Thermo-hydraulic Instability Due to a Blockage of Flow by Vapor in a Boiling Two-phase Flow System*

(Experimental Results Concerning the Mechanism)

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Thermo-hydraulic instability has been investigated experimentally in a boiling two-phase flow system, composed of a vertical N-shaped boiling channel and an adiabatic bypass between an inlet plenum and an outlet plenum, using Freon 113. Instability caused by the blockage of flow by vapor, which cannot be found in Bouré's classification of two-phase flow instabilities, has been observed. The flow maps in each section, static characteristics, stable flow limits and characteristics of this instability have been studied under various conditions to clarify the mechanism. The inlet velocity decreases when a vapor slug combining in the inverted U-shaped bend obstructs the flow. The vapor slug flowing into the downcomer increases the void fraction in the downcomer, resulting in increased gravitational loss. Consequently, flow instability is brought about.

Key Words: Two-phase Flow, Thermo-hydraulic Instability, Flow Map, Flow Excursion, Flow Oscillation, Blockage of Vapor to Flow, Vertical N-shaped Boiling Channel

1. Introduction

Recently, supercritical pressure boilers are being operated at a partial load, under the subcritical pressure, to pare down the consumption of petroleum and electrically-heated calorifiers are being applied to the auxiliary boilers of power reactors to start the turbines using surplus electric power, though a downflow is generally undesirable in a boiling two-phase flow system. Most of these plants consist of risers and downcomers joined by bends. In addition, the application of bends to flow channels is promising for the miniaturization of evaporators of cryogenic fluids such as LNG, and of reboilers to withdraw waste heat. In a boiling two-phase flow system composed of

vertical bends, vapor stagnates in a bend and/or a downcomer, blocks the flow and causes flow instability. The occurrence of flow instability may induce burnout and dryout phenomena, which lead to damage of the heat transfer wall and lowering of the heat-transfer performance.

Many researchers since Ledinegg⁽¹⁾ in 1938 have investigated thermo-hydraulic instabilities in boiling two-phase flow systems, with the density wave instability as the central figure. These works were reviewed by Bouré et al.⁽²⁾, Lahey et al.⁽³⁾ and Bergles⁽⁴⁾, etc. The instability caused by the blockage of the flow by vapor, which cannot be found in Bouré's classification of two-phase flow instabilities, has scarcely been investigated except for the following: The authors⁽⁵⁾ investigated the instability in two vertical U-shaped boiling channels to clarify the mechanism of the limit cycle of flow instability observed in a 1 MW steam generator for liquid-metal cooled fast breeder reactors, without thermally insulated downcomers, which had been developed by the Power Reactor and Nuclear Fuel Development Corp., and Fukuda et al.⁽⁶⁾ experimentally investigated vertical N-shaped boiling channels with inlet velocities lower than 0.1 m/s.

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Therefore, the purpose of this study is to understand the mechanism of flow instability caused by the stagnant vapor in bends.

2. Experimental Apparatus and Procedure

A schematic diagram of a Freon 113 loop is illustrated in Fig. 1. The flow loop is so designed to repress flow fluctuations in the loop and is operated at atmospheric pressure. The flow rate is observed through an orifice and is regulated by a valve set upstream of the entrance of a test section. The temperature of the liquid flowing into the test section is controlled by two subcoolers and a preheater. Although power plants are really made of multi parallel boiling channels, the test section composed of a vertical N-shaped boiling channel and an adiabatic bypass, as shown in Fig. 2, was adopted in the present work because such a construction is superior to two boiling channels for the following reasons: (1) Ledinegg type instability can be suppressed and the instability caused only by stagnant vapor can be studied experimentally, and (2) the reproducibility of the stable flow limit for this instability surpasses that of multi parallel boiling channels. The N-shaped boiling channel has three straight tubes (an entrance riser, a downcomer and an exit riser) made of Pyrex glass (12 mm I. D. and 600 mm long) and two bends (inverted U-shaped and U-shaped tubes) connecting the straight tubes. Each bend is made of acrylic resin, whose inner diameter and straight length are 12 mm and 250 mm, respectively. The radii of the inverted U-shaped and U-shaped bends are 58 mm and 158 mm, respectively. The heater rod is made of stainless steel (5 mm O. D., 0.2 mm thick and 500 mm long), installed concentrically in the entrance riser and heated electrically by an AC power source. Other sections are adiabatic in this paper. The bypass, whose inner diameter is equal to that of the boiling channel, has a flow control valve and an orifice to measure the flow oscillation.

