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Review Article

Flow Instabilities in Boiling Two-Phase Natural Circulation Systems: A Review

A. K. Nayak and P. K. Vijayan

Reactor Engineering Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

Correspondence should be addressed to A. K. Nayak, arunths@barc.gov.in

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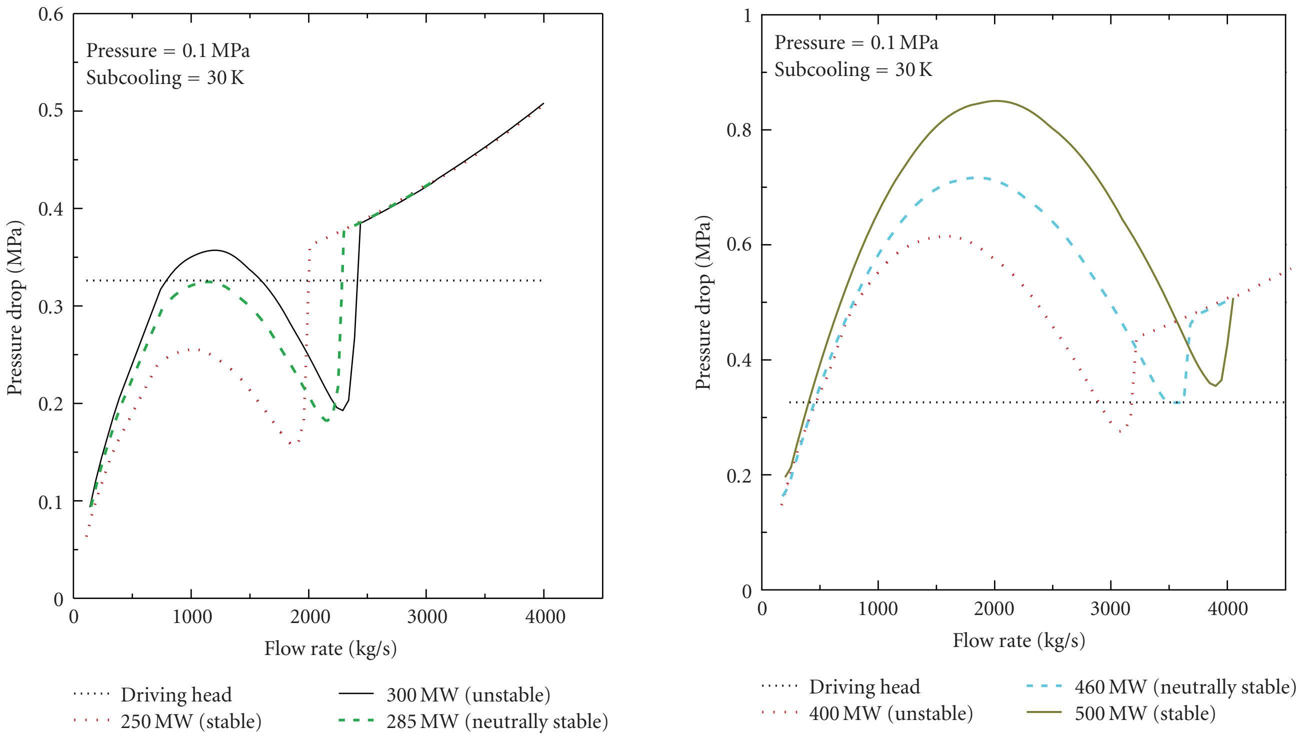
Several decades have been spent on the study of flow instabilities in boiling two-phase natural circulation systems. It is felt to have a review and summarize the state-of-the-art research carried out in this area, which would be quite useful to the design and safety of current and future light water reactors with natural circulation core cooling. With that purpose, a review of flow instabilities in boiling natural circulation systems has been carried out. An attempt has been made to classify the instabilities occurring in natural circulation systems similar to that in forced convection boiling systems. The mechanism of instabilities occurring in two-phase natural circulation systems have been explained based on these classifications. The characteristics of different instabilities as well as the effects of different operating and geometric parameters on them have been reviewed.

1. INTRODUCTION

Natural circulation (NC) systems are susceptible to several kinds of instabilities. Although instabilities are common to both forced and natural circulation systems, the latter is inherently more unstable than forced circulation systems due to more nonlinearity of the NC process and its low driving force. Because of this, any disturbance in the driving force affects the flow which in turn influences the driving force leading to an oscillatory behavior even in cases where eventually a steady state is expected. In other words, a regenerative feedback is inherent in the mechanism causing NC flow due to the strong coupling between the flow and the driving force. Even among two-phase systems, the NC systems are more unstable than forced circulation systems due to the above reasons.

Before we proceed further, let us define the term "instability." Following a perturbation, if the system returns back to the original steady state, then the system is considered to be stable. If on the other hand, the system continues to oscillate with the same amplitude, then the system is neutrally stable. If the system stabilizes to a new steady state or oscillates with increasing amplitude, then the system is considered as unstable. It may be noted that the amplitude of oscillations cannot go on increasing indefinitely even for unstable flow. Instead for almost all cases of instability, the amplitude is limited by nonlinearities of the system and limit cycle oscillations (which may be chaotic or periodic) are eventually established. The time series of the limit cycle oscillations may exhibit characteristics similar to the neutrally stable condition. Further, even in steady state case, especially for two-phase systems with slug flow, small amplitude oscillations are visible. Thus, for identification purposes especially during experiments, often it becomes necessary to quantify the amplitude of oscillations as a certain percentage of the steady state value. Amplitudes more than ± 10% of the mean value is often considered as an indication of instability. However, some authors recommend the use of ± 30% as the cutoff value [1].

Instability is undesirable as sustained flow oscillations may cause forced mechanical vibration of components. Further, premature CHF (critical heat flux) occurrence can be induced by flow oscillations as well as other undesirable secondary effects like power oscillations in BWRs. Instability can also disturb control systems and cause operational problems in nuclear reactors. Over the years, several kinds of instabilities have been observed in natural circulation systems excited by different mechanisms. Differences also exist in their transport mechanism, oscillatory mode, and analysis methods.In addition, effects of loop geometry



(a)

(b)

Figure 1: Typical stable, unstable, and neutrally stable behaviour for Ledinegg-type instability.

and secondary parameters also cause complications in the observed instabilities. Under the circumstances, it looks relevant to classify instabilities into various categories which will help in improving our understanding and hence control of these instabilities.

2. INSTABILITY CLASSIFICATION

Mathematically, the fundamental cause of all instabilities is due to the existence of competing multiple solutions so that the system is not able to settle down to anyone of them permanently. Instead, the system swings from one solution to the other. An essential characteristic of the unstable oscillating NC systems is that as it tries to settle down to one of the solutions, a self-generated feedback appears making another solution more attractive causing the system to swing toward it. Again, during the process of settling down on this solution, another feedback of opposite sign favoring the original solution is self-generated and the system swings back to it. The process repeats itself resulting in perpetual oscillatory behavior if the operating conditions are maintained constant. Although this is a general characteristic it hardly distinguishes the different types of instabilities found to occur in various systems. In general, instabilities can be classified according to various bases as follows:

(a) analysis method;
(b) propagation method;
(c) number of unstable zones;
(d) nature of the oscillations;
(e) loop geometry;
(f) disturbances or perturbations.

2.1. *Based on the analysis method (or governing equations used)*

In some cases, the occurrence of multiple solutions and the instability threshold itself can be predicted from the steady-state equations governing the process (pure or fundamental static instability). The Ledinegg-type instability is one such example occurring in boiling two-phase NC systems. The occurrence of this type of instability can be ascertained by investigating the steady-state behavior alone. The criterion for this type of instability is given by

$$\frac{\partial \Delta p_{\text{int}}}{\partial w} - \frac{\partial \Delta p_{dv}}{\partial w} \leq 0, \tag{1}$$

where Δp_{int} is the internal pressure loss in the system and Δp_{dv} is the driving head due to buoyancy. The internal pressure loss of the system includes the losses due to friction, elevation, acceleration and local in the heated portion, the riser pipes and the steam drum, and all the losses except the elevation loss in the downcomers. The driving head is basically the gravitational head available from the steam drum to the bottom of the heated section. Figures 1(a) and 1(b) show an example of occurrence of Ledinegg-type instability at different powers [2] in a boiling two-phase NC system. The instability is found to occur when the power is more than 285 MWth and less than 460 MWth if the operating pressure is 0.1 MPa and the subcooling is 30 K. When the power is in between the above specified range, the internal pressure loss curve intersects the driving buoyancy curve at three points (i.e., three operating points at a given power level) which makes the system unstable. Thus at 30 K subcooling, the system can have two threshold points of instability.

