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NATURAL CIRCULATION PHENOMENA, MODELING AND RELIABILITY OF PASSIVE SYSTEMS THAT UTILIZE NATURAL CIRCULATION

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On

THERMO-FLUID DYNAMICS AND PRESSURE DROPS IN VARIOUS GEOMETRICAL CONFIGURATIONS

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Thermo-fluid dynamics and pressure drops in various geometrical configurations

Abstract. Pressure drop is an important parameter for design and analysis of many systems and components. Particularly in natural circulation systems, the mass flux and the driving heads are low compared to those of forced circulation systems. Therefore, it is necessary to determine the pressure loss components very accurately. Though it is widely believed that the pressure loss inside a device does not depend on whether the flow is sustained by a pump or by a density difference, under some circumstances, because of local effects the pressure loss may get influenced by the nature of driving force. In the present report an attempt has been made to assess pressure drop correlations for its application in natural circulation loops. In this report, the definition of the pressure drop phenomena has been explained. The various scenario and hardware related to the pressure drop phenomena are explained. Important aspects like transition region, diabatic boundary condition are covered. A comparison of flow characteristics under forced and natural circulation condition has been given. The effect of friction factor correlation on steady state flow and stability prediction for both single-phase as well as two-phase natural circulation has been pointed out. Further, the effect of two-phase friction multiplier on steady state and stability of two-phase natural circulation loop was pointed out. Finally, the recommended two-phase pressure drop found in literature for small as well as large diameter pipe has been included in this report.

1. INTRODUCTION

Pressure drop can be defined as the difference in pressures between two points of interest in a fluid system. A large number of single-phase and two-phase flow pressure drop correlations can be found in literature. Some important pressure drop relationships can be found in the IAEA technical document for “Thermohydraulic relationships for advanced water cooled reactors” (IAEA-TECDOC-1203 (2001)).

Though the effect of natural circulation (or flow developed due to heating) on pressure drops is not well established, it should be noted that most of the pressure drop correlations are developed from data generated in forced circulation systems. The mechanism of flow in natural circulation loop may be complex due to buoyancy effect and formation of secondary flows. Also, natural circulation flows are characterized by low driving head and low mass flux along with potential instabilities under certain operating conditions. On the other hand, natural circulation as a mode of energy removal is gaining momentum in many advanced water reactors due to its passive nature and seemingly higher reliability. Therefore, there is a need to give a closer look to pressure drop phenomena under natural circulation, which is both complex and important.

To deal with it, it is advisable not only to define it, but also to examine it in the backdrop of a particular scenario (*when* it occurs) and in a particular hardware (*where* it occurs), which will enable us to understand and judge its applicability in a particular situation.

1.1. Definition

The focus of this phenomenon is geometric conditions that reflect the lack of fully developed flow and the presence of mixtures of steam, air and water. Pressure drop is the difference in pressure between two points of interest in a fluid system. In general, pressure drop can be caused by resistance to flow, changes in elevation, density, flow area and flow direction. Pressure drops in natural circulation systems play a vital role in their steady state, transient and stability performance.

It is customary to express the total pressure drop in a flowing system as the sum of its individual components such as distributed pressure loss due to friction, local pressure losses due to sudden variations of shape, flow area, direction, etc. and pressure losses (the reversible ones) due to acceleration (induced by flow area variation or by density change in the fluid) and elevation (gravity effect). An important factor affecting the pressure loss is the geometry. In a nuclear reactor, we have to deal with several basic geometrical shapes (circular pipes, annuli, etc.) and a number of special devices like rod bundles, heat exchangers, valves, headers, plenums, pumps, large pools, etc. Other factors are concerned with the fluid status (single or two phase/one component, two-component or multi-component), the flow nature (laminar or turbulent), the flow pattern (bubbly, slug, annular, etc.), the flow direction (vertical upflow, downflow, inclined flow, horizontal flow, countercurrent flow, etc.), flow type (separated and mixed), flow paths (one-dimensional or multi-dimensional, open or closed paths, distributor or collector), and the operating conditions (steady state or transient).

An important focus of this phenomenon is the geometric conditions that hinder the establishment of fully developed flow especially when the fluid in question is a mixture of steam, air and water. This complex thermo-fluid dynamic phenomenon warrants special attention. However, it is worth mentioning here that though in many systems like the primary system of a nuclear power plant, flow is mostly not fully developed, pressure drop relationships used in these systems are invariably those obtained for developed flow. This practice is also experimentally proved to be more than adequate in most of the cases. However, in some specific cases like containment internal geometry, it is necessary to consider thermo fluid dynamics in the developing region.

A final, very important issue, is concerned with the driving force depending on whether the flow is sustained by a density difference in the fluid (natural circulation) or by a pump (forced convection), or whether there will be feedback between the pressure loss and the extracted power or not. Normally the pressure loss inside a device depends on the nature of flow through the device and not on the nature of driving head causing the flow. However, under some circumstances, because of local effects, the pressure loss may get influenced by the nature of driving force.

1.2. Scenario

For a given system or network, a portion of the total pressure that is spent to overcome the resistance forces arising from the flow of real (viscous) fluids through pipes and channels is irretrievably lost. This loss of total pressure (or pressure drop) is due to irreversible conversion of mechanical energy (the work of resistance force) into heat. Therefore, the term loss due to fluid resistance or hydraulic loss, represents the irreversible loss of total pressure over a given system length. There are also reversible component of pressure drop such as elevation pressure drop and acceleration pressure drop.

As stated earlier, the total pressure loss comprises of distributed pressure loss due to friction, local pressure loss due to sudden variations of shape, flow area, direction, etc. and pressure losses (the reversible ones) due to acceleration (induced by flow area variation or by density change in the fluid) and elevation (gravity effect). Various components of pressure drop are further elaborated below.

1. The fluid friction loss is due to the viscosity (both molecular and turbulent) of real liquid and gases in motion, and results from momentum transfer between the molecules (in laminar flow) and between individual particles (in turbulent flow) of adjacent fluid layers moving at different velocities. For two-phase flow, an additional frictional pressure drop may be due to the inter-phase friction between gas-liquid or steam-liquid phases.
2. The local losses of total pressure are caused by the following: local disturbances of the flow; separation of flow from the walls; and formation of vortices and strong turbulence agitation of the flow at places where the configuration of pipeline changes or fluid stream meet or flow past obstructions (e.g. entrance of a fluid into pipeline, expansion, contraction, bending and branching of the flow, flow through orifices, grids or valves, filtration through porous bodies, flow past different bluff bodies etc.).
3. The energy spent in accelerating the molecules of the fluid is manifested as the acceleration pressure drop. This reversible component of pressure drop is caused by a change in flow area or density. Fluid flowing through an expansion, contraction or a heated section are some of the examples where acceleration pressure drop can occur.
4. Some work needs to be done against the gravity to raise the fluid molecules to a height. This energy spent is the reason behind the elevation pressure drop. This reversible component of pressure drop is caused by the difference in elevation. In many instances with vertical test sections, the elevation pressure drop is the largest component.

