Subsequently, experimental data compiled from literature were compared with the theoretical correlations for steady state flow rate. The paper presents the details of the nondimensional correlations derived, the experimental data used for the assessment of the correlations and the results obtained.

3. THEORETICAL DEVELOPMENT

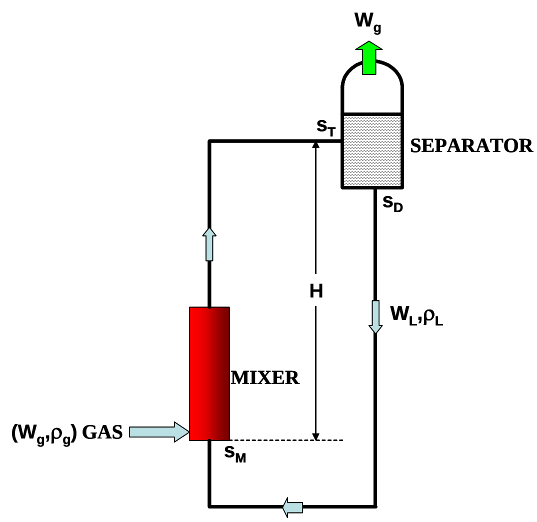

Fig.1: Schematic of adiabatic NCL

The theoretical development described below is based on homogeneous equilibrium model and is valid for both uniform as well as non-uniform diameter adiabatic natural circulation loops. The geometry and coordinate system considered for the theoretical analysis is described in Fig. 1.

The following assumptions are made in the theoretical development.

- Complete separation of gas and water is assumed to occur in the separator so that there is no liquid carryover with the steam and no vapor carry-under with water.
- A constant level is maintained in the SD, so that the single-phase lines always run full.

The one-dimensional steady state Navier-Stokes equations for adiabatic natural circulation system can be written as follows:

Continuity equation: $W = W_l + W_g$

$$W_l = (1-x)W \; ; \; W_g = xW \tag{1}$$

Momentum equation:

$$\frac{W^2}{A^2}\frac{d}{ds}\left(\frac{1}{\rho}\right) = -\frac{dP}{ds} - \rho\, g \sin\theta - \frac{f\,W^2}{2D\rho A^2} - \frac{K\,W^2}{2\,\rho\,A^2 L_t} \tag{2}$$

Where θ is the angle with the horizontal in the direction of flow. The second term on the right hand side of equation (2) represents the body force per unit volume whereas the third and fourth terms respectively represent the distributed and the local friction forces per unit volume. Noting that $v = 1/\rho$ and integrating the momentum equation around the circulation loop

$$\frac{W^2}{A^2}\oint dv = -\oint dP - g\oint \rho\, dz - \frac{f\,W^2 L_t}{2D\rho A^2} - \frac{K\,W^2}{2\,\rho\,A^2} \tag{3}$$

Where $dz = ds \sin\theta$

Noting that $\oint dv = 0$ and $\oint dP = 0$ for a closed loop, we can write

$$0 = -g\oint \rho\, dz - \frac{f\,W^2 L_t}{2D\rho A^2} - \frac{K\,W^2}{2\,\rho\,A^2} \tag{4}$$

$$-g\oint \rho\, dz = \left(\frac{fL}{D}+K\right)_{sp}\frac{W_l^2}{2\,\rho_l A^2} + \left(\frac{fL}{D}+K\right)_{tp}\frac{W^2}{2\,\rho_{tp} A^2} \tag{5}$$

$$-g\oint \rho\, dz = \left(\frac{fL}{D}+K\right)_{sp}\frac{W_l^2}{2\,\rho_l A^2} + \phi_{LO}^2\left(\frac{fL}{D}+K\right)_{sp}\frac{W^2}{2\,\rho_l A^2} \tag{6}$$

$$-g\oint \rho\, dz = \left(\frac{fL}{D}+K\right)_{sp}\frac{(1-x)^2 W^2}{2\,\rho_l A^2} + \phi_{LO}^2\left(\frac{fL}{D}+K\right)_{sp}\frac{W^2}{2\,\rho_l A^2} \tag{7}$$

$$-g\left[\rho_l(-H) + \rho_{tp} H\right] = \frac{W^2}{2\,\rho_l}\left[\sum_{i=1}^{N_{sp}}\left(\frac{fL}{D}+K\right)_i\frac{(1-x)^2}{A_i^2} + \phi_{LO}^2\sum_{i=N_{sp}}^{N_T}\left(\frac{fL}{D}+K\right)_i\frac{1}{A_i^2}\right] \tag{8}$$