Like the Ledinegg instability, the flow pattern transition instability is another static instability caused by the excursion of flow due to differences in the pressure drop characteristics of different flow patterns. To analyze this type instability, it is required to predict the pressure drop characteristics of the system against the flow rate similar to the Ledinegg-type instability [3]. Figure 2 shows an example of the steady-state pressure drop characteristics of the system for analysis of flow pattern transition instability. The gravitational head, which depends on the density of the single-phase fluid, remains constant at a particular core inlet temperature. The different flow patterns in the vertical and horizontal portions of the riser pipes are shown in the two-phase region at the operating conditions. It can be observed from Figure 2 that there can be multiple steady-state flow rates (point at which the driving head intersects the internal loss curve) at this operating condition. The number of flow excursions is seen to be five, unlike that of the Ledinegg-type instability. The type of flow excursion in different flow regimes are observed to be as follows: there can be one flow excursion in the annular region itself due to reduction of pressure drop with reduction in quality as in the Ledinegg-type instability. The next flow excursion occurs due to rise in pressure drop when the flow pattern changes from annular to slug flow in the vertical portion of the riser pipes. The other flow excursion occurs when the flow pattern changes from the annular to dispersed bubbly flow in the horizontal portion of riser pipes due to reduction of pressure drop with flow rate. The last flow excursion occurs when the flow becomes single phase and the pressure drop increases with increase in flow rate. Thus, there can be five different flow rates for a particular operating condition of power and subcooling as indicated in Figure 2 by points A–E. The existence of multiple flow rates as a particular operating power and subcooling makes the system unstable. For example, if the system is initially operating at point C, any slight disturbance causing the flow to increase will shift the flow rate to point D and the to point E. Similarly, any slight disturbance causing the flow rate to decrease will shift the operating point to B and then to point A. Thus, the flow rate can jump from one value to the other even though the operating power and pressure are constant. This makes the system unstable.

However, there are many situations with multiple steady-state solutions where the threshold of instability cannot be predicted from the steady-state laws alone (or the predicted threshold is modified by other effects). In this case, feedback effects are important in predicting the threshold (compound static instability). Besides, many NCSs with only a unique steady-state solution can also become unstable during the approach to the steady state due to the appearance of competing multiple solutions due to the inertia and feedback effects (pure dynamic instability). Neither the cause nor the threshold of instability of such systems can be predicted purely from the steady state equations alone. Instead, it requires the full transient governing equations to be considered for explaining the cause and predicting the threshold. In addition, in many oscillatory conditions, secondary phenomena get excited and they modify significantly the characteristics of the fundamental instability. In such cases, even the prediction of the instability threshold may require consideration of the secondary effect (compound dynamic instability). A typical case is the neutronic feedback responding to the void fluctuations resulting in both flow and power oscillations in a BWR. In this case, in addition to the equations governing the thermalhydraulics, the equations for the neutron kinetics and fuel thermal response also need to be considered.

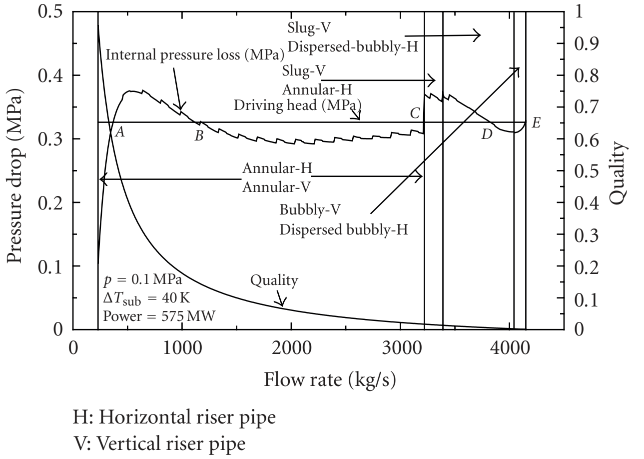


Figure 2: Typical flow pattern transition instability in boiling natural circulation systems.

Thus we find that the analysis to arrive at the instability threshold can be based on different sets of governing equations for different instabilities. Boure et al. [4] classified instabilities into four basic types as follows:

(a) pure static instability;

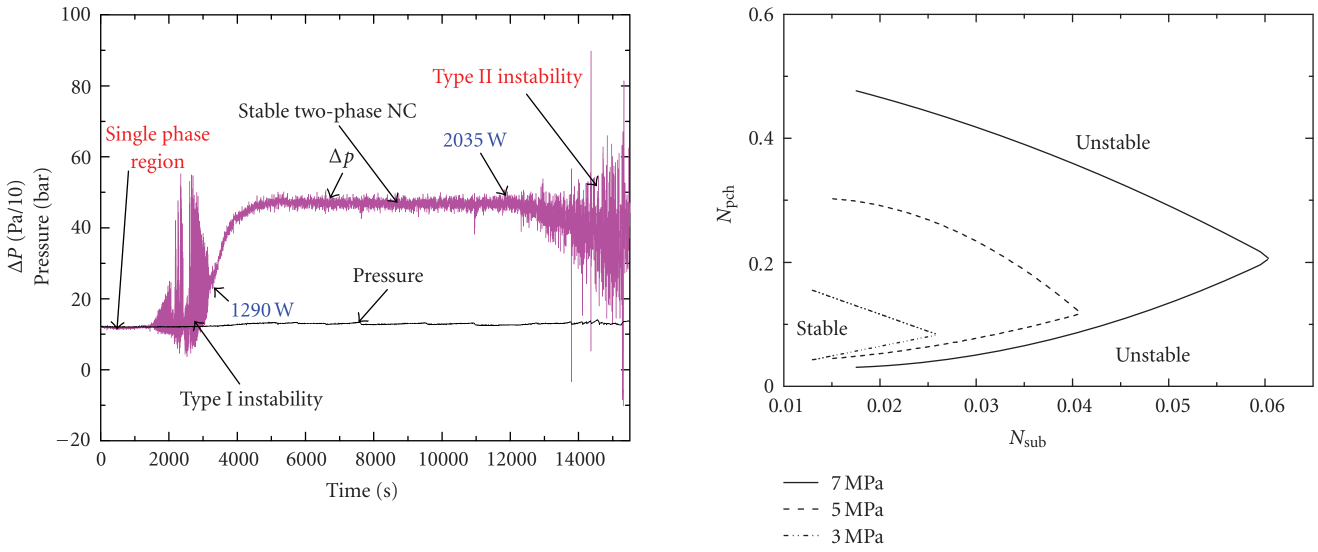
(b) compound static instability (it may be noted that Boure et al. [4] named this instability as compound relaxation instability);

(c) pure dynamic instability;

(d) compound dynamic instability.

2.2. Based on the propagation method

This classification is actually restricted to only the dynamic instabilities. According to Boure et al. [4], the mechanism of dynamic instability involves the propagation or transport of disturbances. In two-phase flow, the disturbances can be transported by two different kinds of waves: pressure (acoustic waves) and void (or density) waves. In any two-phase system, both types of waves are present, however, their



(a) Typical low-power and high-power unstable zones for two-phase NC flow

(b) Typical stability map for two-phase density wave instability [2]

FIGURE 3

velocities differ by one or two orders of magnitude allowing us to distinguish between the two.

2.2.1. *Acoustic instability*

Acoustic instability is considered to be caused by the resonance of pressure waves. Acoustic oscillations are also observed during blowdown experiments with pressurized hot-water systems possibly due to multiple wave reflections. Acoustic oscillations are characterized by high frequencies of the order of 10–100 Hz related to the pressure wave propagation time [4]. Acoustic oscillations have been observed in subcooled boiling, bulk boiling, and film boiling. The thermal response of the vapor film to passing pressure wave is suggested as a mechanism for the oscillations during film boiling. For example, when a compression (pressure wave consists of compression and rarefaction) wave passes, the vapor film is compressed enhancing its thermal conductance resulting in increased vapor generation. On the other hand when a rarefaction wave passes, the vapor film expands reducing its thermal conductance resulting in decreased vapor generation. The process repeats itself.

2.2.2. *Density-wave instability (DWI)*

A density-wave instability is the typical dynamic instability which may occur due to the multiple regenerative feedbacks between the flow rate, enthalpy, density, and pressure drop in the boiling system. The occurrence of the instability depends on the perturbed pressure drop in the two-phase and single-phase regions of the system and the propagation time delay of the void fraction or density in the system. Such an instability can occur at very low-power and at high-power conditions. This depends on the relative importance of the respective components of pressure drop such as gravity or frictional losses in the system. Fukuda and Kobori [5] have classified the density-wave instability as type I and type II for the low power and high-power instabilities, respectively. The mechanisms can be explained as follows [6].

Type I instability

For this type of instability to occur, the presence of a long riser plays an important role such as in a boiling two-phase natural circulation loop. Under low quality conditions, a slight change in quality due to any disturbance can cause a large change in void fraction and consequently in the driving head. Therefore, the flow can oscillate at such low-power conditions. But as the power increases, the flow quality increases where the slope of the void fraction versus quality reduces. This can suppress the fluctuation of the driving head for a small change in quality. Hence, the flow stabilises at higher power (Figures 3(a) and 3(b)).