The pressure loss components in any complex flow situation are inseparable. However, for ease of calculation they are arbitrarily subdivided into components like local losses, frictional losses etc. It is also assumed that the local losses are concentrated in one section, although they can occur virtually over a considerable length, except, of course, for the case of flow leaving the system, when its dynamic pressure becomes immediately lost. This paper mainly deals with irreversible pressure drops.

It should be noted that most of the pressure drop correlations are generated from data obtained from fully developed flow, whereas flow in nuclear reactors are generally not fully developed except in some cases like the steam generator (SG) section and feeder section of PHWR etc. Further, most of the pressure drop correlations reported in literature had been developed from steady state experimental data and mostly under adiabatic conditions.

1.3. Hardware

By hardware it is meant the place where the scenario evolves. The geometries of interest to Nuclear Power Plants (NPPs) will only be considered here. Virtually every component of NPPs comes under the purview of pressure drop. However, emphasis is on geometric conditions that are relevant to the primary loop of NPPs. The secondary loop of NPPs (the steam generator and the piping up to the Main Steam Isolation Valve (MSIV) and the feedwater valves in case of PWRs and PHWRs) is also important and is to be considered. In addition, the Emergency Core Cooling (ECC) lines from the ECC pumps to the injection point along with the different types of valves may also be considered. A list of locations where local and distributed pressure losses are important is given below. Further, particular emphasis is put to deal with locations for local and distributed pressure losses in some of the advanced designs such as AHWR, SWR-1000, AP-600, APWR, ABWR, CAREM etc. Finally, for easy reference, the important locations for pressure drop are described in two categories: channel type reactors and vessel type reactors.

Locations where local and distributed pressure drop are important

	Channel type	**Vessel type**
Distributed pressure drop:	- Feeder and tail pipe - Bare bundle	- Core and core bypasses - Surge line - Steam Generator (SG) tubes
Local pressure drop :	- Fuel bundle assembly - Various header connections - Valves and rupture disc locations	- Pump inlet, outlet and inside - Pressurizer and surge line connections
Safety system pressure drop :	- Accumulator outlet line - ECCS header to water tube connection - Advanced fluidic	- Accumulator connections - ECCS connections

device
- Gravity Driven Water Pool (GDWP) to ECCS header connection

2. SINGLE-PHASE PRESSURE DROP RELATIONSHIPS

2.1 Flow under transition regime

Most of the single-phase pressure drop correlations are applicable to steady state fully developed flow. Fully developed flow conditions are expected to occur in long components like the steam generator U-tubes, feeder pipes etc. A large number of correlations valid for laminar and turbulent flow regime can be found in literature. It may be noted that well established correlations for friction factor do not exist in the transition region between $2000 \leq Re \leq 3000$. Further, in many transients, the flow may change from laminar to turbulent, or vice versa, necessitating a switch of correlations. Numerical calculations, often encounter convergence problems when such switching takes place due to the discontinuity in the friction factor values predicted by the laminar flow and turbulent flow equations. A simple way to overcome this problem is to use the following criterion for switch over from laminar to turbulent flow equation.

$$\text{If } f_t > f_l \text{ then } f = f_t \tag{1}$$

where

f_t and f_l are friction factors calculated by turbulent and laminar flow equations respectively. This procedure, however, causes the switch over from laminar to turbulent flow equation at $Re \approx 1100$. Solbrig's (1986) suggestion to overcome the same is to use friction factor as equal to greater of $(f_t)_{4000}$ and f_l below Reynolds number of 4000. $(f_t)_{4000}$ is the friction factor calculated by the turbulent flow equation at Re = 4000. Effectively this leads to

$$f = (f_t)_{4000} \text{ for } 2000 \leq Re \leq 4000 \tag{2}$$

In addition, a condition to avoid infinite friction factor is required to take care of flow stagnation (i.e. $Re \approx 0$).

2.2 Flow under diabatic condition

Another special kind of pressure drop calculation is that occurring under diabatic single-phase flow conditions. Generally isothermal friction factor correlations are used with properties evaluated at the film temperature $T_f = 0.4\,(T_W - T_b) + T_b$, where T_W and T_b are the wall and bulk fluid temperatures (Knudsen and Katz (1958)). Sometimes the friction factor for non-isothermal flow is obtained by multiplying the isothermal friction factor with a correction coefficient, F. The correction coefficient accounts for the temperature gradient in the laminar layer and the consequent variation in physical properties of the fluid. The correction coefficient can be expressed as a function of the temperature drop in the laminar layer, ΔT_f as given below:

$$F = 1 \pm C\Delta T_f \tag{3}$$

The negative sign shall be used for heat transfer from wall to the fluid, and

$$\Delta T_f = q''/h' \tag{4}$$

Different values of the constant C are given by different investigators. El-Wakil (1971) gives a value of 0.0025, while Marinelli and Pastori (1973) give a value of 0.001.

An alternative approach is to express the correction factor in terms of the viscosity ratio. This approach is more widely used and the following empirical equation proposed by Leung and Groeneveld (1993) is recommended.

$$F = (\mu_b / \mu_w)^{-0.28} \tag{5}$$

where the subscripts "b" and "w" refer to the bulk fluid and wall respectively.

3. TWO-PHASE PRESSURE DROP RELATIONSHIPS

3.1 Flow under adiabatic condition

A large number of two-phase flow pressure drop correlations developed from adiabatic experimental data can be found in literature. These correlations can be classified into the following four general categories.

(1) Empirical correlations based on the homogeneous model,
(2) Empirical correlations based on the two-phase friction multiplier concept,
(3) Direct empirical models,
(4) Flow pattern specific models.

These pressure drop correlations are comprehensively covered in the CRP on Thermohydraulic relationships for Advanced Water Cooled Reactors (IAEA-TECDOC-1203).

3.2 Models using interfacial friction

Another form of two-phase pressure drop correlations are that uses interfacial friction models. The two-fluid model used in many of the advanced system codes require correlations for interfacial friction in addition to wall friction. Complete description of the models used in computer codes like TRAC-PFI/MOD1 [Liles and Mahaffy (1984)] and RELAP5/MOD3.2 [the RELAP5/MOD3 development team (1995)] are readily available in the open literature. For specific flow patterns, models are proposed by Wallis (1970), Coutris (1989) and Stevanovic and Studovic (1995). For use in computer codes, it is also essential that such correlations for the various flow patterns be consistent. For example, when the flow pattern changes from bubbly to slug, the interface force predicted at the transition point by correlations for the bubbly and slug flow should be same. A consistent set of interfacial and wall friction correlations for vertical upward flow has been proposed by Solbrig (1986) along with a flow pattern map for use in two-fluid models.

