THE EFFECT OF SYSTEM PRESSURE AND GRAVITY ON THE STABILITY OF TWO-PHASE FLOW NATURAL CIRCULATION OPEN LOOPS

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Abstract. *Instability maps for density wave and excursive instabilities that may occur in open two-phase flow natural circulation loop are presented. The one-dimensional homogeneous equilibrium model of two-phase flow is assumed. Linear system stability criteria are used for the analysis. Heater power, liquid inlet subcooling, system pressure and gravity acceleration are taken as parameters for the analysis. The stable region appears for lower values of the liquid inlet subcooling, bounded by two boundaries whereas the excursive instability region appears for higher values of the liquid inlet subcooling. It has been observed that increasing the system pressure has a stabilizing effect whereas reducing the gravity term has a destibilizing effect on the boiling loop system.*

Keywords. *two-phase flow, loop instabilities, density-wave instability, excursive instability, linear stability analysis*

1. Introduction

In the design of thermosyphon reboilers, solar collectors, and various cooling systems, the concept of two-phase natural circulation is usually adopted. The two-phase natural circulation mode is expected in hypothetical loss of coolant accident in a nuclear reactor as well as in some modern nuclear concepts and passive safety systems. In such a two-phase natural circulation mode, various types of flow instabilities occur depending on the system geometry, fluid properties and operating conditions, and often lead to abnormal behaviors such as limit cycle oscillations or premature burnout. That is, the self-sustained flow oscillations may cause mechanical vibrations of components, and affect the local heat transfer characteristics which can induce a boiling crisis. Thus the prediction of stable operating conditions in two-phase natural circulation systems is of primary concern.

When the condenser section has a very large cross section compared to the other parts, the liquid level inside the condenser does not change during operations. Therefore, the velocity and enthalpy fluctuations at the exit of the riser section damp out and do not directly affect the flow behavior in the downcomer section. Thus the system is considered to be “open”, and the flow is very similar to the forced natural circulation with the constant driving head.

The methods of stability analysis can be divided into two majors groups: one is based on linearized models and the other on full nonlinear models. The main advantage of the former method (Yadigaroglu, 1981; Lee and Lee, 1990,1991; Fukuda and Kobori, 1989; Lahey and Podowski, 1989, Podowski and Zhou, 1991) is that by perturbing the governing equations around a steady-state operating point, and converting the resultant linear model from time to frequency domain, exact analytical solutions can be obtained for the transfer functions. These transfer functions can be analyzed using well established quantitative criteria, to obtain rigorous conditions for the system stability. In fact, such an approach has been successfully applied to several boiling systems, from small-scale experimental facilities to commercial boiling water reactors (BWR) and other thermal power systems. Whereas the linear approach proves very useful in determining if a particular operating point of the system is stable (more specifically - linearly stable, since the equilibrium point may be unstable for sufficiently large perturbations) and in establishing the onset-of-instability conditions, it does not provide information about the properties of the response of an unstable system. To obtain such information, full nonlinear models should be used. In this case, the most common practice is via direct integration of the governing equations in the time domain (Rosa and Podowski, 1994; Podowski and Rosa, 1997; Moberg and Tangen, 1986 and March-Leuba, 1986).

In a previous work (Rosa, 2002) the author presented instability maps, for an open two-phase natural circulation loop, which show both static (excursive) and dynamic (density wave) instability boundaries, for several loop geometry configurations and sizing. The present work aims to show the effect of the fluid properties and the gravitational term on the stability of the loop and on the naturally induced circulation flow rate. The system pressure and the gravity acceleration are taken as parameter, respectively, for these purposes. The one-dimensional homogeneous thermodynamic equilibrium two-phase flow model as well as the Nyquist stability criterion for linear systems have been used for the analysis.

2. Loop Modeling

Let us consider the boiling loop shown in Fig. 1. The loop consists of five regions, namely, the adiabatic liquid region, heated liquid region, heated two-phase region, adiabatic two-phase region and the condenser region. Uniform heat flux is applied at the heater section. Since the cross-sectional flow area of the condenser is much larger than that of the other parts of the loop, the liquid level is assumed to remain constant during each operation. For the purpose of the stability analysis, the following simplifying assumptions were also adopted:

- one-dimensional flow;
- homogeneous two-phase flow;
- no subcooled boiling;
- constant system pressure;
- constant inlet subcooling.