Type II instability

Unlike the type I instability, the type II instability occurs at high-power conditions. This instability is driven by the interaction between the single and two-phase frictional component of pressure losses, mass flow, void formation, and propagation in the two-phase region. At high power, the flow quality or void fraction in the system is very large. Hence, the two-phase frictional pressure loss may be high owing to the smaller two-phase mixture density. Having a large void fraction will increase the void propagation time delay in the two-phase region of the system. Under these conditions, any small fluctuation in flow can cause a larger fluctuation of the two-phase frictional pressure loss due to fluctuation of density and flow, which propagates slowly in the two-phase region. On the other hand, the fluctuation of the pressure drop in the single-phase region occurs due to fluctuation of flow alone since the fluctuation of the density is negligible. The pressure drop fluctuation in this region travels much faster due to incompressibility of single-phase region. If the two-phase pressure drop fluctuation is equal in magnitude but opposite in phase with that of the single-phase region, the fluctuation or oscillation is sustained in the system since there are no attenuating mechanisms. Divergent oscillations can occur depending on the magnitude of the pressure-loss fluctuation in the two-phase and single-phase regions and the propagation time delay.

Because of the importance of void fraction and its effect on the flow as explained above, this instability is sometimes referred to as flow-void feedback instability in two-phase systems. Since transportation time delays (related to the spacing between the light and heavy packets of fluid as explained above) are crucial to this instability, it is also known as "time-delay oscillations". Density-wave instability (DWI) or density-wave oscillations (DWO), first used by Stenning and Veziroğlu [7], is the most common term used for the above described phenomenon as it appears that a density wave with light and heavy fluid packets is traveling through the loop.

2.3. Based on the number of unstable zones

Fukuda and Kobori [5] gave a further classification of density-wave instability based on the number of unstable zones. Usually, there exists a low-power and a high-power unstable zone for density wave instability in forced as well as NC two-phase flows (Figure 3(a)). For the two-phase flow density-wave instability, the unstable region below the lower threshold occurs at a low power and hence at low quality and is named as type I instability by Fukuda and Kobori [5]. Similarly, the unstable region beyond the upper threshold occurs at a high power and hence at high qualities and is named as type II instability. However, in certain cases depending on the geometry and operating conditions, islands of instability have been observed to occur [8–10]. In these cases, more than two zones of instability were observed. Chen et al. [11] also observed hysteresis in a two-phase loop. As an unstable single-phase system progresses through single-phase NC to boiling inception and then to fully-developed two-phase NC with power change, it can encounter several unstable zones. In view of the existence of more than two unstable zones, this method of classification could be confusing at times.

2.4. Based on the nature of the oscillations

All instabilities eventually lead to some kind of oscillations. The oscillations can be labeled as flow excursions, pressure drop oscillations, power oscillations, temperature excursions or thermal oscillations, and so on. Besides, classifications based on the oscillatory characteristics are sometimes reported for dynamic instability. For example, based on the periodicity sometimes oscillations are characterized as periodic and chaotic. Based on the oscillatory mode, the oscillations are characterized as fundamental mode or higher harmonic modes [12]. In boiling NC systems with multiple parallel channels, inphase and out of phase modes are present depending on the geometry of the channels and heating conditions. Sometimes, dual oscillations also are possible. In natural circulation loops, flow direction can also change during oscillations. Based on the direction of flow, the oscillations can be characterized as unidirectional, bidirectional, or it can switch between the two. Such switching is often accompanied by period doubling, tripling, or n-tupling.

2.5. Based on the loop geometry

Certain instabilities are characteristic of the loop geometry. Examples are the instabilities observed in open U-loops, symmetric closed loops, and asymmetric-closed loops. In addition, pressure-drop oscillations and the parallel-channel instability are also characteristic of the loop geometry. Another type instability which can occur in systems with a compressible volume (e.g., a pressurizer) at the inlet of the heated channel is the pressure-drop-type instability. Similarly, interaction among parallel channels can also lead to various complex instabilities as discussed above.

2.6. Based on the disturbances

Certain two-phase flow phenomena can cause a major disturbance and can lead to instability or modify the instability characteristics significantly. Typical examples are boiling inception, flashing, flow pattern transition, or the occurrence of CHF. Cold water injection can also cause a major disturbance and instability in natural circulation systems.

3. CHARACTERISTICS OF INSTABILITIES

Several types of flow regimes can be associated in a natural circulation loop as heating proceeds. Some of these flow regimes are stable while others are unstable. For example, [13] observed seven different types of flow modes in a boiling two-phase natural circulation loop with increase in heater power such as (i) surface evaporation, (ii) a static instability characterized by periodic exit large bubble formation, (iii) a steady flow with continuous exit of small bubbles, (iv) a static instability characterized by periodic exit of small bubbles, (v) another static instability characterized by periodic extensive small bubble formation, (vi) a steady natural circulation, and (vii) the density-wave oscillation (dynamic instability). The static instabilities observed in their loop are due to the high heat flux and subcooled boiling occurring in the heated section, which are ideal for the cause of chugging-type instability. The characteristics of the instabilities are different from one to the other due to the differences in the physical mechanism associated with their initiations.

3.1. Characteristics of Instabilities associated with boiling inception

Boiling inception is a large enough disturbance that can bring about significant change in the density and hence the buoyancy driving force in an NCS. A stable single-phase NCS can become unstable with the inception of boiling. Boiling inception is a static phenomenon that can lead to instability in low-pressure systems. However, feedback effects also are paramount in the phenomena. Hence the instability belongs to the class of compound-static instability. In this case, however, the instability continues with limit cycle oscillations. The oscillatory mode during boiling inception can also be significantly affected by the presence of parallel channels.

3.1.1. *Effect of boiling inception on unstable single-phase NC*

With increase in power, subcooled boiling begins in an unstable single-phase system leading to the switching of flow between single-phase and two-phase regimes. Experiments in a rectangular loop showed that subcooled boiling occurs first during the low flow part of the oscillation cycle [14]. The bubbles formed at the top horizontal-heated wall flows along the wall into the vertical limb leading to an increase in flow rate. The increased flow suppresses boiling leading to single-phase flow. Several regimes of unstable flow with subcooled boiling can be observed depending on the test section power such as (a) instability with sporadic boiling (boiling does not occur in every cycle), (b) instability with subcooled boiling once in every cycle; (c) instability with subcooled boiling twice in every cycle, and (d) instability with fully developed boiling. The change in power required from the first to the last stage is quite significant and it may not be reached in low-power loops.

U-tube manometer-type instabilities have been observed in boiling NC systems at reduced downcomer level [15] when the loop is heated from single-phase condition. The flow is found to reverse even before boiling is initiated (Figure 4). However, with initiation of boiling, no flow reversal is observed (Figure 5). The characteristics of oscillation were similar as previous cases (i.e., periodic large amplitude oscillation with few small amplitude oscillations in between). However, regular flow stagnation is observed, which is of concern for the safety of nuclear reactors. Also the amplitude of oscillation was found to be larger than that under single-phase conditions.

3.1.2. *Effect of boiling inception on steady single-phase NC*

A common characteristic of the instabilities associated with boiling inception is that single-phase conditions occur during part of the oscillation cycle. With the bubbles entering the vertical tubes, the buoyancy force is increased which increases the flow. As the flow is increased, the exit enthalpy is reduced leading to suppression of boiling. This reduces the buoyancy force and the flow, increasing the exit enthalpy resulting in boiling and leading to the repetition of the process. Krishnan and Gulshani [16] observed such instability in a figure-of-eight loop. They found that the single-phase circulation was stable. However, with power increase, the flow became unstable as soon as boiling was initiated in the heated section. Other examples of instabilities associated with boiling inception in stable single-phase NCs are the following.

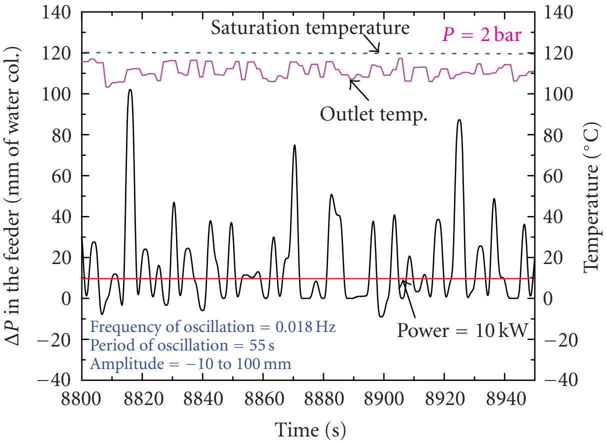


Figure 4: Typical flow instability behavior at low power under single-phase condition (power 10 kW).