3.3 Flow under diabatic condition

The correlations discussed so far are applicable to adiabatic two-phase flow. The effect of heat flux on two phase pressure drop has been studied by Leung and Groeneveld (1991), Tarasova (1966) and Koehler and Kastner (1988). Tarasova (1966) observed that two phase friction pressure drop is higher in a heated channel compared to that in an unheated channel for same flow condition. However, Koehler and Kastner (1988) concluded that two phase pressure drops are same for heated and unheated channels. Studies conducted by Leung and Groeneveld indicate that the surface condition is significantly influenced by heat flux. Effective surface roughness increases due to the formation of bubbles at heated surface leading to larger pressure drop. They concluded that for the same flow conditions, the two phase multiplier is larger for low heat flux than high heat flux. They further observed that maximum value of two phase multiplier is obtained when heat flux approaches Critical Heat Flux value. In the absence of established procedure to take the affect of heat flux into account the following procedure for calculation of two phase diabatic pressure drop is generally followed.

For diabatic two-phase flow, the quality, void fraction, flow pattern, etc. change along the heated section. To calculate the pressure drop in such cases, two approaches are usually followed. In the first approach, the average ϕ_{LO}^2 is calculated as:

$$\phi_{LO}^2 = \frac{1}{L}\int_0^L [\phi_{LO}^2(z)]dz \tag{6}$$

The approach can be used in cases where the $\phi_{LO}^2(z)$ is an integrable function. Numerical integration is resorted to in other cases. An example of such an approach is proposed by Thom (1964). Thom has derived average values of $\phi_{LO}^2(z)$. Similar integrated multiplication factors for diabatic flow as a function of outlet quality are also available for the Martinelli-Nelson method. Thom has also obtained multiplication factors for calculating the acceleration and elevation pressure drops for diabatic flow in this way.

In the second approach the heated section is subdivided into a large number of small segments. Based on average conditions (i.e., x_i, α_i and flow pattern) in that segment, the pressure drop is calculated as in adiabatic two-phase flow using one of the models described previously.

3.4 Void fraction relationships

Void fraction plays an important role, not only in pressure drop calculation, but also in flow pattern determination and neutron kinetics. All the four components of pressure drop (skin friction, local, acceleration and elevation) directly or indirectly depend on the void fraction. For certain situations of practical interest, accurate prediction of all the components are required. For example, steady state flow prevails in a natural circulation loop when the driving pressure differential due to buoyancy (i.e. the elevation pressure drop) balances the opposing pressure differential due to friction, acceleration and local effects. For such cases, accurate estimation of each component of pressure drop is required. Therefore, it is very important to have a reliable relationship for the mean void fraction. In general, the published void fraction correlations can be grouped into three, viz., (a) slip ratio models, (b) $K-\beta$ models, and (c) correlation based on drift flux models.

In addition, there are some empirical correlations, which do not fall in any of the three categories. Detailed void fraction relationships can be found in IAEA-TECDOC-1203.

3.5 Assessment of two-phase pressure drop correlations

The table given below gives the assessment of pressure drop correlations by various authors and their recommendation.

Authors	Categories	No. of correlations tested	No. of data points	Recommended correlation
Weisman-Choe (1976)	Homogeneous model	---	---	McAdams (1942) and Dukler et al. (1964)
Idsinga et al. (1977)	Homogeneous model	18	3500	Owens (1961) and Cicchitti (1960)
Beattie-Whalley (1982)	Homogeneous model	12	13500	Beattie and Whalley (1982)
Dukler et al. (1964)	Multiplier concept	5	9000	Lockhart and Martinelli (1949)
Idsinga et al. (1977)	Multiplier concept	14	3500	Baroczy (1966) and Thom (1964)
Friedel (1980)	Multiplier concept	14	12868	Chisholm (1973) and Lombardi-Pedrocchi (1972)
Snoek-Leung (1989)	---	9	1217	Friedel (1979)
Vijayan et al. (2000)	---	14	424	Lockhart and Martinelli (1949) with Chexal et al. (1996) for void fraction.
Weisman-Choe (1976)	Flow pattern specific	11	*Separated flow*: Agrawal et al. (1973) and Hoogendoorn (1959)	
		10	*Homogeneous flow* : McAdams (1942), Dukler et al. (1964) and Chisholm	

			(1968)	
		7	*Intermittent flow*: Dukler (1964), Lockhart-Martinelli (1949) and Hughmark (1965)	
		6	*Annular flow*: Dukler (1964) and Lockhart- Martinelli (1949)	
Mandhane et al. (1977)	Flow pattern specific	14	10500	*Bubbly*: Chenoweth and Martin (1956)
				Stratified: Agrawal et al. (1973)
				Stratified wavy: Dukler et al (1964)
				Slug: Mandhane et al. (1974)
				Annular, annular mist: Chenoweth and Martin (1956)
				Dispersed bubble : Mandhane et al. (1974)

4. NATURAL AND FORCED CIRCULATION PRESSURE DROP

A final, very important issue is concerned with the driving force. Driving force may be due to buoyancy caused by a density difference in the fluid (natural circulation) or due to a pump (forced convection). There may be feedback between the pressure loss and the extracted power. For example, the flow transition from laminar to turbulent for a heated pipe occurs much earlier than for an unheated pipe due to the effect of secondary flow. There is a fundamental difference between the forced circulation loop and natural circulation loop. For forced circulation loops, the driving force is due to the pressure developed by the pump which is generally far greater than the buoyancy driving head. For natural circulation loops, however, the buoyancy pressure differential, being the driving force, is always the largest component of pressure drop. Further, the buoyancy pressure differential is essentially the elevation pressure difference over the closed loop and is directly proportional to the elevation difference. Usually the elevation difference in natural circulation loops is limited to a few meters. Thus, all the pressure loss terms are generally one to two orders of magnitude less than that under forced flow. Therefore, natural circulation flows are characterized by low driving head and low mass flux. Hence, pressure drop correlations with greater accuracy at low mass flux conditions are required for the analysis of natural circulation loops.