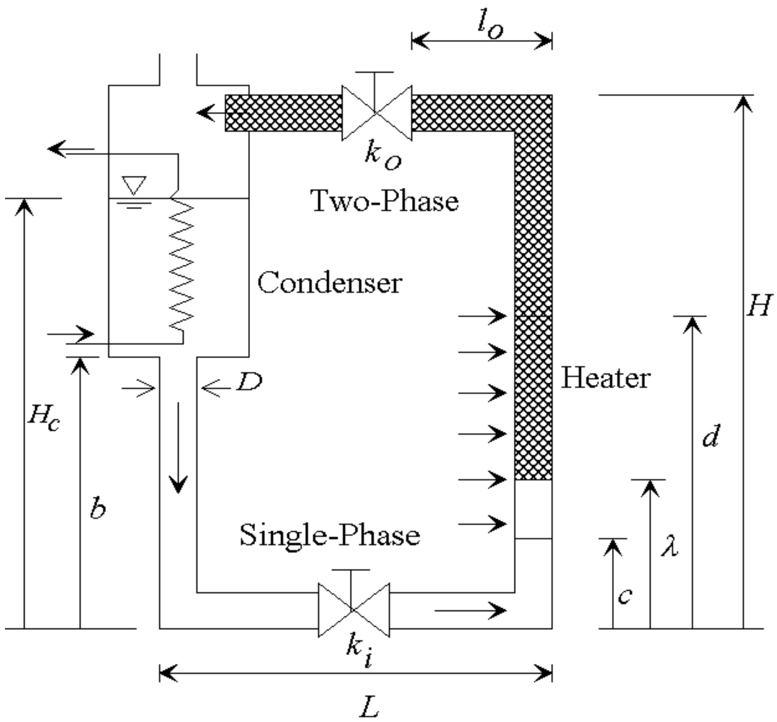

Figure 1. Natural circulation open loop schematic.

Conservation equations of mass, energy and momentum for each region are:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial z}=0 \tag{1}$$

$$\frac{\partial \rho h}{\partial t}+\frac{\partial u \rho h}{\partial z}=\frac{q'}{A_{xs}} \tag{2}$$

$$\frac{\partial \rho u}{\partial t}+\frac{\partial \rho u^2}{\partial z}+\frac{f}{2D}\rho u^2+\frac{k_i}{2}\rho u^2 \delta(z-z_i)+\frac{k_o}{2}\rho u^2 \delta(z-z_o)+g\rho=-\frac{\partial p}{\partial z} \tag{3}$$

The linear heat, q', becomes zero in the adiabatic regions and, k_i and k_o are the local loss coefficients at the inlet and exit line restrictions of the loop, respectively. The "δ " is the Dirac function and z_i and z_o represent the locations of the restrictions.

The model formed by the set of equations just described is nonlinear. The stability of such a system in the small, i.e. for small perturbations to the system equilibrium point, can be studied using techniques which determine the nature of the poles of a system transfer function. Such techniques have been developed for systems of linear equations, therefore, first, perturbation techniques about a steady-state operating point are normally used to linearize the time domain nonlinear equations [Eqs. 1 through 3], then the resultant linear equations are Laplace transformed and integrated analytically along the loop in order to obtain suitable transfer functions to be analyzed (Park et al., 1984, Lee and Lee,1991), in the form

$$\delta\ \Delta P_{loop}=G(s)\,\delta\ u_l \tag{4}$$

for

$$u_l = \bar{u}_l + \delta u_l \tag{5}$$

where $\bar{u}_l$ is the steady (time-averaged) liquid velocity, δu_l and $\delta \Delta P_{loop}$ are the Laplaced transformed perturbations to the liquid velocity and loop pressure drop, and $G(s)$ is the transfer function relating these quantities.

The liquid velocity, $\bar{u}_l$, should satisfy the loop system of equations at steady-state condition subjected to the open loop pressure drop boundary condition, $\Delta P_{loop} = 0$. Therefore,

$$\Delta \bar{P}_{loop}(\bar{u}_l) = \Delta \bar{P}_{loop,f}(\bar{u}_l) + \Delta \bar{P}_{loop,g}(\bar{u}_l) + \Delta \bar{P}_{loop,acc}(\bar{u}_l) = 0 \tag{6}$$

where the bars over the variables represent steady-state values.

Applying the open loop boundary condition to Eq. (4), yields

$$G(s)\, \delta u_l = 0 \tag{7}$$

Eq. (7) always has a solution for the steady-state case, $\delta u_l = 0$, but can also have a nonzero periodic solution provided that,

$$G(s) = 0 \tag{8}$$

In this case, the loop is self-excited and will undergo self-sustained periodic oscillations at the angular frequency, ω, where $s = j\omega$. Eq. (8) is the characteristic equation of the boiling loop, therefore, the asymptotic stability of the system can be determined from the nature of the roots of this equation. All roots of this equation must have negative real parts for loop stability condition. This flow instability is classified as of the dynamic type since inertia and feedback effects are part of the process governing the flow. The Nyquist stability criterion has been applied for this purpose.

Another kind of flow instability analyzed in this work is the excursive instability. This flow instability is classified as of static type since a small perturbation from an original steady-state flow leads to a new steady-state condition which is not in the vicinity of the original state. Static instabilities are analyzed using steady-state laws and the threshold of instability is predicted from these laws. The criterion for instability of the loop shown in Fig. 1 (Lahey and Moody, 1984, Rust, 1979) is

$$\frac{\partial \Delta \bar{P}_{loop}(\bar{u}_l)}{\partial \bar{u}_l} < 0 \tag{9}$$

therefore, excursive instability may occur only if there exists a flow rate range where the system pressure drop increases for decreasing flow rate.