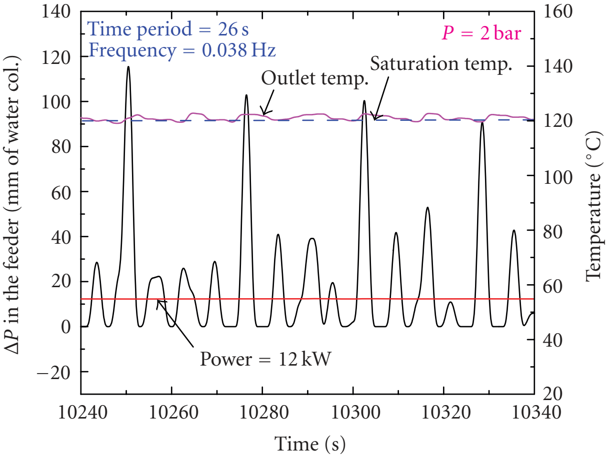
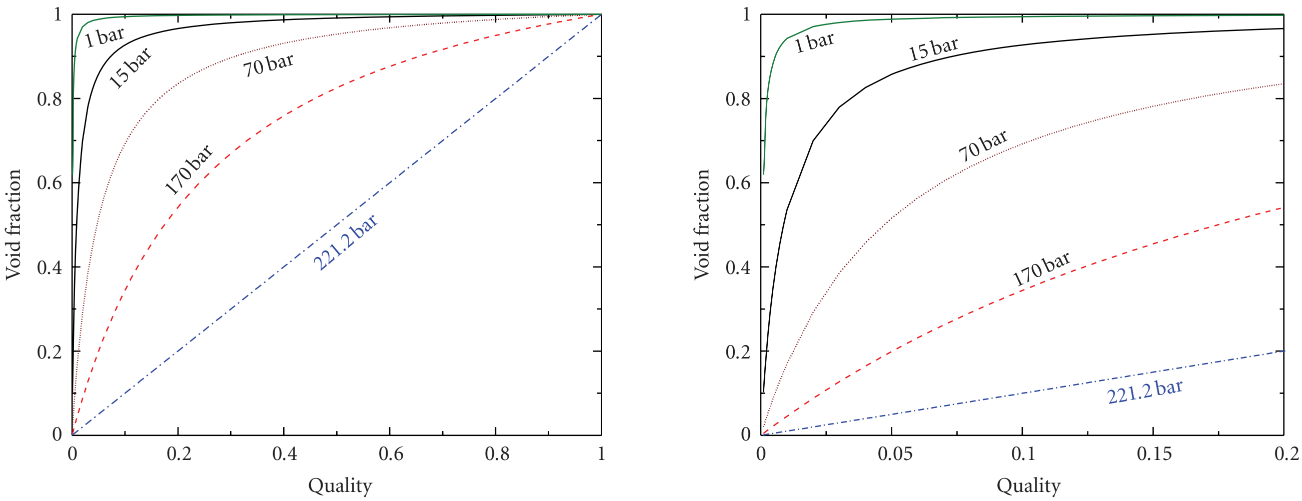


Figure 5: Typical flow instability behavior at low power under two-phase condition (initiation of boiling, power 12 kW).

(a) Flashing instability

Flashing instability is expected to occur in NCSs with tall, unheated risers. The fundamental cause of this instability is that the hot liquid from the heater outlet experiences static pressure decrease as it flows up and may reach its saturation value in the riser causing it to vaporize. The increased driving force generated by the vaporization, increases the flow rate leading to reduced exit temperature and suppression of flashing. This in turn reduces the driving force and flow causing the exit temperature to increase once again leading to the repetition of the process. The necessary condition for flashing is that the fluid temperature at the inlet of the riser is greater than the saturated one at the exit [17]. The instability is characterized by oscillatory behavior and gets suppressed with rise in pressure [18, 19]. Furuya et al. [18] did systematic analyses to characterize the difference between



(a) For the entire range of qualities

(b) For low qualities

Figure 6: Effect of pressure on the void fraction.

flashing instability from other flow instabilities in boiling systems such as geysering, natural circulation instabilities like a DWI, and flow pattern transition instability. Their main observations were that the oscillation period in flashing instability correlates well with the passing time of single-phase liquid in the chimney section regardless of the system pressure, the heat flux, the inlet subcooling, and the wave-form. Out of phase flashing, oscillations were observed in the parallel channels of the CIRCUS facility by Marcel et al. [20].

(b) Geysering

Geysering was identified by both Boure et al. [4] and Aritomi et al. [21] as an oscillatory phenomenon which is not necessarily periodic. The proposed mechanism by both the investigators differ somewhat. However, a common requirement for geysering is again a tall riser at the exit of the heated section. When the heat flux is such that boiling is initiated at the heater exit and as the bubbles begin to move up the riser they experience sudden enlargement due to the decrease in static pressure and the accompanying vapor generation, eventually resulting in vapor expulsion from the channel. The liquid then returns, the subcooled nonboiling condition is restored, and the cycle starts once again. The main difference with flashing instability is that the vapor is produced first in the heated section in case of geysering, whereas in flashing the vapor is formed by the decrease of the hydrostatic head as water flows up.

The mechanism as proposed by Aritomi et al. [21] considers condensation effects in the riser. According to him, geysering is expected during subcooled boiling when the slug bubble detaches from the surface and enters the riser (where the water is subcooled), where bubble growth due to static-pressure decrease and condensation can take place. The sudden condensation results in depressurization causing the liquid water to rush in and occupy the space vacated by the condensed bubble. The large increase in the flow rate causes the heated section to be filled with subcooled water suppressing the subcooled boiling, and reducing the driving force. The reduced driving force reduces the flow rate. Increasing the exit enthalpy and eventually leading to subcooled boiling again and repetition of the process. Geysering involves bubble formation during subcooled conditions, bubble detachment, bubble growth, and condensation. Geysering is a thermal nonequilibrium phenomenon. On the other hand, during flashing instability, the vapor is in thermal equilibrium with the surrounding water and they do not condense during the process of oscillation. Both these instabilities are observed during low-pressure conditions only.

Instability due to boiling inception usually disappears with increase in system pressure due to the strong influence of pressure on the void fraction and hence the density (Figure 6).

3.2. Characteristics of two-phase static instability

Static instability can lead either to a different steady state or to a periodic behavior. Commonly observed, static instabilities are flow excursion and boiling crisis.

3.2.1. Flow excursion or excursive instability

The characteristics of the flow excursion instability or Ledinegg type instability depend very much on the geometry as well as the system pressure, power, and channel inlet subcooling [22]. Figure 7 shows an example of the stability maps for Ledinegg type instability at different pressures for a natural circulation boiling water reactor [2]. The Ledinegg-type instability decreases with an increase in pressure. This may be due to the fact that with an increase in pressure, the void fraction decreases with quality significantly in the

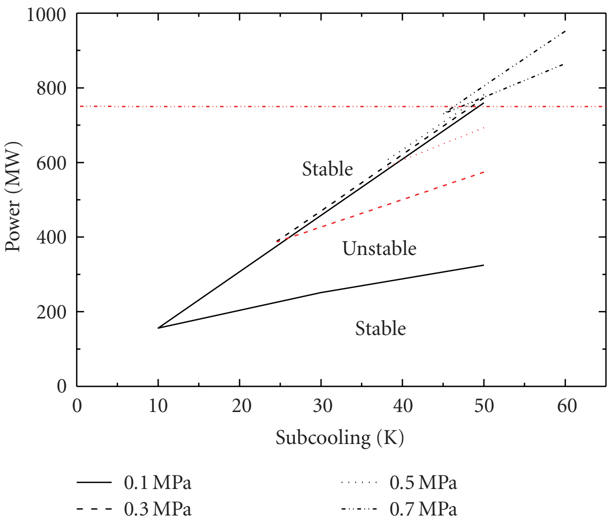


Figure 7: Characteristics of Ledinegg-type instability in NCS.

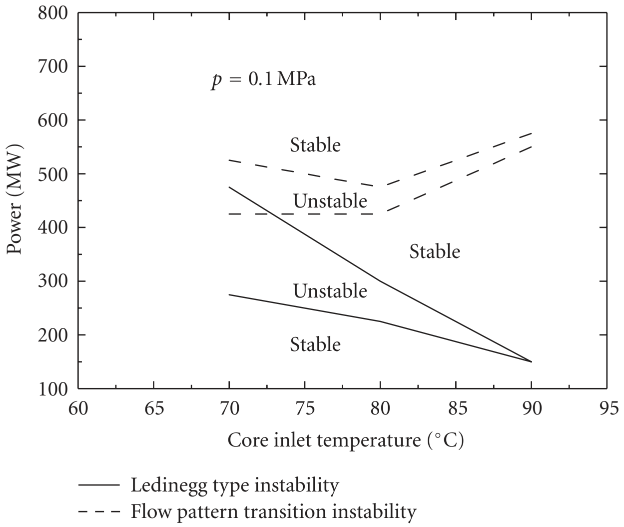


Figure 8: Comparison between Ledinegg and flow pattern transition instability maps for NC.

two-phase region, which can reduce the S-shaped variation of the irreversible losses (i.e., $\partial \Delta p_{\text{int}}/\partial w$) responsible for the occurrence of the Ledinegg-type instability. Similar to the type I and type II density-wave oscillations, two types of Ledinegg instabilities are observed at any subcooling depending on the operating power. With increase in pressure, the threshold power for the lower instability boundary moves to much higher power and the upper threshold boundary does not change significantly. The interesting thing which can be observed from the figure is that this instability almost vanishes when the operating pressure is more than 0.7 MPa.