There is a need to reassess the existing correlations and to develop new correlations, if required for natural circulation loops as the existing correlations are mainly applicable for forced circulation loop. The mechanism of flow in natural circulation loops can be different from that of forced circulation loops. For example, due to buoyancy effect and presence of secondary flows, the velocity profile in a heated pipe may get modified which also depends on the orientation of the pipe (horizontal, vertical upward or downward). This was also observed experimentally by Bau and Torrance (1981). These secondary flows are driven by transverse temperature variations within the fluid which, in turn, cause localized natural convection circulations within the duct. The time required to establish these circulations is small compared to the time required to initiate a flow through the loop. He also opined that secondary flows may also arise from centrifugal effects in the curved sections of the duct. The secondary flow may, in turn, affect the friction factor for the pipe, as the friction factor is mainly dependent upon the velocity gradient. For a natural circulation loop, due to low velocities and improper mixing, thermal stratification may occur during single-phase condition especially in horizontal pipes. There is also a concern for flow separation during two-phase flow in a horizontal pipe. The pressure drop under these conditions has to be predicted correctly. Some of the important characteristics of natural circulation flow in comparison to forced circulation flows are as follows. The driving head for forced circulation flows are generally large as compared to natural circulation flows. The thermally induced secondary flow has little effect on the forced circulation flow owing to its large driving head, whereas it may significantly affect the natural circulation flow. Also, the transition from laminar to turbulent flow may occur at lower Reynolds number in natural circulation flows (Creveling et al. (1975); Hallinan and Viskanta (1985)) than that for forced circulation due to the presence of secondary flow in natural circulation. Also the velocity profile in a natural circulation fully developed flow may not follow the classical profile shape (parabolic for laminar, logarithmic for turbulent) again because of secondary flows. As the natural circulation systems are characterized by low driving head, the pressure drop correlations should be highly accurate particularly at low mass flux conditions. Further, owing to the large driving head in forced circulation systems, the associated transients are also relatively fast as compared to that of natural circulation systems. The potential occurrence of instabilities, especially at low pressure, is relatively higher in natural circulation systems as compared to forced circulation systems. Finally, under oscillatory flow conditions, the critical heat flux (CHF) for natural circulation systems are generally lower than steady forced circulation CHF (Kim et al. (1999)).

4.1 Pressure drop under low mass flux, low pressure conditions

Natural circulation reactors are characterized by relatively low mass flux and low driving pressure differential compared to forced circulation systems. Therefore, correlations chosen for the analysis of natural circulation systems require improved accuracy at low mass fluxes. For the analysis of critical flow, following a break in high pressure systems, pressure drop correlations valid for very high mass fluxes (10-20 Mg/m^2s) are required. For investigations on the start-up procedure for natural circulation boiling water reactors, correlations valid over a wide range of pressures starting from atmospheric pressure are required. At the start up, the flow is very less and hence the low flow pressure drop correlations are important. Further, for a natural circulation loop the flow builds up virtually from zero flow condition. Hence the friction factor and loss coefficient correlations should cover the whole range from very low flow to very high flow condition. Low flows are also important due to the fact that natural circulation loops are particularly susceptible to instabilities at low power and low flow conditions. These flow instabilities may be characterized by repetitive flow reversals. Hence even for a simple circular pipe flow may vary from negative to very high positive flow which again calls for a pressure drop correlation applicable for all flow regimes (laminar, transition and turbulent). In addition to this, flow regime transition criteria are important as it is used in computer codes to switch the friction factor/ loss coefficient correlation used for the component. In fact, in some cases these correlations can greatly affect the prediction e.g. during the prediction of the stability boundary in a natural circulation system.

Figure 1 shows the comparison of measured and calculated pressure drop (Chisholm model) under low mass flux condition in a vertical pipe of diameter 26.64 mm with diabatic flow. The experimental results are in good agreement with the calculated pressure drop. Further the experiments were conducted at various system pressure and heat fluxes for low mass flux region. The measured pressure drops were compared with pressure drop calculated using CNEN (1973) correlation. CNEN correlation was able to predict the measured pressure drop with an error of ± 30%.

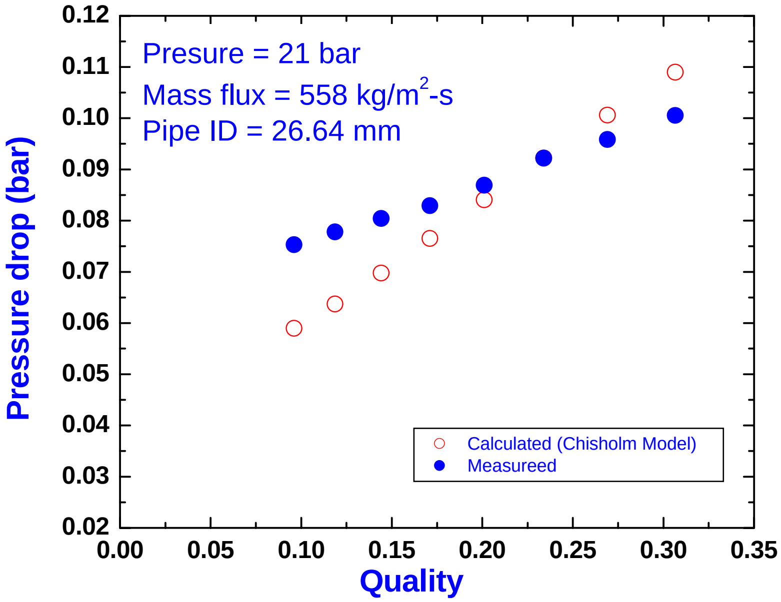

Fig. 1: Comparison of measured and calculated pressure drop in a vertical pipe with diabatic flow

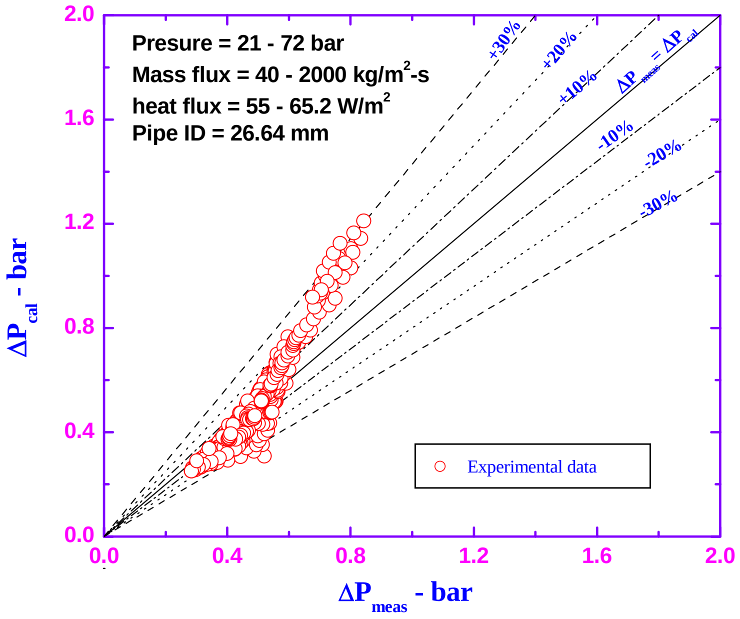

Fig. 2: Comparison of measured and predicted pressure drop using CNEN (1973) correlation for vertical upward diabatic flow in a tube