Now the above equations can be non-dimensionalized using the following substitutions:

$$\omega = \frac{W}{W_{ss}},\; Z = \frac{z}{H},\; S = \frac{s}{H},\; a_i = \frac{A_i}{A_r},\; d_i = \frac{D_i}{D_r},\; l_i = \frac{L_i}{L_t}$$

$$A_r = \frac{\sum_{i=1}^{N} A_i L_i}{\sum L_i} = \frac{V_t}{L_t},\quad D_r = \frac{\sum_{i=1}^{N} D_i L_i}{L_t},\quad \left(l_{eff}\right)_i = \frac{\left(L_{eff}\right)_i}{L_t} \tag{9}$$

$$K = \frac{fL_{eq}}{D},\quad f_i = \frac{p}{\mathrm{Re}_i^b} = \frac{p}{\mathrm{Re}_{ss}^b}\frac{\omega^{-b} a_i^b \mu_i^b}{d_i^b \mu_r^b},\quad \mathrm{Re}_{ss} = \frac{D_r W_{ss}}{A_r \mu_r}$$

$$L_{eff} = L_i + L_{eq} \quad \text{and} \quad \mu_r = \frac{\sum_i \mu_i L_i}{\sum_i L_i}$$

At steady state putting $\omega = \frac{W}{W_{ss}} = 1$, $\mu_i = \mu_r$ the non-dimensional equations will become

$$gH\left(\rho_l - \rho_{tp}\right) = \frac{W_{ss}^2}{2\rho_l A_r^2}\frac{p}{\mathrm{Re}_{ss}^b}\frac{L_t}{D_r}\left[\sum_{i=1}^{N_{sp}}\frac{\left(l_{eff}\right)_i}{d_i^{1+b} a_i^{2-b}}(1-x)^2 + \phi_{LO}^2\sum_{i=N_{sp}}^{N_T}\frac{\left(l_{eff}\right)_i}{d_i^{1+b} a_i^{2-b}}\right] \tag{10}$$

Putting

$$\rho_{tp} = \alpha\rho_g + (1-\alpha)\rho_l \quad and \quad N_G = \frac{L_t}{D_r}\left[\sum_{i=1}^{N_{sp}}\frac{\left(l_{eff}\right)_i}{d_i^{1+b} a_i^{2-b}}(1-x)^2 + \phi_{LO}^2\sum_{i=N_{sp}}^{N_T}\frac{\left(l_{eff}\right)_i}{d_i^{1+b} a_i^{2-b}}\right] \tag{11}$$

$$gH\alpha\left(\rho_l - \rho_g\right) = \frac{W_{ss}^2}{2\rho_l A_r^2}\frac{p}{\mathrm{Re}_{ss}^b}N_G \tag{12}$$

From definition of homogeneous void fraction,

$\alpha = \frac{Q_g}{Q_g + Q_l} = \frac{Q_g}{Q} = \frac{W_g}{\rho_g}\frac{\rho_{tp}}{W}$ since $W_g = \rho_g Q_g$ and $W = \rho_{tp} Q$ we have (13)

$$\frac{\rho_{tp} W_g}{\rho_g W_{ss}} gH\left(\rho_l - \rho_g\right) = \frac{W_{ss}^2}{2\rho_l A_r^2}\frac{p}{\mathrm{Re}_{ss}^b}N_G \tag{14}$$

$$W_{ss}^3 = \frac{2}{p}\mathrm{Re}_{ss}^b\frac{gH\left(\rho_l - \rho_g\right)\rho_l A_r^2}{N_G}\frac{\rho_{tp} W_g}{\rho_g} \tag{15}$$

$$\mathrm{Re}_{ss}^{3-b} = \frac{2}{p}\frac{D_r^3\, gH\left(\rho_l - \rho_g\right)\rho_l}{A_r\,\mu_r^3}\frac{\rho_{tp} W_g}{\rho_g}\frac{1}{N_G} \tag{16}$$

$$\mathrm{Re}_{ss} = \left[\frac{2}{p}\frac{Gr_m}{N_G}\right]^{\frac{1}{3-b}} \text{ where } Gr_m = \frac{D_r^3\, gH\left(\rho_l - \rho_g\right)\rho_l}{A_r\,\mu_r^3}\frac{\rho_{tp} W_g}{\rho_g} \tag{17}$$