3.2.2. Flow pattern transition instability

While there are several experimental and analytical studies to understand the characteristics of Ledinegg-type instability, there are not many studies on flow pattern transition instability. Nayak et al. [3] were probably the first to clarify some characteristics of this type of instability theoretically. They compared the stability maps between the Ledinegg and the flow pattern transition instability (Figure 8). The Ledinegg-type instability is found to occur at a lower power as compared to the flow-pattern transition instability at any subcooling. However, both instabilities increase with rise in subcooling. More experimental and theoretical studies are required to further clarify this instability.

The problems associated with static instability is that the amplitude of oscillations can be very high and sometimes the static instability can initiate the dynamic oscillations in the system [17]. There are limited studies on the excursive instability behavior of a parallel downward flow system (Babelli and Ishii [23]). While the mechanism of instability is same for upward- and downward-flow systems, however, one important finding is that the flow excursion can be the dominant mode of instability as compared to the density-wave instability in boiling NCs.

3.2.3. Boiling crisis

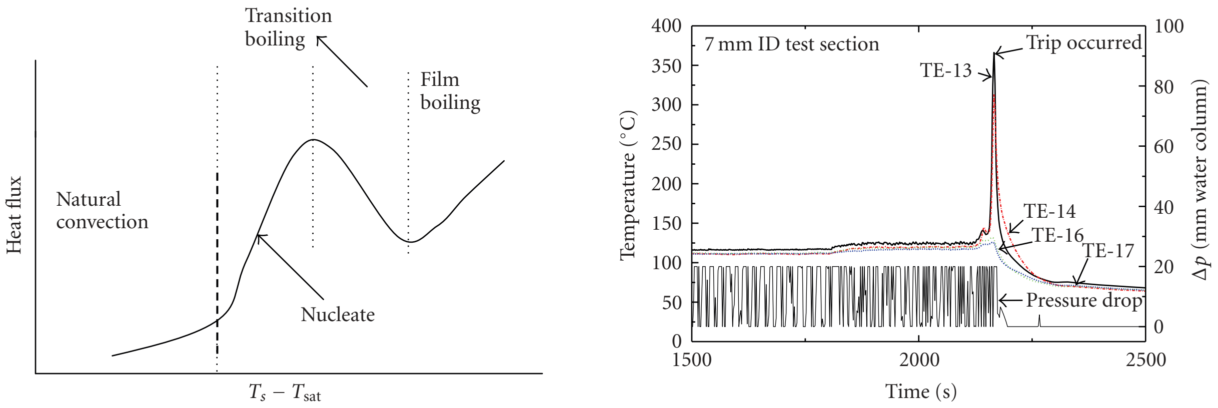
Following the occurrence of the critical heat flux, a region of transition boiling, may be observed in many situations as in pool boiling (see Figure 9(a)). During transition boiling a film of vapor can prevent the liquid from coming in direct contact with the heating surface resulting in steep temperature rise and even failure. The film itself is not stable causing repetitive wetting and dewetting of the heating surface resulting in an oscillatory surface temperature. The instability is characterized by sudden rise of wall temperature followed by an almost simultaneous occurrence of flow oscillations. This will not be confused with the premature occurrence of CHF during an oscillating flow, in which case the oscillations occur first followed by CHF (see Figure 9(b)).

3.3. Characteristics of two-phase dynamic instabilities

Unlike the static instabilities, there are several investigations in the area of dynamic instabilities, particularly the density-wave oscillations. In fact, numerous experiments and analytical studies are found in literature to clarify the characteristics of the density-wave oscillations.

3.3.1. Experimental investigations

Experimental investigations in two-phase natural circulation loops having single boiling heated channel have been carried out by [13, 17, 24–27]. They observed density-wave instability in their experiments, which was found to increase with increase in channel exit restriction and inlet subcooling. Also low water level in downcomer and low system pressure increases the density-wave instability in NCs. Such behavior was also observed in parallel heated channels of a two-phase natural circulation loop by Mathisen [28]. Lee and Ishii [25] found that the nonequilibrium between the phases created flow instability in the loop. Kyung and Lee [26]



(a) Pool boiling heat transfer regimes

(b) CHF occurrence during unstable oscillations

Figure 9: Instability due to boiling crisis.

investigated the flow characteristics in an open two-phase natural circulation loop using Freon-113 as test fluid.They observed three different modes of oscillation with increase in heat flux such as (a) periodic oscillation (A) characterized by flow oscillations with an incubation period. The mean circulation rate and void fraction at the riser section were found to increase with heat flux, (b) continuous circulation which is maintained with the churn/wispy-annular flow pattern. This was found to be a stable operation mode in which the flow was found to increase with heat flux first and then decrease with increase in heat flux, and (c) periodic circulation (B) characterized by flow oscillations with continuous boiling inside the heater section (i.e., there is no incubation period) and void fraction fluctuates from 0.6 to 1.0 regularly. In this mode, mean circulation rate was found to decrease with increase in heat flux, although the mean void fraction kept on increasing. Jiang et al. [17] observed three different kinds of flow instability such as geysering, flashing, and density-wave oscillations during startup of the natural circulation loop. Wu et al. [27] observed that the flow oscialltory behavior was dependent on the heating power and inlet subcooling. Depending on the operating conditions, the oscillations can be periodic or chaotic. Fukuda and Kobori [5] observed two modes of oscillations in a natural circulation loop with parallel heated channels. One was the U-tube oscillation characterized by channel flows oscillating with 180^0 phase difference, and the other was the inphase mode oscillations in which the channel flow oscillated alongwith the whole loop without any phase lag among them. Out of phase oscillations were also observed in the parallel channels of the CIRCUS facility by Marcel et al. [20].

3.3.2. *Theoretical investigations*

Linear analyses of boiling flow instabilities in natural circulation systems with homogeneous flow assumptions have been carried out by Furutera [29], S. Y. Lee and D. W. Lee [22], Wang et al. [30], and Nayak et al. [2]. Advantage of homogeneous flow assumption is that it is easier to apply and the model is also found to predict the stability boundary or the threshold of instability with reasonable accuracy. Linear stability analyses with homogeneous flow assumption and empirical model for the slip to calculate void fraction as a function of mixture quality have been carried out by Fukuda et al. [31]. Linear stability analysis using a four-equation drift flux model has been carried out by Ishii and Zuber [32], Saha and Zuber [33], Park et al. [34], Rizwan-Uddin and Dorning [35], van Bragt et al. [36], and Nayak et al. [37]. These models are based on kinematic formulation which considers the problem of mechanical nonequilibrium between the phases by having a relationship between the quality and void fraction through superficial velocities of liquid and vapor phases, vapor drift velocity, and void distribution parameter. The adoption of drift flux model allows to replace two separated momentum equations for liquid and vapor as used in the rigorous two-fluid models, by one momentum equation for the mixture plus a nondifferential constitutive law for the relative velocity. Besides, it considers equilibrium phasic temperature as in case of homogeneous model. Saha and Zuber [33] considered subcooled boiling in the drift flux model and applied the model to the stability of a natural circulation system. They found that consideration of thermal nonequilibrium condition results in a more stable system at low subcooling and a more unstable system at high subcooling as compared to the thermal equilibrium model. Rizwan-Uddin and Dorning [35] found that the threshold power for stability in boiling channel is sensitive to the void distribution parameter considered in the analysis. They found that with an increase in void distribution parameter, the stability of boiling channel increases. Similar results were also reported by Park et al. [34] and van Bragt et al. [36] for boiling channel systems. Nayak et al. [37] observed that the results are true not only for forced convection boiling systems, but also for the type I and type II instabilities observed in boiling natural circulation systems (Figures 10 to 12).