4.2 Generalized flow correlation

4.2.1 Single-phase natural circulation

The generalized flow correlation for single-phase loops (Vijayan and Austregesilo (1994)) is given by, $\mathrm{Re}_{ss} = C\left(Gr_m \dfrac{D}{L_{eff}}\right)^r$ (7)

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 $Gr_m\, D/L_{eff}$ 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 $C = (2/p)^r$ and $r = (1/3 - b)$

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 components p and b, the flow correlation is given as

$$\mathrm{Re}_{ss} = 0.1768\left(\frac{Gr_m}{N_G}\right)^{0.5} \quad \text{laminar flow } (p = 64, b = 1) \tag{8}$$

$$\mathrm{Re}_{ss} = 1.96\left(\frac{Gr_m}{N_G}\right)^{0.364} \quad \text{turbulent flow } (p = 0.316, b = 0.25\text{; Blasius correlation}) \tag{9}$$

where $Gr_m = \dfrac{D_r^3 \rho_0^2 \beta_T g Q_h H}{A_r \mu^3 C_p}$, $N_G = \dfrac{L_t}{D_r} \displaystyle\sum_{i=1}^{N}\left(\frac{l_{eff}}{d^{1+b} a^{2-b}}\right)_i$ and $\mathrm{Re}_{ss} = \dfrac{D_r W_{ss}}{A_r \mu}$ (10)

Experimental result obtained from a natural circulation loop is compared with results obtained with above relationships in Fig. 3(a). Good agreement is obtained though forced flow correlation (Blasius) is used. The results obtained with other forced flow correlations are also compared with experimental result in Fig. 3(a). Further to this an extensive comparison of single-phase natural circulation data reported in literature has been carried out with the equations (8) and (9) as shown in Fig.3(b). Subsequently data on non-uniform diameter loop were also compared with the generalized correlation neglecting effect of local losses (Fig. 3(c)). In general, a reasonably good agreement is obtained with all reported data. However, in experiments where complex geometries are involved, the friction factor correlation used may be insufficient to obtain reasonable agreement. In such cases, it may be required to determine the pressure drop experimentally and then the flow rate can be calculated as suggested below.

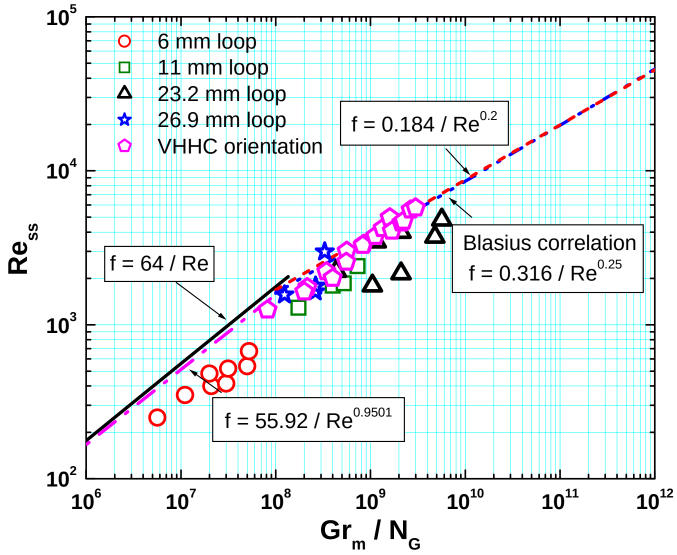

Fig. 3(a): Effect of friction factor on steady state flow rate in a single-phase natural circulation loop as predicted by generalized flow correlation and comparison with experimental results (Vijayan and Austregesilo (1994))

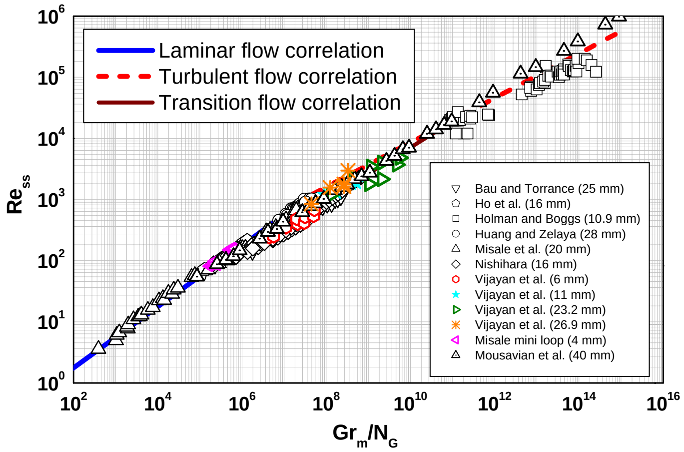

Fig. 3(b): Steady state performance of single-phase loops differing in diameter

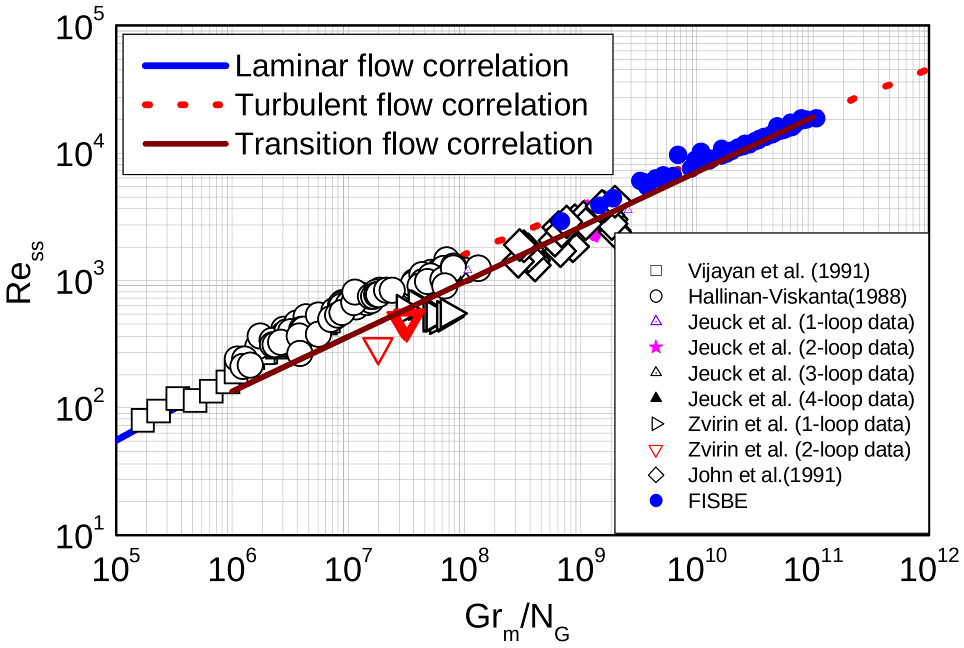

Fig. 3(c): Steady state performance of non-uniform diameter single-phase natural circulation loop neglecting local losses

4.2.2 Flow dependency on power in single-phase natural circulation loop

The steady state flow rate can be obtained from the generalized correlation as

$$W_{ss} = \left[\frac{2\, g\, \rho_0^2\, \beta_T\, H\, Q_h}{R\, Cp} \right]^{\frac{1}{3}} \tag{11}$$

where the total hydraulic resistance of the loop is given by, $R = \sum_{i=1}^{N_t} \left(\frac{f_i L_i}{D_i} + K_i \right) \frac{1}{A_i^2}$

Steady state flow rate in a single-phase natural circulation loop was predicted using two different turbulent forced flow correlations. The variation of flow for different power using different friction factor correlation along with the experimental data obtained from 23.2 mm single-phase natural circulation loop has been shown in Fig. 4.