3. Results and Discussion

Calculations were performed for water and the loop reference parameters presented in Table 1. In the first part of the analysis, it is shown the behavior of several two-phase flow parameters on the system stability threshold. In the last part of the analysis, it is studied the effect of system pressure and the gravity term on the stability and flow rate of the loop. For this purpose, the pressure is varied from 1 to 5 atm and the gravity acceleration from g to $g/8$ where g is the earth gravity acceleration at sea level. The liquid inlet subcooling varies from zero to the liquid saturation temperature.

Fig. 2 shows two typical curves of the loop flow rate as function of the heater power for different degree of subcooling of the liquid entering the heater section. In the low power range, the increasing rate of flow driving head due to gravity is larger than that of the frictional pressure drop since the two-phase flow velocity is still very small in this range. Therefore, higher liquid velocity is induced by higher powers. In the higher power range there is an opposite trend since the frictional pressure drop is dominant due to the high two-phase velocity, therefore lower liquid velocity is induced by a higher power. Another important aspect observed in the curve for the higher inlet subcooling in Fig. 2b is that there is a power range ($P_{\min} < P < P_{\max}$) where there are three velocity values (points A, B and C) for each power value which satisfy the open loop natural circulation condition whereas the curve for the lower inlet subcooling in Fig. 2a shows that there is only one velocity value for each possible power. It has been shown in Rosa (2002) that point B, in Fig. 2b, satisfies the condition of excursive instability given by Eq. (9), therefore, the flow is unstable. In this case, a slight increase in flow at point B causes flow to excursively increase to the flow at point A. Conversely, a slight decrese in flow causes flow to excursively fall to point C. The decreased flow rate at point C could cause heater burnout which should not be allowed to occur. So, excursive instability is only possible in the power range which yields three steady-state flow rate values for each heater power. As can be seen in Fig. 2a, there is no such a power range for smaller inlet subcoolings which indicates that this type of instability can only be observed for specific loop parametric conditions.

Therefore, the excursive instability may only be possible for powers in a range, $P_{\min} < P < P_{\max}$, if such type of instability can occur, for a specific liquid inlet subcooling.

Table 1. Loop parameters used as reference for all calculations.

Reference Loop Parameters	
p (atm)	1
g (m/s²)	9.8
D (m)	0.018
c (m)	0.
L (m)	1.15
l_o (m)	0.60
d (m)	1.00
H (m)	4.15
b (m)	3.25
H_c (m)	3.75
k_i	1000
k_0	10

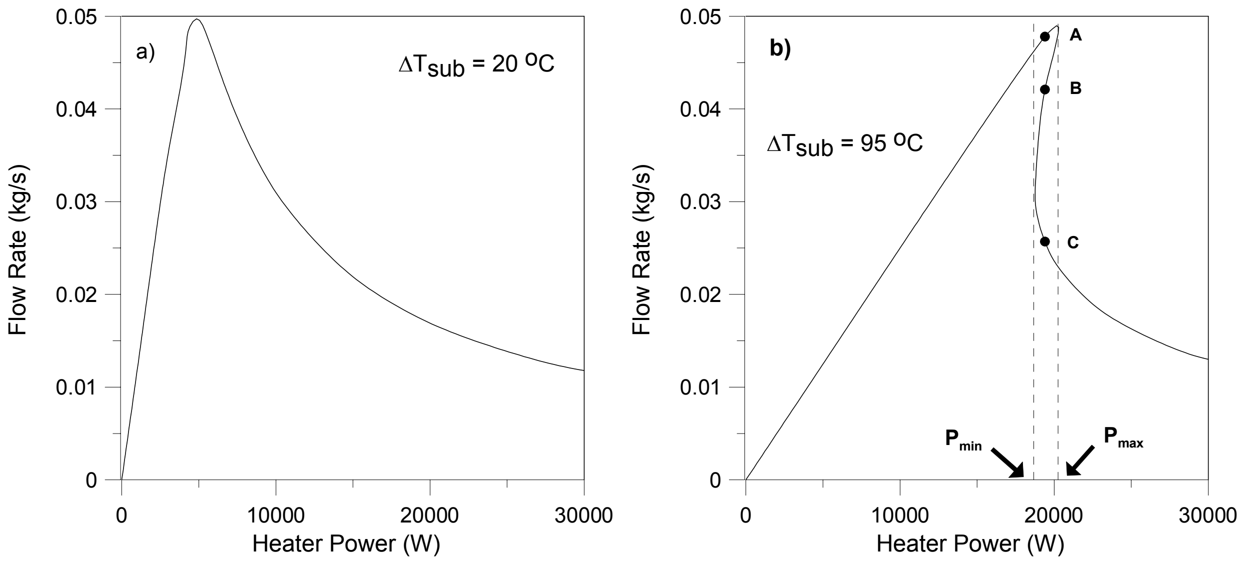

Figure 2. Natural circulation flow rate as function of heater power for different liquid inlet subcoolings using the loop parameters in Table 1.