3.1 Comparison of non-dimensional parameters

Single-Phase Natural Circulation Loop
$\mathrm{Re}_{ss} = \left[\frac{2}{p}\frac{Gr_m}{N_G}\right]^{\frac{1}{3-b}}$

$$Gr_m = \frac{D_r^3 g H \rho_r^2 \beta_T q_h}{A_r \mu_r^3 Cp} \ , \quad \beta_T = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p$$

$$N_G = \frac{L_t}{D_r}\sum_{i=1}^{N_t}\left(\frac{l_{eff}}{d^{1+b} a^{2-b}}\right)_i \tag{18}$$

Two-Phase Natural Circulation Loop

$$\mathrm{Re}_{ss} = \left[\frac{2}{p}\frac{Gr_m}{N_G}\right]^{\frac{1}{3-b}}$$

$$Gr_m = \frac{D_r^3 g H \rho_r \rho_l \beta_{tp} q_h}{A_r \mu_r^3} \ , \quad \beta_{tp} = \frac{1}{v}\left(\frac{\partial v}{\partial h}\right)_p$$

$$N_G = \frac{L_t}{D_r}\left[\begin{array}{l}\displaystyle\sum_{i=1}^{N_{sp}}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}} + \bar{\phi}_{LO}^2 \sum_{i=N_{sp}}^{N_{he}}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}} \\ \displaystyle + \phi_{LO}^2 \sum_{i=N_{he}}^{N_t}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}}\end{array}\right] \tag{19}$$

Adiabatic Natural Circulation Loop

$$\mathrm{Re}_{ss} = \left[\frac{2}{p}\frac{Gr_m}{N_G}\right]^{\frac{1}{3-b}}$$

$$Gr_m = \frac{D_r^3 g H (\rho_l - \rho_g)\rho_l}{A_r \mu_r^3}\frac{\rho_{tp} W_g}{\rho_g}$$

$$N_G = \frac{L_t}{D_r}\left[\sum_{i=1}^{N_{sp}}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}}(1-x)^2 + \phi_{LO}^2 \sum_{i=N_{sp}}^{N_T}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}}\right] \tag{20}$$

3.2 Algorithm to find the mass flow rate in adiabatic natural circulation loops

Given: W_g, P, T

1. Assume W
2. Calculate $x = W_g / W$
3. Calculate ρ_l, ρ_g corresponding to the system pressure (P) and temperature (T) of liquid and gas respectively.
4. Calculate $\rho_{tp} = \dfrac{\rho_l \rho_g}{\rho_g + x(\rho_l - \rho_g)}$
5. Calculate $\phi_{LO}^2 = \dfrac{\rho_l}{\rho_{tp}}\left[\dfrac{1}{1 + x(\mu_l/\mu_g - 1)}\right]^b$
6. $N_G = \dfrac{L_t}{D_r}\left[\displaystyle\sum_{i=1}^{N_{sp}}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}}(1-x)^2 + \phi_{LO}^2 \sum_{i=N_{sp}}^{N_T}\frac{(l_{eff})_i}{d_i^{1+b} a_i^{2-b}}\right]$
7. $W = \left[\dfrac{\rho_{tp} W_g}{\rho_g} gH(\rho_l - \rho_g)\dfrac{2\rho_l A_r^{2-b} D_r^b}{p \mu_r^b}\dfrac{1}{N_G}\right]^{\frac{1}{3-b}}$
8. Compare $\dfrac{W_{New} - W_{Old}}{W_{New}} \le 1\%$; Otherwise again assume W. Finally, $W_l = W - W_g$

4. EXPERIMENTAL VALIDATION

4.1 DIMNP Adiabatic NCL (Ambrosini et al. (2005))

The details of the experimental apparatus have already been described in Ambrosini et al. (2005). The schematic of the experimental set-up is shown in Fig. 2. The loop mainly consists of 1.5 in. i.d. stainless steel pipes connected by flanges. The riser is made of a 3m long tube, at whose bottom gas at ambient temperature is injected through an appropriate nozzle, thus making possible to study gas-injection enhanced circulation. Injected air is separated and vented at the top of the riser, through an expansion tank, having also the purpose to allow for thermal expansion of the fluid during transient operation.