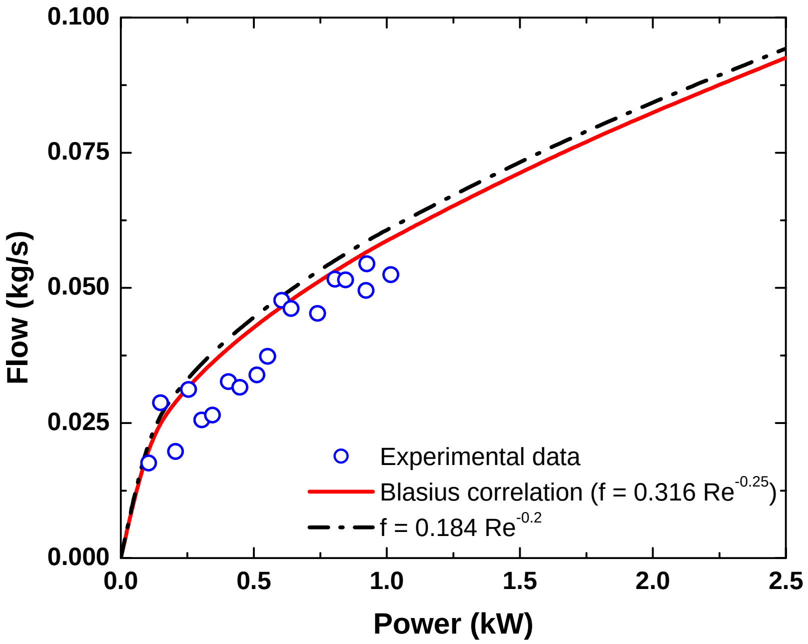

Fig. 4: Effect of friction factor on steady state flow rate in a single-phase natural circulation loop

4.2.3 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,

$$\mathrm{Re}_{ss} = C\left(Gr_m / N_G\right)^r \qquad (12)$$

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. 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, both formulation based on forced flow, 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 $\beta_{tp} = \frac{1}{v_m}\left({}^{\partial v}\!/\!{}_{\partial h} \right)_p$ has been used in Gr_m, where, v_m is mean specific volume and h is the enthalpy.

In Fig. 5(a), 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. Further, data on both uniform diameter loop (UDL) and non-uniform diameter loop (NDL) were compared with the two-phase generalized correlation (Fig. 5(b)). In general, a reasonably good agreement is obtained with all reported data. However, in experiments where complex geometries are involved (e.g. in NDL), the friction factor correlation used may be insufficient to obtain reasonable agreement. Hence, large deviations are found in case of non-uniform diameter loop data as shown in Fig. 5(b). In such cases, it may be required to determine the pressure drop experimentally and then the flow rate can be calculated as suggested in equation (13).

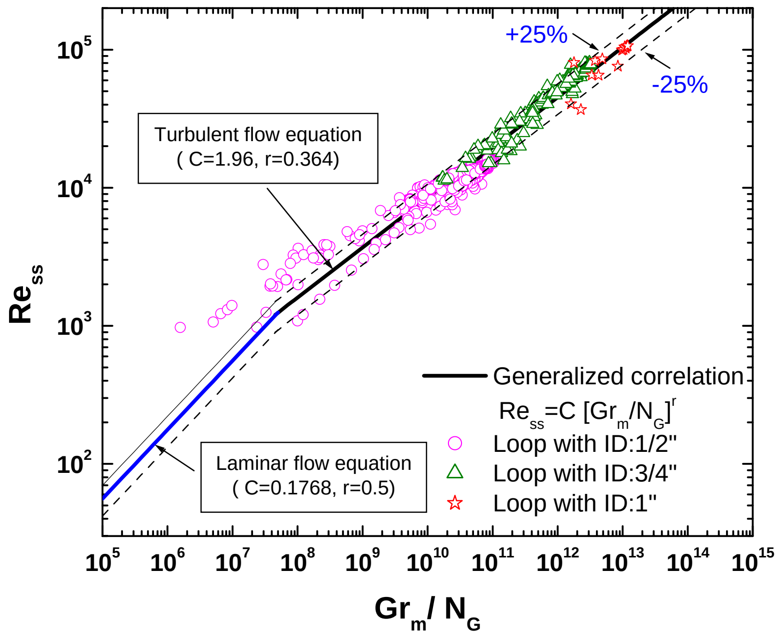

Fig. 5(a): Effect of friction factor on steady state flow rate in a two-phase natural circulation loop (Gartia et al. (2006))

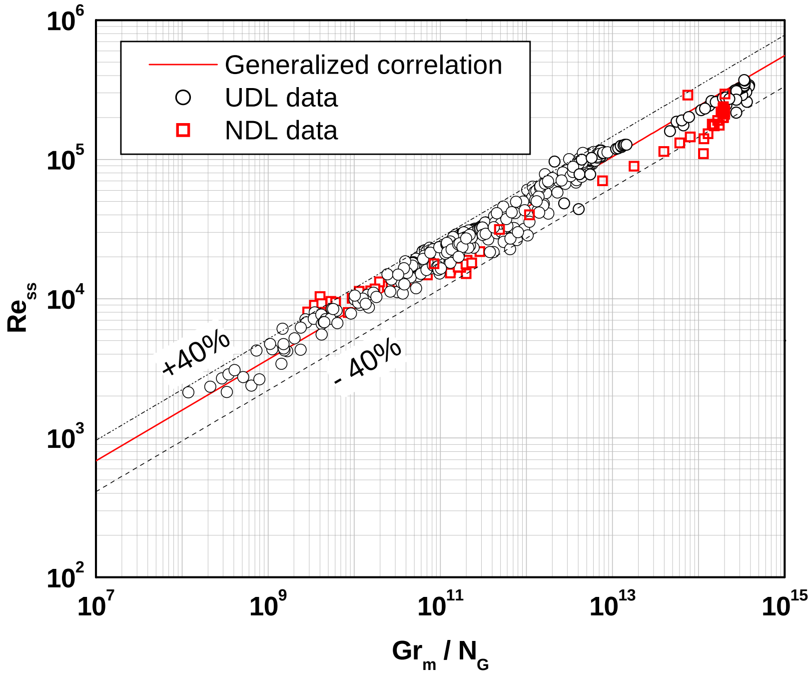

Fig. 5(b): Steady state performance of uniform and non-uniform diameter two-phase natural circulation loops