Fig. 3 shows the stability map in the liquid inlet subcooling versus heater power plane for excursive (static) and density wave (dynamic) instabilities of an open natural circulation loop for the reference parameters in Tab. 1. As is shown in this figure, the two instability boundaries, boundaries A and B of the dynamically stable region get close to each other as the inlet subcooling increases and eventually merge depending on the operating conditions imposed. As can be seen in Fig. 4.a, for boundary A, the location of the transition from single to two-phase flow takes place near the top of the heater and varies very little along this boundary, therefore the gravitational and frictional two-phase flow pressure drops are basically given by the ones in the adiabatic section. The unstable region in the left side of boundary A in Fig. 3 is characterized by a very small exit heater quality, as shown in Fig. 4b, mainly at small powers leading to larger changes in the gravitational two-phase flow pressure drop than that in the frictional one, since the two-phase flow velocity is small (see Fig. 5.a and 5.b). Therefore, the gravitational pressure drop component in the unheated riser plays the dominant role for small powers. As can be seen in Fig. 5.b, as the power is increased along boundary A, the rate of change in the frictional pressure drop overcomes the gravitational one, therefore the frictional pressure drop component becomes the dominant one, although the gravitational effect is still important. On the other hand, the exit quality in the unstable region in the right side of boundary B is high (see Fig. 4.b), this is because for such a high power, evaporation starts at lower locations of the heater and also the rate of increase of quality in the two-phase part of the heater is higher leading to a high two-phase flow velocity in the unheated riser, therefore the two-phase frictional pressure drop plays the dominant role in this region all over boundary B where the gravitational effect is always negligible, as can be seen in Fig. 5.b. As also can be seen in Fig. 3, the excursive instability region lies outside of the density wave one, therefore, the analysis of the density wave stability is sufficient for the purpose of stability analyses. Although it is not shown in Figures 4 and 5, the lines for both boundaries will merge in a very little increase of the liquid inlet subcooling to form a single curve, as can be observed in Fig. 3. This is not shown because it is very tedious to obtain additional points with the required precision and mainly because is not important for the proposed analysis.

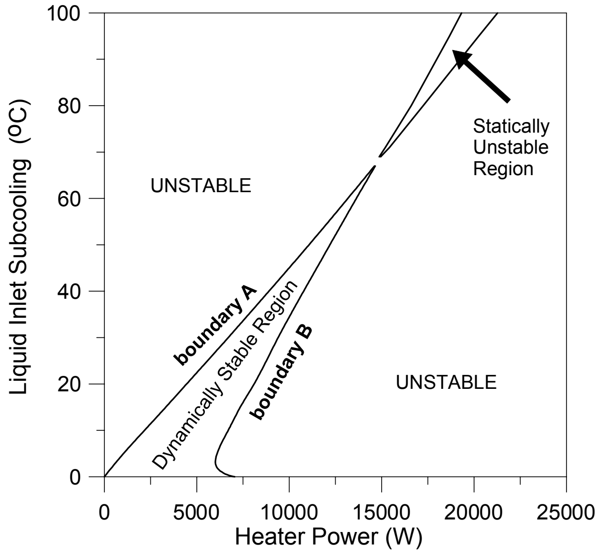

Figure 3. Typical static and dynamic instability maps.

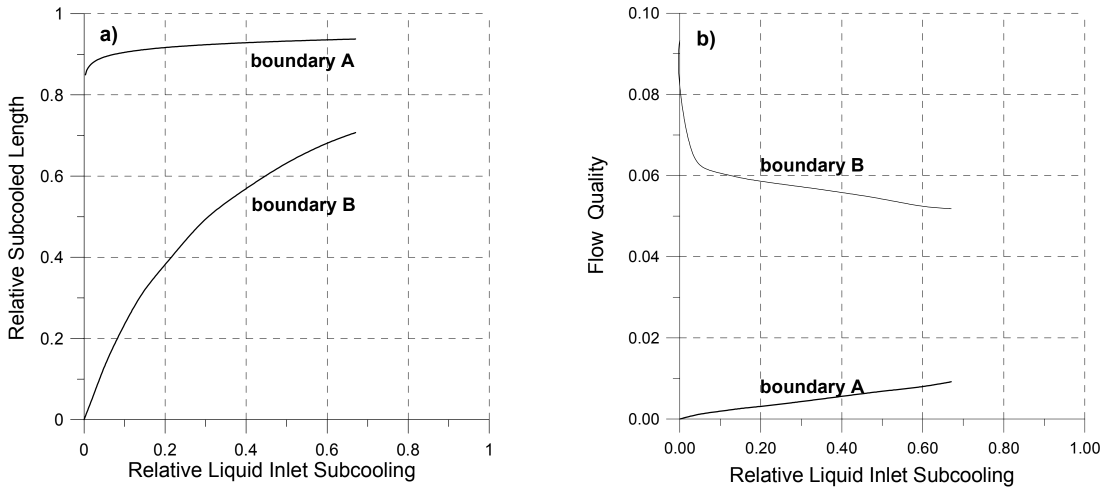

Figura 4. a) Relative Subcooled length [$\lambda/(d-c)$] and b) Flow quality along both boundaries shown in Fig. 3 as function of the relative liquid inlet subcooling [$\Delta T_{sub}/T_{sat}$].