Measuring instrumentation includes flow rate measurements for liquid and gas. The primary flow rate is measured by an ultrasonic flow meter (error≈±1.6%), placed on the bottom horizontal pipe of the loop. The air flow injected at the bottom of the riser is measured through a rotameter (error ≈±0.3%). Though both "hot test" (diabatic natural circulation) and "cold test" (adiabatic natural circulation) experiments were conducted in this loop, we have used only the cold test results for the comparison.

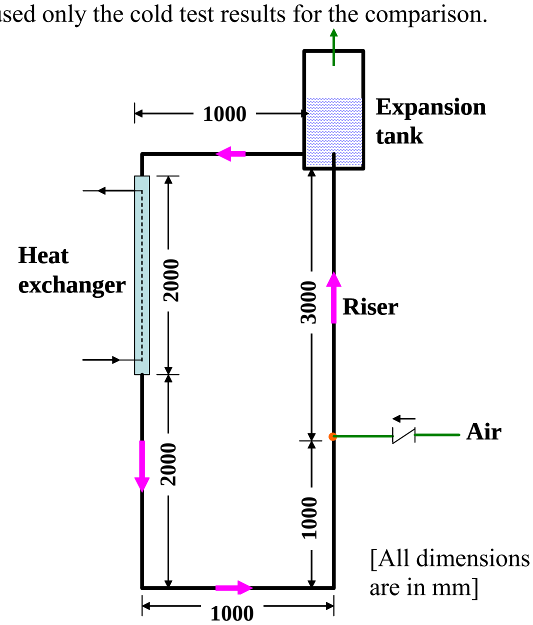

Fig. 2: Schematic of DIMNP Adiabatic NCL

4.2 Adiabatic Air-Water Loop (Salve et al. (2004))

The schematic of experimental set-up is shown in Fig. 3. The experimental apparatus consists of two vertical plexiglass pipes 3.8 m long, 0.08 m I.D., namely the riser and the downcomer, that are connected at the bottom by a horizontal pipe and at the top by a large open tank. The air is injected near the bottom of the instrumented test section (TS) and is separated at the top from the liquid free surface within the plexiglass tank. The air can be injected into the liquid either through a porous bronze device or a gas sparger with multiple small orifices. It is a typical external loop airlift system from a geometrical point of view. The mixing region between the injection point and the test section is a plexiglass pipe 0.42 m long, 0.08 m I.D.; downstream of the mixing region there is a ball valve 0.18 m long. The reference test section for the two-phase flow is a plexiglass pipe 0.08 I.D., 2.5 m long. Above the test section there is a second identical ball valve and a 0.52 m long pipe connected to the separation tank, to ensure separation of air without any special device at the liquid free surface which is at atmospheric pressure. The downcomer is a plexiglass vertical pipe 3.8 m long, 0.08 m I.D. The horizontal region of the loop is a 5.81 m long, 0.082 m I.D. This region includes a Venturi meter (throat diameter 0.0349 m) and four 90 ° bends (0.140 m radius). The single phase pressure drops are changed by inserting an orifice of known diameter across the horizontal pipe: two diameters (35 and 45 mm) have been tested. Further details of the loop can be found in Salve et al. (2004).

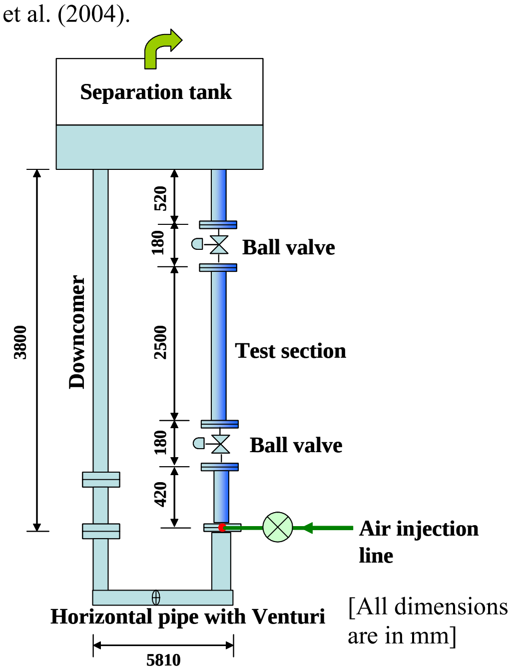

Fig. 3: Schematic of Adiabatic Air-Water Loop

5. GENERALIZED FLOW CORRELATION

Earlier the authors were successful in deriving a generalized correlation for steady state flow applicable to both single-phase and two-phase natural circulation systems. It was shown that for both single-phase and two-phase natural circulation systems, the steady state behavior can be simulated by preserving Gr_m / N_G same in the model and prototype. The given correlation has been tested with data from several single-phase and two-phase natural circulation loops. For the completeness of the report, the results for single-phase and two-phase generalized correlation have been described here.