4.2.4 Effect of friction factor on two-phase flow prediction

The steady state flow rate in a two-phase natural circulation loop can be obtained from the generalized correlation as

$$W_{ss} = \left[\frac{2}{p} \frac{g\,\rho_r\,\beta_{tp}\,H\,Q\,D_r^b\,A_r^{2-b}\,\rho_l}{\mu_r^b\,N_G} \right]^{\frac{1}{3-b}} \tag{13}$$

The variation of two-phase steady state flow rate with power using different single-phase friction factor correlations is shown in Fig. 6. Figure 6 shows that the steady state flow prediction can differ with different single-phase friction factor model.

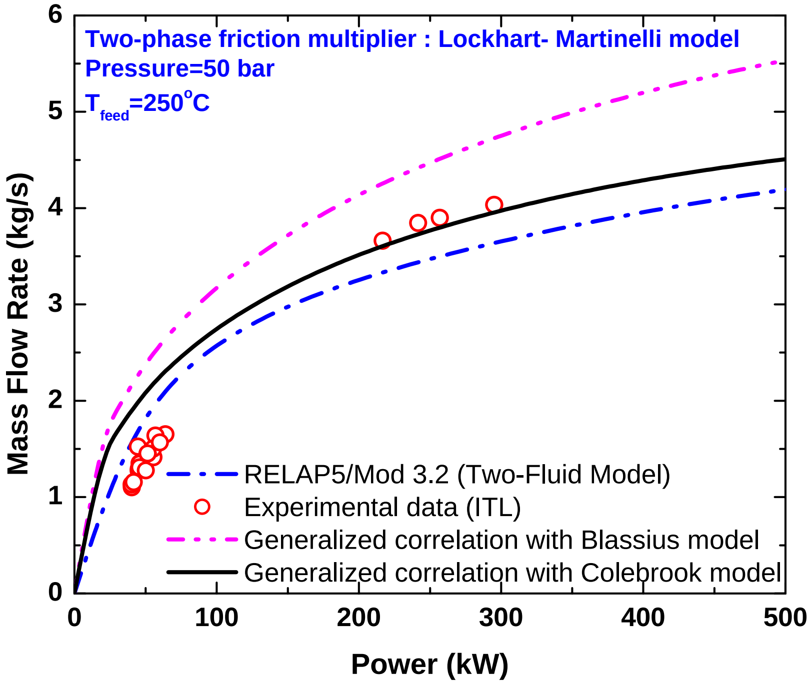

Fig. 6: Effect of friction factor on steady state flow rate in a two-phase natural circulation loop as predicted by generalized flow correlation

4.3 Effect of two-phase friction multiplier on the flow prediction

4.3.1. Flow dependency on power

The effect of changing the two-phase friction multiplier (ϕ_{LO}^2) correlation in two-phase generalized correlation is shown in Fig. 7. It is clear from the figure that even at same power the steady state flow may change because of friction multiplier correlation.

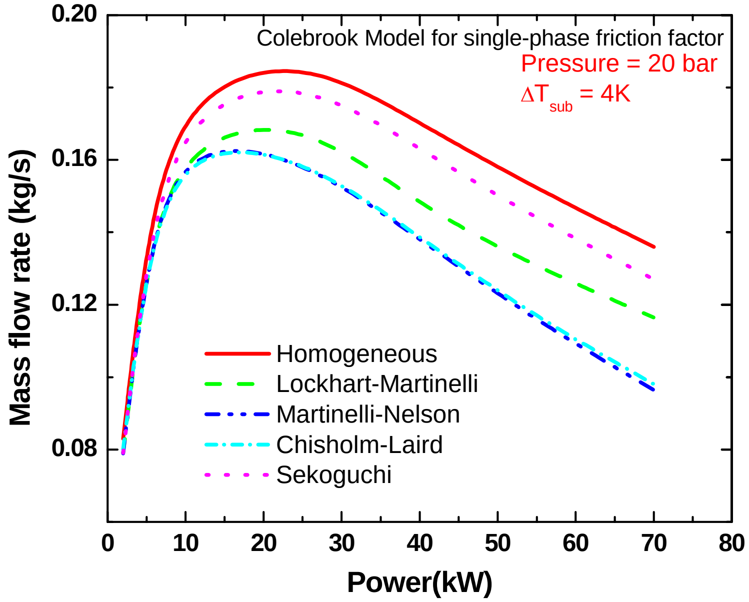

Fig. 7: Effect of two-phase friction factor multiplier on steady state flow rate in a two-phase natural circulation loop using generalized correlation (Nayak et al.(2006))

4.3.2 Flow dependency on pressure

The variation of steady state flow rate with pressure at different two-phase friction multiplier (ϕ_{LO}^2) correlation is shown in Fig. 8.

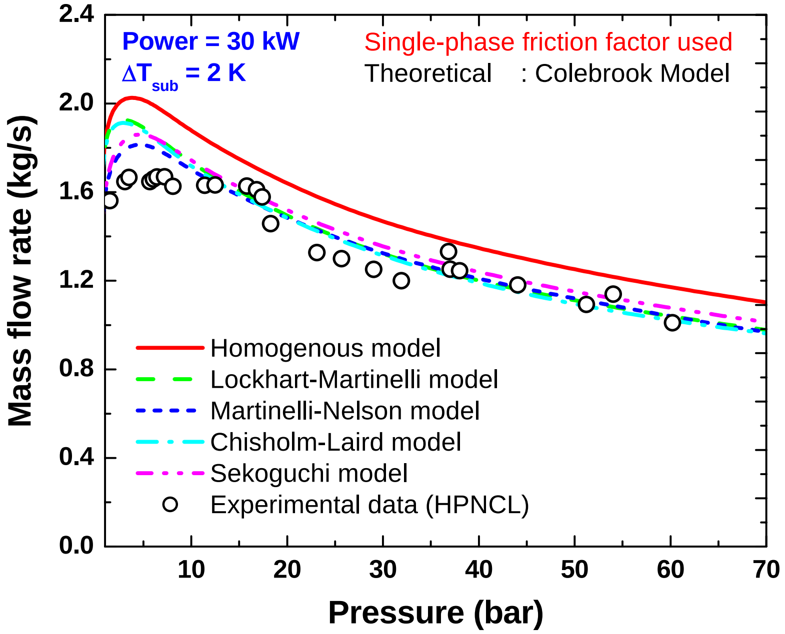

Fig. 8: Effect of pressure on steady state flow rate in a two-phase natural circulation loop

4.4 Effect of friction factor on stability

4.4.1 Single-phase natural circulation

Figure 9 shows the stability map for a single-phase natural circulation loop with HHHC (Horizontal-Heater and Horizontal-Cooler) orientation (Vijayan (2002)). This figure shows that the stability boundary changes with the choice of friction factor correlation even in single-phase loops.