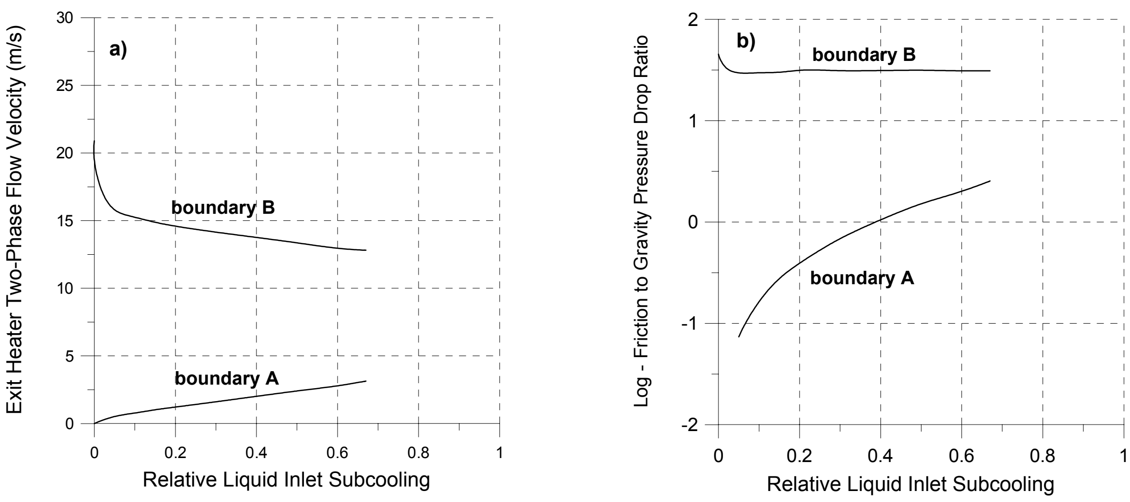

Figure 5. a) Two-phase flow velocity at the heater exit, and b) Ratio of the frictional to gravitational pressure losses in the two-phase part of the loop along both boundaries.

Next, the effect of the gravitational term on the stability of the loop and the naturally induced flow rate will be analyzed. In order to study the effect of the gravitational term, the gravity acceleration will be varied. Figure 6 shows the effect of reducing the gravity acceleration on the stability and flow rate of the loop. As can be seen in Fig. 6.a, by reducing the gravity acceleration, both boundaries A and B move to lower values of the heater power for the same liquid inlet subcooling. Also both the dynamically stable and the statically unstable regions narrow down. Therefore, not only the average power but also the power range for stability is reduced by decreasing the gravity acceleration. Also can be observed in this figure that the maximun liquid inlet subcooling for stability is only slightly reduced. Therefore, as result of the gravity acceleration decrease, the capability of the system to transport energy should be reduced in order to mantain system stability. As also can be noticed in this figure, the region of static instability is moved to lower power values similarly to the dymamic stable region. Fig. 6.b shows the natural circulation flow rate as function of the heater power for a liquid inlet subcooling of 20 ^{o}C. As can be seen, the maximum induced flow rate decreases as the gravity is reduced because of the reduction in the driving head (buoyancy). Also can be seen in this figure that for the same gravity acceleration, in the low heat flux range, the increasing rate of driving head due to gravity is larger than that of frictional pressure drop, so that the higher flow rate is induced with the higher heating rate. The trend is opposite in the high heat flux range, where the frictional pressure drop plays the dominant role due to the high two-phase velocity. The thicker portion of each curve in Fig. 6.b corresponds to the range for which the system is stable. As can be observed, no matters the value of the gravity acceleration, this range is located in the upper part of the curves.

The subcooled length and flow quality along each boundary are shown in Fig. 7. As can be seen, gravity has very little effect on the transition location between single and two-phase flows along boundary A and, consequently, on the flow quality at the exit of the heater. Along boundary B, the subcooled length and the flow quality have the same trends for different gravity accelerations. The subcooled length increases whereas the flow quality decreases slightly for a reduction in the gravity acceleration which indicates a slighty reduction in the power to flow rate ratio.