5.1 Single-phase natural circulation

The generalized flow correlation for single-phase loops (Vijayan and Austregesilo (1994)) is given by,

$$\mathrm{Re}_{ss} = C\left(Gr_m / N_G\right)^r \tag{21}$$

where the constant C and r depends on the constants of the friction factor correlation as shown below. The above correlation suggest that if we plot Re vs Gr_m / N_G on a log-log plot, the constant C and r can be obtained as the intercept and exponent. From the values of C and r, the p and b values applicable to the friction factor correlations can be obtained as

$$C = (2/p)^r \quad \text{and} \quad r = (1/3 - b) \tag{22}$$

where p and b are given by the friction factor correlation of the form $f = p/\mathrm{Re}^b$. Depending on the value of the constants p and b, the flow correlation is given as

$$\mathrm{Re}_{ss} = 0.1768\left(\frac{Gr_m}{N_G}\right)^{0.5} \quad \text{laminar flow } (p = 64, b = 1) \tag{23}$$

$$\mathrm{Re}_{ss} = 1.96\left(\frac{Gr_m}{N_G}\right)^{0.364} \quad \text{turbulent flow } (p = 0.316, b = 0.25\text{; Blasius correlation}) \tag{24}$$

Where Gr_m and N_G are as defined in equation (18). Experimental data obtained from five different natural circulation loops were compared with results obtained with above relationships and found to be in good agreement as shown in Fig. 4.

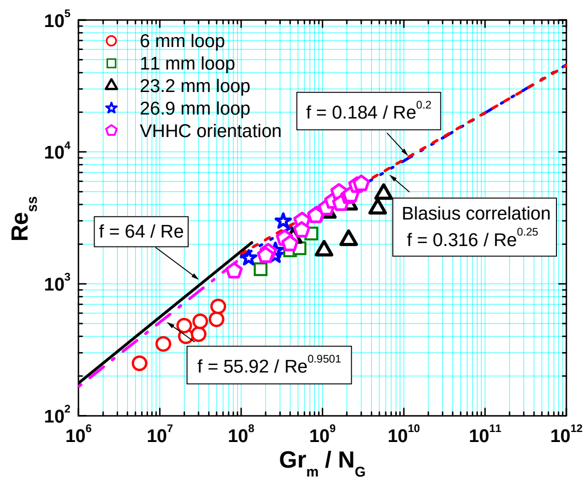

Fig. 4: Steady state flow rate in single-phase natural circulation loops as predicted by generalized flow correlation (Vijayan and Austregesilo (1994))

5.2 Two-phase natural circulation

A generalized flow correlation of the same form as that of single-phase has been developed (Gartia et al. (2006)) to estimate the steady state flow rate in two-phase natural circulation loops which is given by,

$$\mathrm{Re}_{ss} = C\left(Gr_m / N_G\right)^r \tag{25}$$

where, Re_{ss} is the Reynolds Number, Gr_m is the Modified Grashoff Number, N_G is the contribution of loop geometry to the friction number as defined in equation (19). The value of C is 0.1768 and 1.96 for laminar and turbulent flow respectively and corresponding values for 'r' are 0.5 and 0.3636 respectively. For laminar flow $f = 64/\mathrm{Re}$ and for turbulent flow Blasius equation have been used. The above correlation shows that, it is possible to simulate the steady state behavior with just one non-dimensional parameter. To account for the density variation in the buoyancy term, a new parameter $\beta_{tp} = \frac{1}{v_m}\left(\partial v \big/ \partial h\right)_p$ has been used in Gr_m, where, v_m is mean specific volume and h is the enthalpy.

In Fig. 5, experimental result obtained from three different natural circulation loops are compared with theoretical results based on the above relationships. As can be seen, reasonably good agreement is obtained.