4.4.2 Two-phase natural circulation

Figure 10 (Nayak et al. (2006)) shows the stability map for a two-phase natural circulation loop along with the threshold of instability obtained experimentally. It is clear that the threshold of instability predicted by the code may vary with the choice of two-phase friction factor multiplier in a two-phase natural circulation loop.

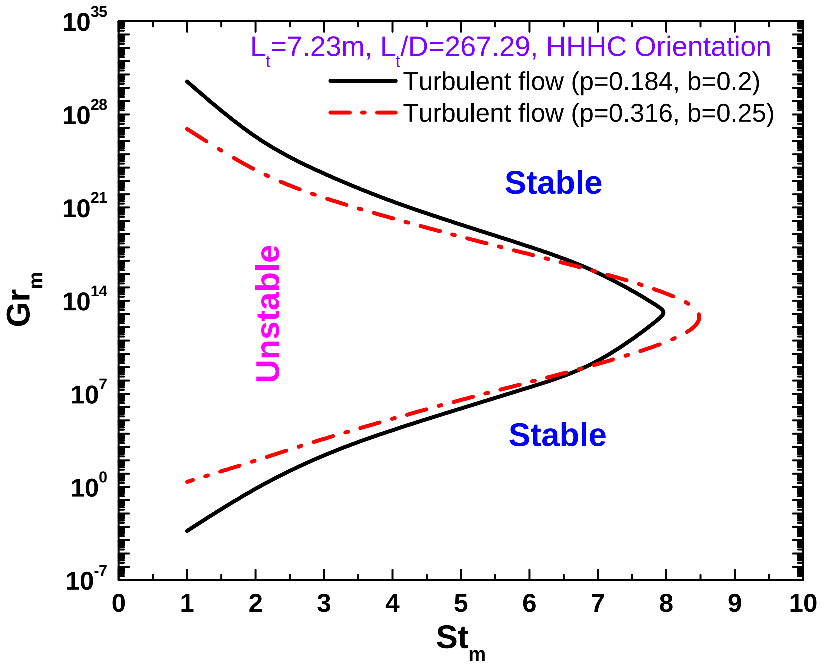

Fig. 9: Effect of friction factor on stability in a single-phase natural circulation loop (Vijayan (2002))

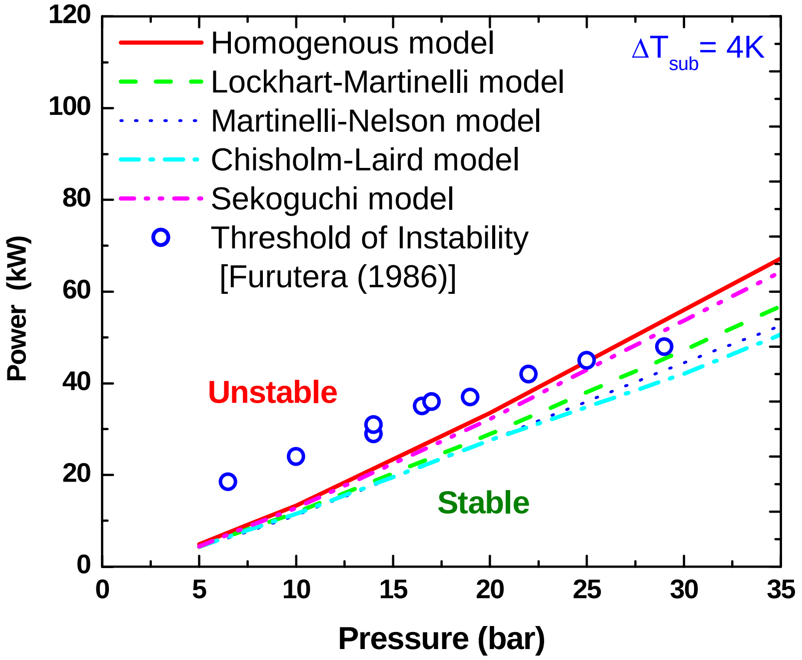

Fig. 10: Effect of two-phase friction factor multiplier on the stability of a two-phase natural circulation loop (Nayak et al. (2006))

4.5 Effect of large flow areas on pressure drops

Although large diameter pipes, large manifolds such as header, plena, water box in steam generators etc. are widely used in PHWRs, PWRs, BWRs or even in new generation advanced reactors (AHWR, SBWR, ABWR etc.), still there is no valid correlation for such geometry. Simpson et al. (1977) compared six pressure drop correlations with data from large diameter (127 and 216 mm) horizontal pipes. None of the pressure gradient correlations studied predicted the measured pressure drops adequately. In particular, measured pressure gradients for stratified flow differed by an order of magnitude from those predicted by the various correlations. In view of this, the validity of the existing correlations which are generally developed from experiments conducted at scaled experimental set up needs to be checked. However, this is not unique to only natural circulation systems. Also there is a need to generate correlations for loss coefficients for such geometry under both single as well as two-phase conditions. Further, there is lack of experimental data on 3-D large flow paths (e.g. around open doors and stair wells) in open literature. These flow phenomena are particularly relevant to containment studies and flow between compartments of large water pool meant for long term recirculation. Therefore, attention must be given for generating such experimental data owing to the greater stress on the reliability of such systems in advanced reactors.

5. CONCLUDING REMARKS

Within the range of parameter studied so far, relationships for forced circulation as given in TECDOC-1203 were found to be adequate for studying natural circulation and stability of natural circulation. More accurate prediction capability is required at low mass flux and for large area flow paths. However, this issue is not unique to only natural circulation systems. Also, applicability of existing correlations to natural circulation needs to be assessed covering wider range of parameters. In addition to this, geometries for which pressure drop correlations are not readily available, such as advanced fluidic devices, large geometry relevant to containment, large flow paths etc. will also be included in the next report.

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' : heat transfer coefficient, $W/m^2\, K$
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 (10)
p : constant in friction factor correlation, $f = a / Re^b$
q'' : heat flux, W/m^2
Q : total heat input rate, W
Re : Reynolds number, $DW/A\mu$
v : specific volume, m^3/kg
W : mass flow rate, kg/s

Greek Symbols

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
i : i^{th} segment
l : liquid
LO : liquid only
m : mean
r : reference value
ss : steady state
t : total
tp : two-phase

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