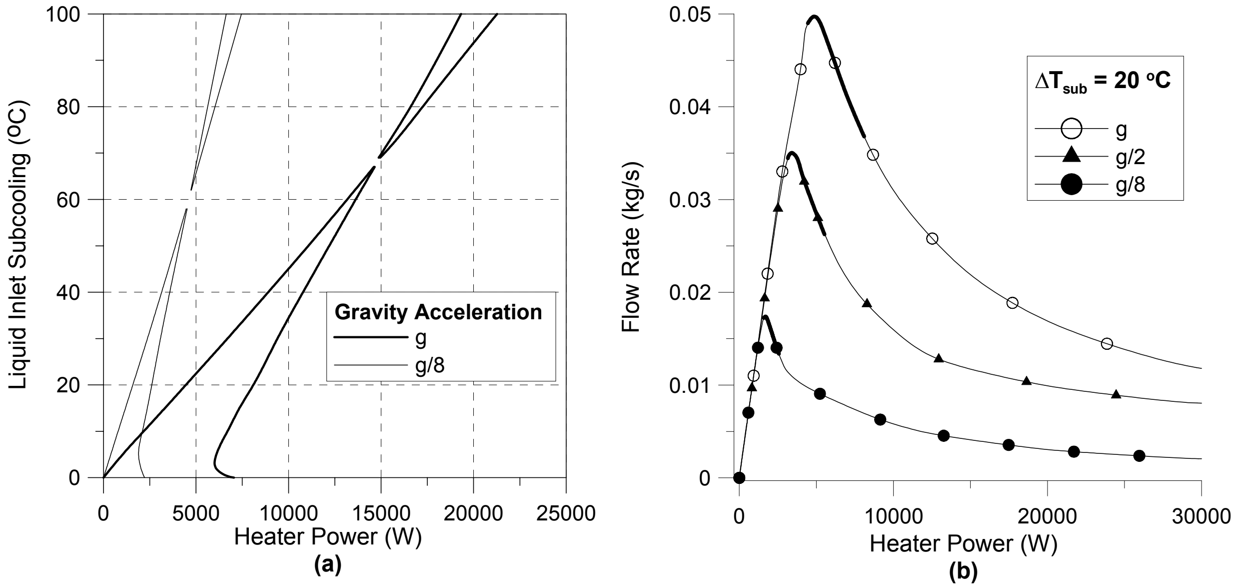

Figure 6. a) Stability maps; and b) Naturally induced loop flow rate as function of heater power for different values of gravity acceleration.

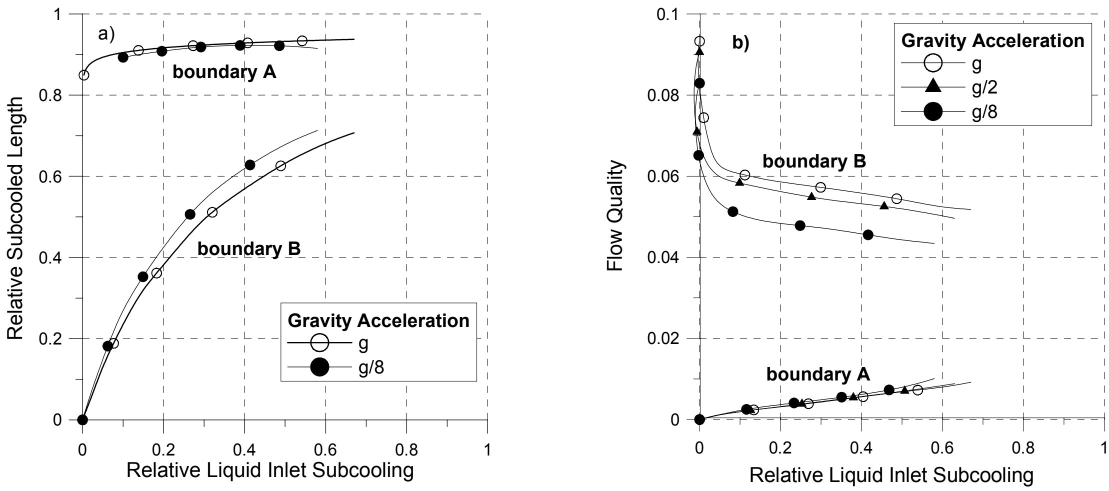

Figure 7. a) Subcooled length and b) Flow quality along both boundaries for differente values of gravity acceleration.

The next results intend to show the influence of the system pressure, through the variation of the fluid properties, on the system parameters and stability of the loop. Figure 8 shows the stability maps and loop flow rates for 1 and 5 atm system pressures. Also shown in this figure is the maximum permissible liquid inlet subcooling (MPLIS) which increases with the system pressure. As can be observed in Fig. 8.a, by increasing the pressure from 1 to 5 atm the dynamically stable region is considerably enlarged and the statically unstable region desappears. Also, the baundary A remains practically unchanged whereas the boundary B moves to much higher powers indicating that the power range for system stability at a specific liquid inlet subcooling is considerably increased by increasing the system pressure. Therefore, the effect of increasing system pressure is clearly of stabilizing the system. In regard to excursive instability, it is more unlikely to occur with pressurization of the loop.

Figure 8.b shows the natural circulation flow rates for the two values of system pressure for a specific liquid inlet subcooling. Both flow rates have the same behavior, i.e., the flow rate initially increases with power reaching a maximum and then decreases with increasing power. The maximum flow rate is not much affected by pressure but the corresponding power is shifted to a higher value. The flow rates are basically the same at small powers but they differ considerably at high powers where the flow rate is higher for the higher pressure. This can be explained by considering the points on boundary B for both pressures. These are the right end points on the thicker portions of both curves shown in Fig. 8.b. As can be seen, they have basically the same flow rates, therefore the void fractions should also be about the same in order to have approximately the same two-phase frictional pressure drops. In order to have similar void fractions, for the higher pressure, the flow quality should be higher, as can be seen in Fig. 9.b., which by its turn imposes a higher power.