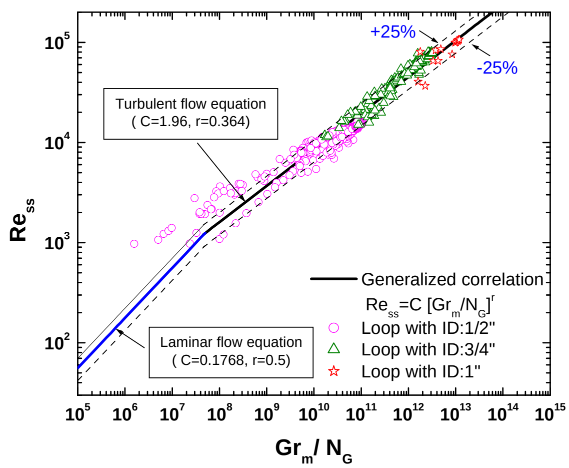

Fig. 5: Steady state flow rate in two-phase natural circulation loops as predicted by generalized flow correlation (Gartia et al. (2006))

6. RESULTS AND DISCUSSIONS FOR ADIABATIC NATURAL CIRCULATION LOOPS

The steady state experimental data from four different adiabatic natural circulation tests were compared with the theoretical correlation in Fig. 6 and 7. The comparison of experimental data with generalized correlation ignoring the local losses effects is shown in Fig. 6. Figure 7 describes the comparison between theoretical correlation and experimental data considering local losses (bends, valves, expansion / contraction at the separator etc.). The large variation between theoretical results and experimental data in Fig.6 clearly shows the significance of local loss terms in generalized correlation for adiabatic NCLs. As seen from Fig. 7 the experimental data are reasonably close to the theoretical correlation (within an error bound of $\pm$20%) for all the adiabatic natural circulation loops confirming the validity of the correlations given in equation (17).

It can be seen that the variation between pure air injection test data at (8°C, 30°C) with the theoretical correlation is large as compared to other test data. Actually, these tests were performed by supplying power to the heaters for a relatively short period, then switching off the power and waiting a sufficiently long time for making sure that no fluid heating was taking place as an effect of heater thermal capacitance. The decrease in water viscosity of a factor roughly equal to 1.75 from 8 to 30°C can be considered the main reason for this variation. This may be also due to the fact that there is no source term (power or temperature) considered in the generalized correlation to account for this affect of change in viscosity due to temperature.

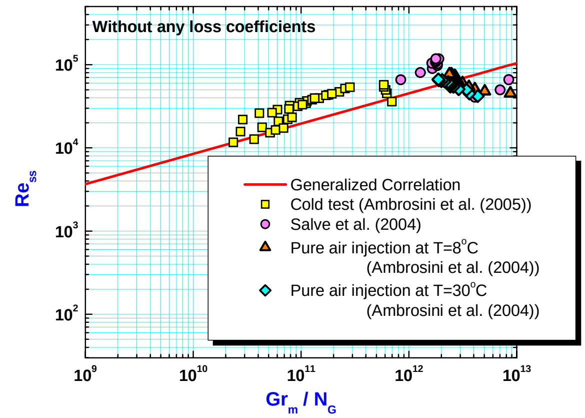

Fig. 6: Comparison of theoretical prediction with experimental data without considering any local losses

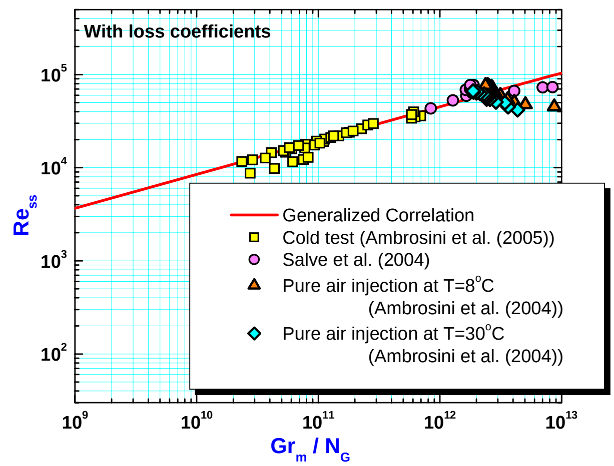

Fig. 7: Comparison of theoretical prediction with experimental data with considering local losses

6.1 Prediction of flow rate using generalized correlation

One of the drawbacks of dimensionless correlations is that important parametric effects are sometimes masked. Therefore, the generalized flow correlation for adiabatic natural circulation loops as defined in equation (20) was also used to calculate the dimensional flow rate using the algorithm described in section 3.2. The variation of liquid flow rate with gas flow rate for different valve angles are shown in Fig. 8. The solid lines here correspond to predictions by generalized flow correlation. All these experimental data are from cold test performed in DIMNP adiabatic NCL (Ambrosini et al. (2004, 2005) and Struckmann et al. (2004)). Further experiments performed in the same loop at different gas flow rate and different valve angles were also predicted using the theoretical correlation. The close match (error of -6% to +20%) between the theoretical and experimental results in dimensional form further reaffirms the validity of the present flow correlation.