Similar results were also found for the effect of drift velocity on both type I and type II instabilities [37]. For any mixture quality, the void fraction is smaller for larger

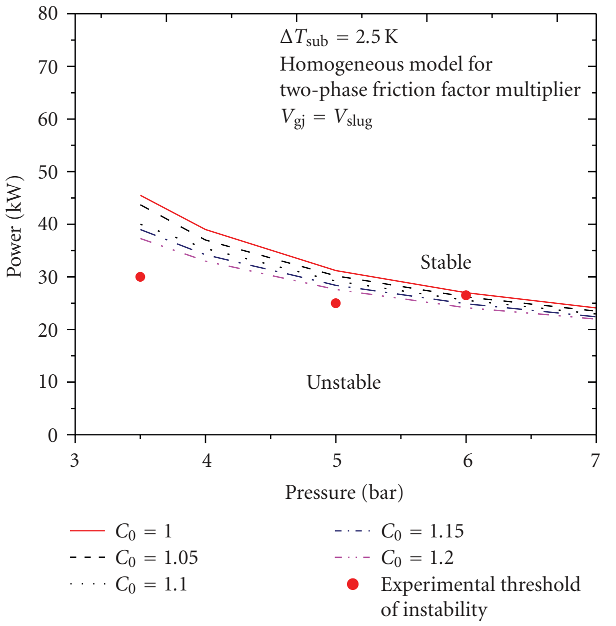


Figure 10: Effect of void distribution parameter on threshold of Type I instability observed in HPNCL.

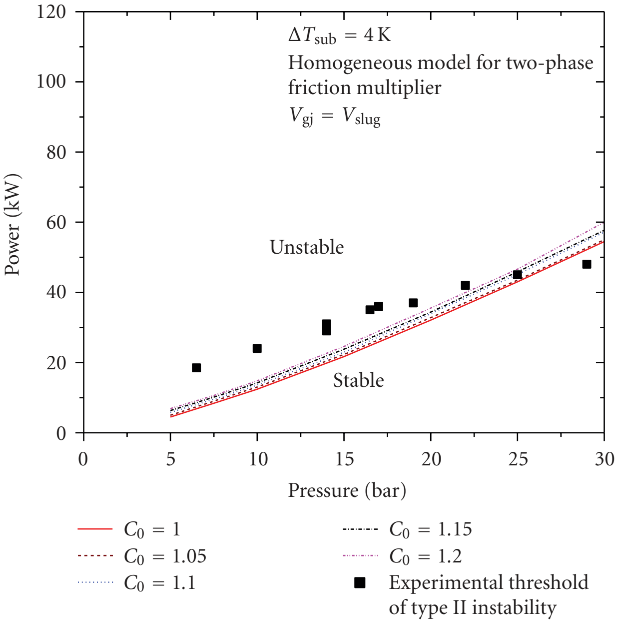


Figure 11: Effect of void distribution parameter on threshold of Type II instability observed in the Apparatus-A of Furutera.

drift velocity. If the quality is disturbed by a small amount, the void fraction with smaller drift velocity can have larger fluctuation than the other due to larger slope of void fraction versus quality.Hence,the flow will be disturbed larger for a smaller fluctuation in quality in this case. That is the reason for the reduction of type I instability with increase in drift velocity (Figure 13). An increase in drift velocity is also found to reduce the unstable region in the type II instability observed in Figures 14 to 15. With increase in drift velocity, the vapor propagation time lag in two-phase region reduces, which has a stabilizing effect.

Moreover, from these results it is interpreted that the homogeneous model for void fraction, which considers a zero drift velocity and unity void distribution parameter, predicts the most unstable region as compared to the slip models. Limited studies by Nayak et al. [38] and Bagul et al. [39] have shown that the homogeneous model predicts a more unstable region even as compared to the two-fluid models such as RAMONA-5 and RELAP/MOD3.2 (Figures 16 and 17). Usually, the homogeneous model predicts a larger void fraction than the two-fluid model for the same mixture quality due to the absence of slip between the water and steam in this model. The larger the void fraction in the system, the greater the buoyancy force, and consequently a higher flow rate will be encountered. At high flow rate, the frictional and local pressure drop in the two-phase region become greater, which has a destabilizing effect.

3.3.3. Effect of geometric and operating parameters on instability

Almost all the theoretical and experimental studies agree well that the DWI can be suppressed in boiling two-phase NC systems by increasing the system pressure. This is true both for type I and type II instabilities. An increase in power suppresses the type I instabilities, while enhances the type II instabilities according to the basic classification of these instabilities. The effects of subcooling on these instabilities are always debatable. While type I instabilities are always found to enhance with rise in subcooling, type II instabilities may enhance or reduce with subcooling depending on its magnitude and the system geometry and

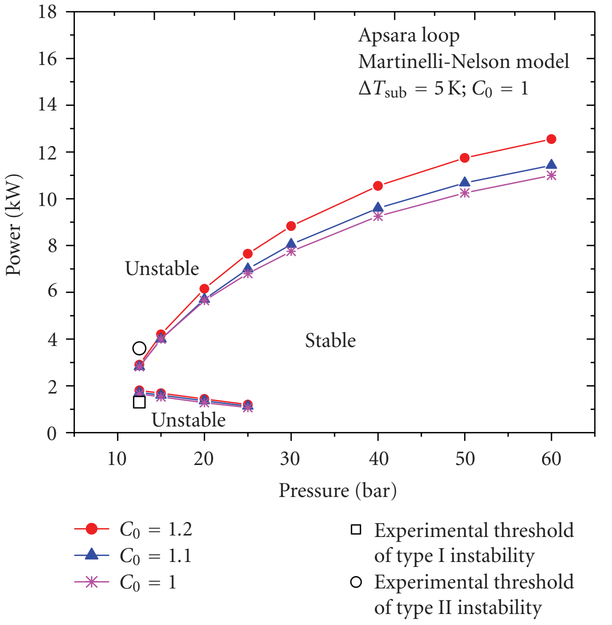


Figure 12: Effect of void distribution parameter on threshold of Type I and Type II instabilities observed in the Apsara loop.

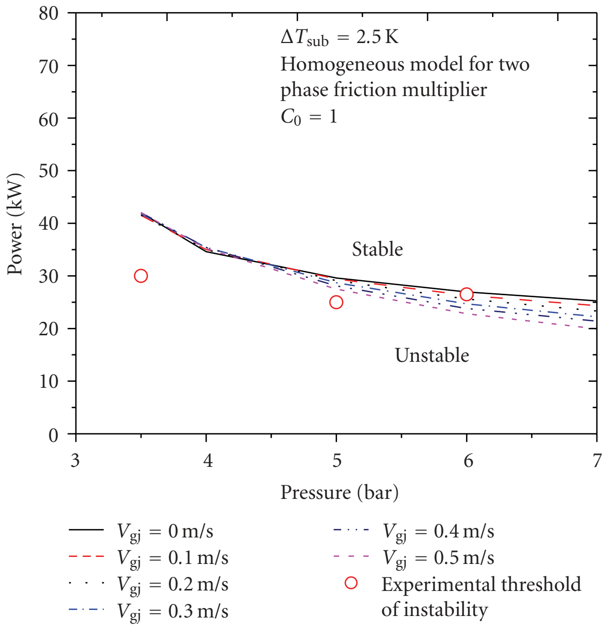


FIGURE 13: Effect of drift velocity on threshold of Type I instability observed in high pressure natural circulation loop (HPNCL).

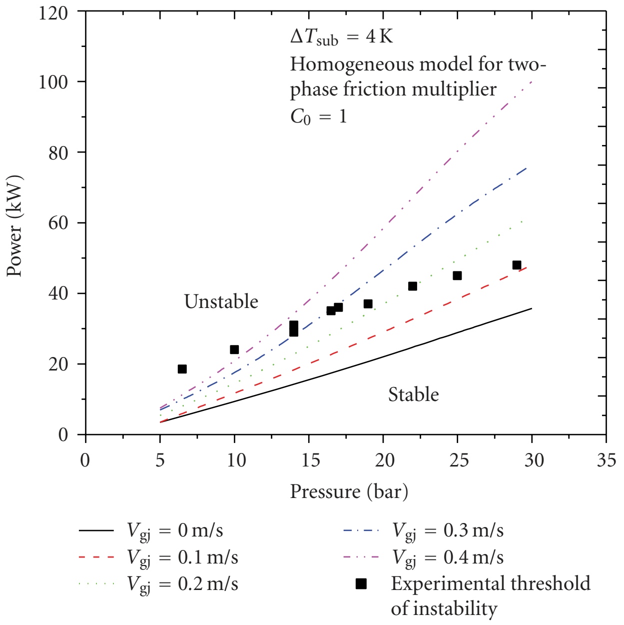


FIGURE 14: Effect of drift velocity on threshold of Type II instability observed in the Apparatus-A of Furutera.