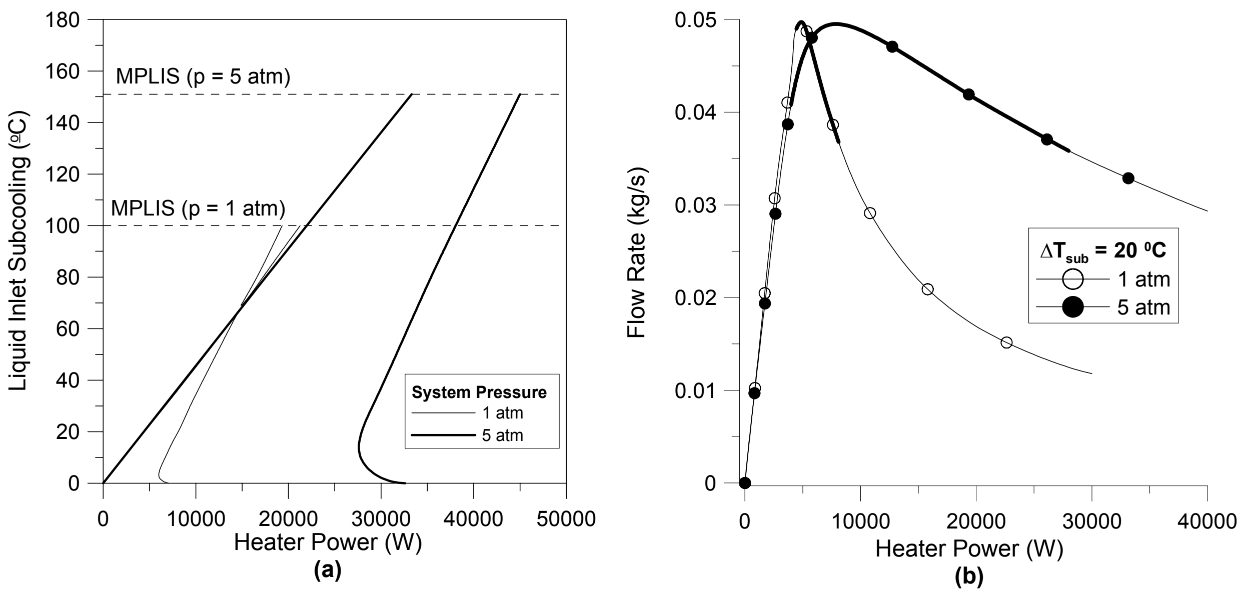

Figure 8. a) Stability maps; and b) Naturally induced loop flow rates as function of heater power for different values of system pressure. The thicker portions of the curves refer to the stable system operating points.

Figure 9 shows the flow quality along boundaries A and B for different pressures. As can be seen in Fig. 9.a, there is a small increase in the flow quality at boundary A as the pressure increases but the quality is still very small. On the other hand, the quality at boundary B increases substantially with the pressure, as is shown in Fig. 9.b. The quality variation along this boundary is similar for the different system pressures. For small liquid inlet subcoolings the quality is quite high. As the subcooling is increased the quality reduces and the reduction is slower as the subcooling approaches the maximum liquid inlet subcooling. Actually, it can be said that the quality remains almost constant for most of the liquid inlet subcooling range. Therefore, for a specific loop geometry and pressure, this information can be used to set a maximum permissible flow quality, for system stability, for the entire range of liquid inlet subcooling. This might not be very good only for small subcoolings where this approach may be too conservative. Figure 10 shows that the void fraction along boundary B is very little affected by the system pressure although the quality may vary significantly. In cases that the operating system pressure may change, this information can also be taken into account for avoiding instabilities of the loop.

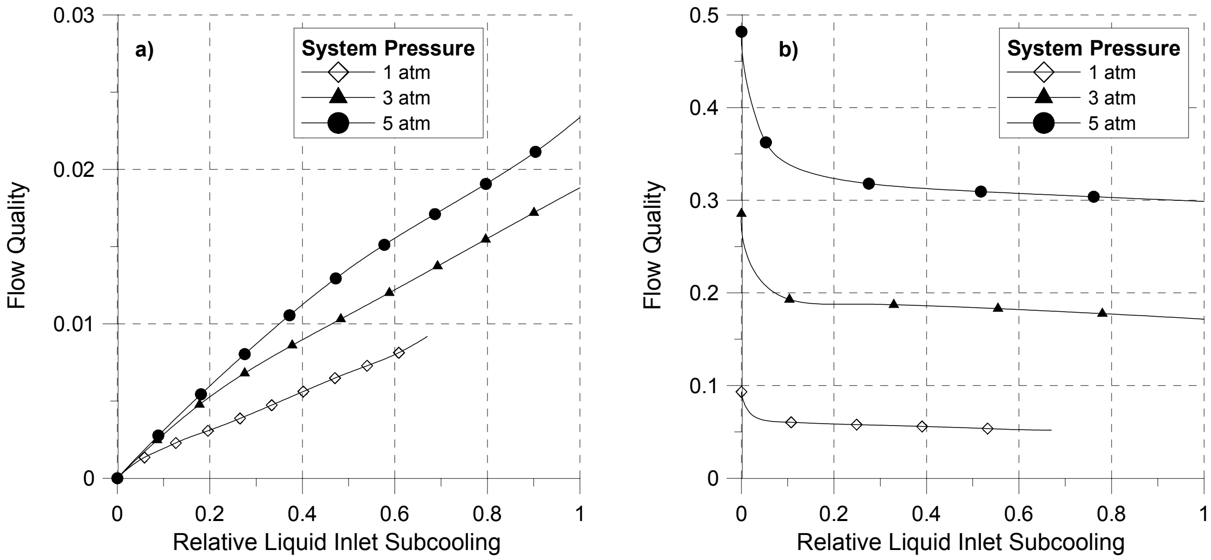

Figure 9. Flow quality at (a) boundary A and (b) boundary B, for differente values of system pressure.