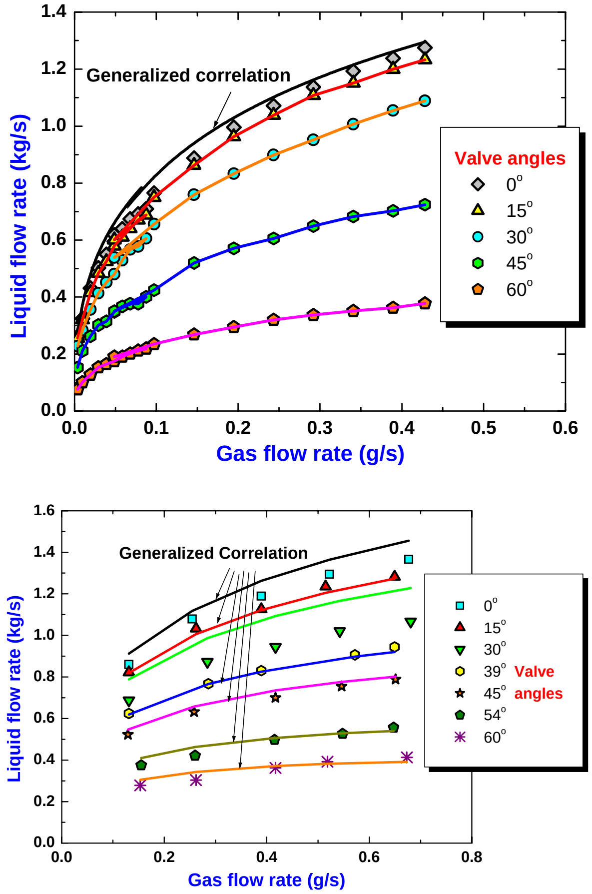

Fig. 8: Variation of primary loop flow rate (liquid) with injected gas flow rate for DIMNP Adiabatic NCL

7. CONCLUSIONS

A unified approach to calculate steady state flow rate applicable to single-phase, two-phase (diabatic) and adiabatic natural circulation systems has been presented. For all the cases, single-phase, two-phase as well as adiabatic natural circulation systems, the steady state behavior can be simulated by preserving Gr_m/N_G same in the model and prototype. The given correlation has been tested with data from several single-phase, two-phase and adiabatic natural circulation loops. The experimental results are found to be in reasonable agreement with the proposed correlations.

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NOMENCLATURE

General symbols

A : flow area, m^2
a : dimensionless flow area, A/A_r
b : constant in friction factor correlation, $f = a / Re^b$
C_p : specific heat, $J / kg\ K$
D : hydraulic diameter, m
d : dimensionless hydraulic diameter, D/D_r
f : Darcy-Weisbach friction factor
g : gravitational acceleration, m/s^2
Gr_m : modified Grashof number
h : enthalpy, J/kg
H : loop height, m
l : dimensionless length, L_i/L_t
L : length, m
N : total number of pipe segments
N_G : dimensionless parameter defined by equation (11)
p : constant in friction factor correlation, $f = a / Re^b$
q : volumetric flow rate, W
Q : volumetric flow rate, m^3/s
Re : Reynolds number, $DW/A\mu$
T : temperature, K
v : specific volume, m^3/kg
W : mass flow rate, kg/s
x : quality

Greek Symbols

α : void fraction
β_T : single-phase thermal expansion coefficient, kg/J
β_{tp} : two-phase thermal expansion coefficient, kg/J
μ : dynamic viscosity, $N\ s/m^2$
ϕ_{LO}^2 : two-phase friction multiplier
ρ : density, kg/m^3
ρ_r : reference density, kg/m^3

Subscripts

eff : effective
g : gas
i : i^{th} segment
l : liquid
LO : liquid only
r : reference value
ss : steady state
t : total
tp : two-phase

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