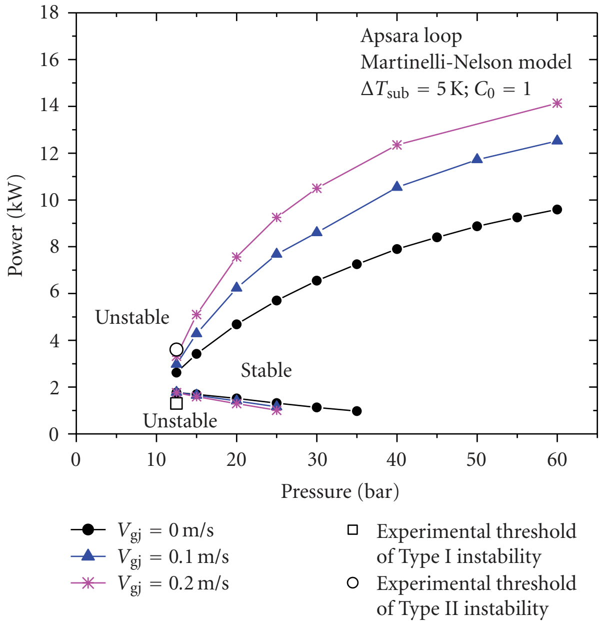


FIGURE 15: Effect of drift velocity on the Type I and Type II instabilities threshold observed in the Apsara loop.

heat input [1, 36, 38]. Invariably, it has been observed that with increase in local losses in two-phase region, both type I and type II instabilities increase. On the other hand, with increase in local losses in the single-phase region (such as orificing at the inlet of channels), the improvement in stability has been found to be conditional [2, 40] unlike in forced circulation systems wherein it has been observed that with increase in local losses in the single-phase region always improves the flow stability. In a natural circulation system, the flow rate in the channel depends on the heating power and the channel resistance. With increase in inlet throttling coefficient for same heating power, the channel flow rate decreases, which in turn causes an increase in channel exit quality. This may reduce the threshold power for instability for that channel which may cause the other channel to be unstable. So increase in orificing at channel inlet does not always increase the stability of a natural circulation system with multiple parallel channels (Figure 18).

The effect of riser geometry such as riser height and area on flow stability is important. In a natural circulation system, the low-power type I instability increases with increase in riser height. But the type II instability may increase or decrease depending on the flow resistance and heating power. For smaller riser height, lesser is the channel flow rate and larger is the channel exit quality for same heating power. This gives larger two-phase pressure drop due to large channel exit quality. Larger the riser height, larger is the channel flow rate which may cause larger two-phase pressure drop due to larger riser length. So a reduction or an increase in riser height on type II instability of natural circulation system is competitive [2].

The effect of riser area on flow instability has been discussed in great detail in a companion paper by the authors and hence will not be repeated here. However, for sake of completeness, only a brief discussion is presented below. For smaller riser flow area, the flow rate is smaller due to larger resistance in small riser pipes. As the flow area is increased, the flow rate increases, which gives rise to small frequency oscillations, typical of low quality type I density-wave instability (Figure 19) due to reduction in void fraction.

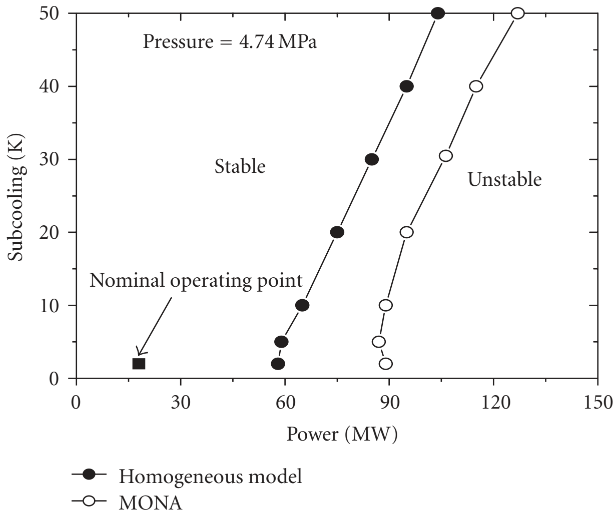


FIGURE 16: Comparison of stability maps between the homogeneous model and the two-fluid model (RAMONA5).

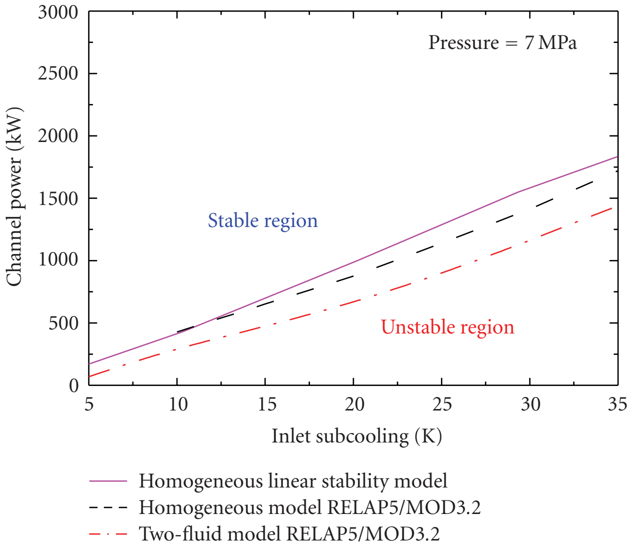


FIGURE 17: Comparison of stability maps between the homogeneous model and the two-fluid model (RELAP5/MOD3.2).

Hence, with increase in riser flow area, the type I instability appears [38]. However, the type II instability, which occurs at high power or void fraction, disappears with increase in riser diameter [38] due to reduction in void fraction or decrease in two-phase pressure drop.With an increase in riser area,the time period of oscillation reduces due to the increase in flow rate in the system.

3.4. Characteristics of compound dynamic instability

Instability is considered compound when more than one elementary mechanisms interact in the process and cannot be studied separately. If only one instability mechanism is at work, it is said to be fundamental or pure instability. Examples of compound instability are (1) thermal oscillations, (2) parallel channel instability (PCI), (3) pressure-drop oscillations, and (4) BWR (boiling water reactor) instability.

3.4.1. Thermal oscillations

In this case, the variable heat transfer coefficient leads to a variable thermal response of the heated wall that gets coupled with the DWO. Thermal oscillations are considered as a regular feature of dryout of steam-water mixtures at high pressure [4]. The steep variation in heat transfer coefficient typical of transition boiling conditions in a post CHF scenario can get coupled with the DWO. During thermal oscillations, dryout or CHF point shift downstream or upstream depending on the flow oscillations. Hence thermal oscillations are characterized by large amplitude surface temperature oscillations (due to the large variation in the heat transfer coefficient). The large variations in the heat transfer coefficient and the surface temperature causes significant variation in the heat transfer rate to the fluid even if the wall heat generation rate is constant. This variable heat transfer rate modifies the pure DWO.

3.4.2. Parallel channel instability (PCI)

Interaction of parallel channels with DWO can give rise to interesting stability behaviors as in single-phase NC. Experimentally, both inphase and out of phase oscillations are observed in parallel channels. However, inphase oscillation is a system characteristic and parallel channels do not generally play a role in it. With inphase oscillation, the amplitudes in different channels can be different due to the unequal heat inputs or flow rates, but there is no phase difference among them. Occurrence of out of phase oscillations is characteristic of PCI. The phase shift of out-of-phase oscillations (OPO) is known to depend on the number of parallel channels. With two channels, a phase shift of 180° is observed. With three channels, it can be 120° and with five channels it can be 72° [41]. With n-channels, Aritomi et al. [42] report that the phase shift can be $2\pi/n$. However, depending on the number of channels participating, the phase shift can vary anywhere between π and $2\pi/n$. For example, in a 3-channel system one can get phase shift of 180° or 120° depending on whether only two or all the three channels are participating.

3.4.3. Pressure-drop oscillations (PDO)

Pressure-drop oscillations are associated with operation in the negative sloping portion of the pressure drop-flow curve of the system. It is caused by the interaction of a compressible volume (surge tank or pressurizer) at the inlet of the heated section with the pump characteristics and is usually observed in forced circulation systems. DWO occurs at flow rates lower than the flow rate at which pressure-drop oscillation is observed. Usually, the frequency of pressure-drop oscillation is much smaller and hence it is easy to distinguish it from density-wave oscillations. However, with a relatively stiff system, the frequency of PDO can be comparable to DWO making it difficult to distinguish between the two. Very long test sections may have sufficient internal compressibility to

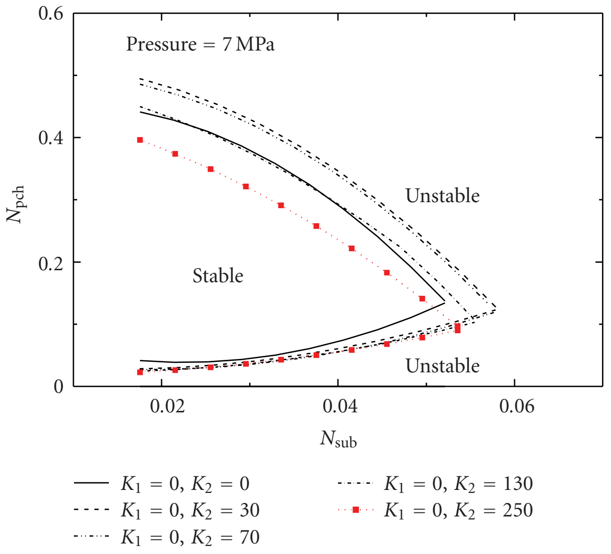


Figure 18: Effect of orificing of channels on the stability of boiling natural circulation systems (K_1 and K_2 refer to the throttling coefficients of channel 1 and 2, resp.).