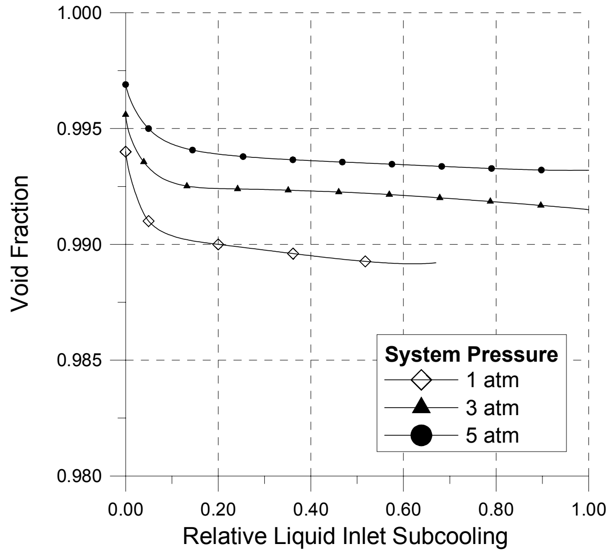

Figure 10. Void fraction variation along boundary B for different system pressure.

Comparisons of the analytical results, using the homogenous equilibrium model and linear stability criteria, with experimental ones performed by Fukuda and Kobori (1979) have shown that the trends of boundary B reasonably agree except in the low liquid inlet subcooling range. Similarly, Lee and Lee (1991) have found the same results when they compared their analytical results against the experimental ones by Chexal and Bergles (1973). Therefore, the simplifying assumption of one-dimensional homogeneous two-phase flow may still yield good qualitative results for the high exit quality stability boundary except in the low liquid inlet subcooling range where certain deviations were observed. The same observations were made by Rosa and Podowski (1995) for a boiling channel with fixed Froude number (Fr), using the time domain computer code DYNOBOSS (Rosa and Podowski, 1997) and the experimental data obtained by Saha and Zuber (1978).

3. Comments and Conclusions

It has been presented a loop modeling and a methodology based on linear criteria for obtaining stability maps for both density wave and excursive instabilities in open two-phase natural circulation loops. The dynamic stability region appears at the lower left part of the liquid inlet subcooling versus heater power plane, bounded by two boundaries whereas the excursive instability region appears at the upper right part of the map and eventually touches the line of maximum inlet subcooling. The effect of loop geometry and sizing was investigated in a previou work by the same author (Rosa, 2002) using the same modeling and methodology. The present work complements the other one showing the effects of both the fluid properties due to changes in the system pressure and the environment gravity acceleration on the loop parameters and stability.

As the most important result of the present analysis, it was shown that reduction of both system pressure and gravity acceleration has the effect of destabilizing the system. It should be mentioned that the system stability trends, for system pressure variation, obtained herein agree with the experimental ones obtained by Fukuda and Kobori (1979). Although the two-phase flow model used in this work should still be experimentally checked regarding its applicability in a moderate to low gravity environment, mainly because the gravitational effects on two-phase flows are yet not entirely known, these preliminary results have shown that this conventional heat transport system can still be used in such an environment by making appropriate choices of system parameters such as loop geometry and sizing, flow restrictions, operating pressure, type of fluid, and so on. Besides, some interesting observations can be done from the results. For instance, it is noticed that the subcooled length along boundary A is basically the same for the entire range of liquid inlet subcooling operating conditions and it is not affected by changes in the gravity acceleration. Also, the flow quality increases considerably with increasing pressure at boundary B although the void fraction is very little affected. These kinds of information can be used to establish very simple and quick-check criteria that provide indications about the stability of the system.

In the work by Rosa and Podowski (1995), the authors have showed that subcooled boiling and phasic slip play important roles in the stability of the system as previously reported by Saha and Zuber (1978). Therefore, in order to improve the results, it is important to use more elaborated models that incorporate such two-phase flow situations and then apply linear stability criteria. This will certainly yield a more powerful tool for stability analysis of two-phase flow systems.

4. Nomenclature

A_{xs}	flow area
$b, \cdots d$	lengths
D	pipe hydraulic diameter
f	friction factor
g	gravity acceleration
G	transfer function
h	mixture enthalpy
H, H_c	lengths
k_i, k_o	inlet and exit friction loss coefficients
l, l_o, L	lengths
p	pressure
P	heater power
q'	linear heat rate
s	Laplace transform variable
t	time
u	mixture velocity
u_l	liquid velocity
z	axial direction coordinate
T_{sat}	liquid saturation temperature
δ	perturbation symbol
λ	boiling boundary transition
ρ	mixture density
ω	angular frequency
ΔP	pressure drop
ΔT_{sub}	liquid inlet temperature subcooling

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