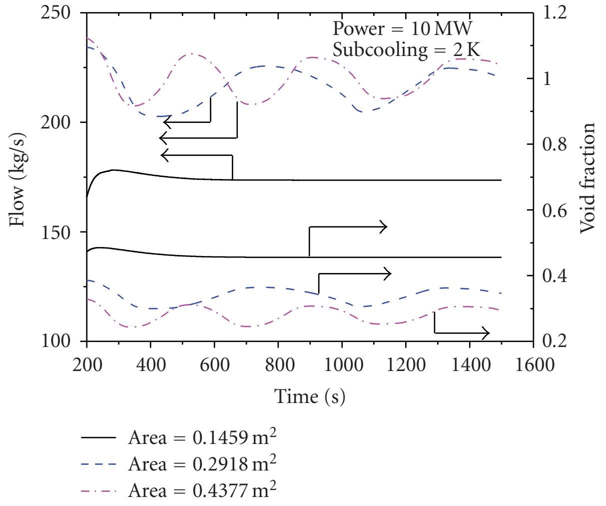


Figure 19: Effect of an increase in riser area on stability.

initiate pressure drop oscillations. Like Ledinegg instability, there is a danger of the occurrence of CHF during pressure drop oscillations. Also inlet throttling (between the surge tank and the boiling channel) is found to stabilize PDO just as Ledinegg instability.

3.4.4. *Instability in natural circulation BWRs*

The flow velocity in natural circulation BWRs is usually smaller than that of forced circulation BWR. Besides, due to the presence of tall risers in natural circulation BWRs, the frequency of density-wave oscillation can be much lower due to longer traveling period of the two-phase mixture in the risers. The effects of negative void reactivity feedback are found to stabilize the very low frequency type I instabilities [43, 44]. But it may stabilize or destabilize type II instabilities depending on its time period [44].

In case of a natural circulation BWR, the existence of a tall riser or chimney over the core plays a different role in inducing the instability. Series of experiments carried out by van der Hagen et al. [45] in the Dodewaard natural circulation BWR in The Netherlands showed that instabilities could occur at low as well as at high powers in this reactor. From measured decay ratio, it was evident that at very low power there is a trend of increase in decay ratio and similar results are seen at higher power also. The low-power oscillations are induced by the type I density-wave instabilities and high power oscillations are induced by the type II density-wave instabilities. type I and type II instabilities have been predicted to occur in the Indian AHWR which is a natural circulation pressure tube type BWR, away from the nominal operating condition [44]. It may be noted that in case of forced circulation BWRs, instabilities observed under natural circulation conditions are due to pump trip transients when the core exit quality is high due to low flow and high power. Hence these are induced by the type II density-wave instabilities only.

4. CONCLUDING REMARKS

Several decades have been spent on the study of flow instabilities in boiling two-phase natural circulation systems. A large number of numerical and experimental investigations in this field have been carried out in the past. Many numerical codes in time domain as well as in frequency domain have been developed using various mathematical modelling techniques to simulate the flow instabilities occurring in the NCSs. It is felt to have a review and summarize the state-of-the-art research carried out in this area, which would be quite useful to design and safety of current and future light water reactors with natural circulation core cooling. With that purpose, a review of flow instabilities in boiling natural circulation systems has been carried out. An attempt has been made to classify the instabilities occurring in natural circulation systems similar to that in forced convection boiling systems. It was found that the instabilities can be classified based on the mechanism of their occurrence into broadly two groups such as static and dynamic instabilities. The analytical tools based on the above mechanisms predicts the stability threshold and characteristics of instabilities reasonably well. Other classifications are in fact subcategories of a particular class of the instabilities covered under this classification. While classifying instabilities of NCSs, a need was felt to consider the instabilities associated with single-phase condition, boiling inception, and two-phase condition separately as a natural circulation system progresses through all these stages before reaching the fully developed two-phase circulation. Most instabilities observed in forced circulation systems are observable in natural circulation systems. However, natural circulation systems are more unstable due to the regenerative feedback inherent in the mechanism causing the flow. While most of the work has been devoted to generate data for steady state and threshold of flow instabilities in NCSs, however, it was felt that more investigations on characteristics of these flow instabilities must be conducted in future, which is not understood enough. Moreover, it is found that these instabilities do not occur in isolated manner in NCSs, however, many times, they occur together which are known as compound instabilities. Different models of two-phase flow have been used for modelling these flow instabilities, which range from the simplest HEM to more rigorous two-fluid model. While the HEM is found to model the threshold of instability of density-wave type in NCS with reasonably accuracy, however, there are concerns for using this model since the drift velocity and void distribution parameters which are indications of slip between the phases, are found to affect the stability threshold. Computer codes developed considering more rigorous models such as RELAP5 are yet to be established for their applicability for simulation of stability in boiling NCS. In view of this, more research needs to be conducted to explore the capability of existing mathematical models for prediction of these instabilities in NCSs in future.

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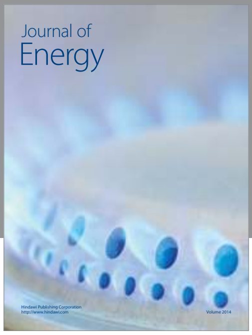
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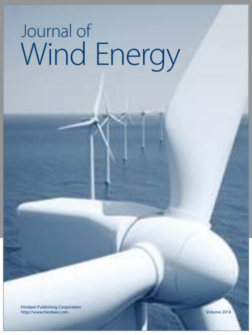
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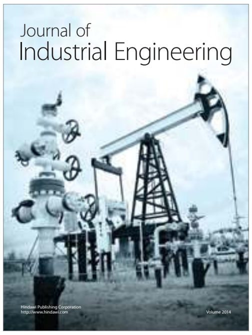
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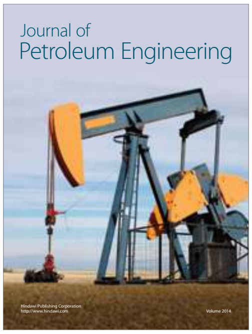
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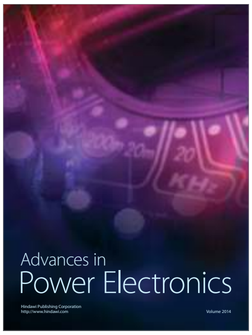
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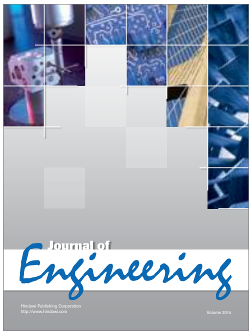
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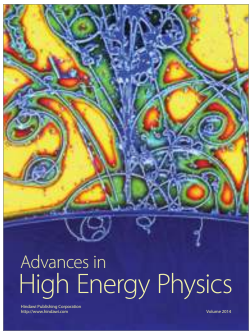
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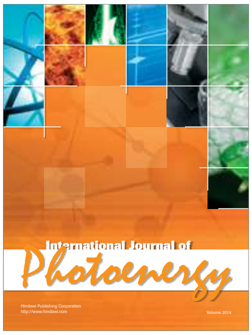
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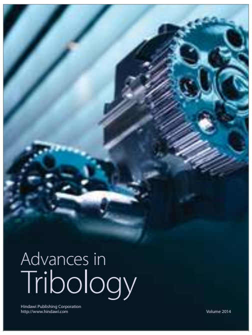
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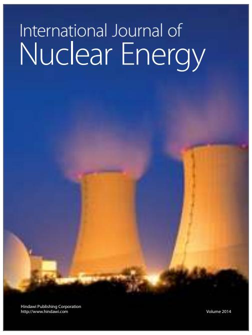
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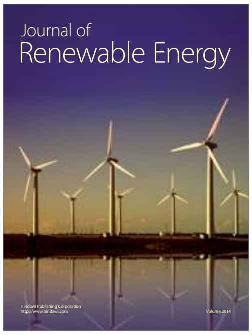
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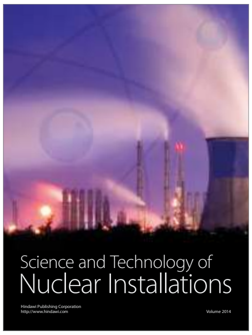
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