The differential pressures between the inlet and

outlet plenums and between the entrance and exit of the inverted U-shaped bend, the differential pressure of the orifice of the bypass and the temperatures in the outlet plenum and at the entrance and exit of the inverted U-shaped bend were measured. The flow maps and the static characteristic curves of the boiling channel were examined in a single channel with a closed bypass. On the other hand, the stable flow limit was studied in two channels with the same flow rate of the boiling channel as that of the bypass by regulating the flow control valve of the bypass, and the characteristics of two channel unstable flow were also measured by adjusting the valve so that a stable flow limit was obtained. The experimental conditions and parameters are summarized in Table 1.

3. Flow Maps and Static Characteristics

3.1 Flow maps

Figure 3 shows a sequence of sketches of the flow pattern observed in a single channel with a closed bypass. Subcooled bubbly flow appears in the whole

Table 1 Experimental conditions and parameters

	Single channel	Parallel channels
Inlet subcooling		10K
Inlet velocity	0.15 ~ 0.6m/s	0.2 ~ 0.6m/s
Heat flux	0 ~ 150kW/m ²	0 ~ 130kW/m ²
Radius of bends		
Inverted U-shaped		58mm
U-shaped		158mm

Fig. 1 Freon 113 flow loop

Fig. 2 Test section

Fig. 3 Sketches of flow pattern

channel and bubbles flow along the upper walls in both bends, as shown in Fig.3(a) under low heat input. When the heat input is increased, the bubbly flow remains only in the entrance riser, but a slug bubble is formed, stagnates under a subcooled condition, and combines with bubbles at $\theta \sim 120^\circ$ of the inverted U-shaped bend (shown in Fig.3(b)) because the velocity of the bubbles is decelerated. The slug starts to block the flow and increases in size with the absorption of fluxing bubbles. When the lead of the slug reaches $\theta \sim 180^\circ$, it flows to the downcomer with a disunion or combination, soon runs into the U-shaped bend, stagnates at $\theta \sim 60^\circ$ of the bend and is brought up again with the absorption of bubbles. As soon as the lead of the slug arrives at $\theta \sim 90^\circ$, the whole stagnant vapor therein debouches into the exit riser with irregular splits.

The flow maps obtained from observation are illustrated in Fig. 4. The feature of the flow maps in an N-shaped boiling channel is the formation of a slug bubble in the inverted U-shaped bend under a subcooled condition, and the reduction in the region of bubbly flow downstream from there. In the downcomer, the region of bubbly flow expands under low inlet velocity because a slug undergoes fission to give bubbles with diameters of the order of the channel ones.

3.2 Static characteristics

Figure 5 presents typical results of the static characteristic curve between the inlet velocity and the differential pressure between the inlet and outlet plenums. For the latter, the differential pressure is defined by

$$\Delta P_{\text{plenum}} = \Delta P_{\text{true}} - \rho_l H g \quad (1)$$

where ΔP_{true} is the true value, ρ_l the density of the liquid, H the height between plenums and g the acceleration due to gravity. In the N-shaped boiling two-

Fig. 4 Flow maps in each section

phase system, the static characteristic curve has a large negative slope which shifts to the higher side of the inlet velocity as the heat input is increased.

These flow maps and static characteristics were obtained only in the case where the heat input was increased with constant inlet velocity, and their reproducibilities were excellent. On the other hand, a good reproducibility could not be obtained in the case of diminishing heat input because of the hysteresis of

the stagnant state of vapor in the bends with the change in the input power.

4. Instability Caused by Stagnant Vapor

4.1 Stable flow limit and occurring mechanisms

The differential pressure between the plenums changes with an increase in the heat input as shown in Fig. 5, so that the flow rate of the boiling channel becomes different from that of the bypass, in the case of two channels. For low heat input, the difference in the flow distribution is limited to the change in the static characteristic curve and can be corrected easily by regulating the flow control valve of the bypass. When the heat input reaches a certain value, the difference far exceeds the change in the static characteristic curve and a drop in the flow rate of the boiling channel, which is called flow excursion, suddenly occurs. Therefore, the stable flow limit is defined by this condition in the present work. There are two characteristics of unstable flows after flow excursion; 299 (1) perfect blockage, where the inlet velocity of the boiling channel becomes zero and is kept intact, and (2) flow oscillation, where the inlet velocity is reduced to a certain velocity and oscillates around it. Representative results of the two types, measured near the stable flow limit, are shown in Figs. 6 and 7. ΔP_{plenum} and ΔP_{invU} mean the differential pressures between the plenums and between the entrance and exit of the inverted U-shaped bend; T_{in} and T_{out} , the

temperatures at the entrance and exit of its bend; G_{bypass} , the flow rate of the bypass and q'' , the heat flux of the entrance riser.

In the case of perfect blockage, shown in Fig. 6, bubbles combined at $\theta \sim 120^\circ$ of the inverted U-shaped bend form a slug bubble which discharges into the downcomer and stagnates at $\theta \sim 60^\circ$ of the U-shaped bend. As soon as these phenomena occur, the inlet velocity of the boiling channel diminishes gradually due to the flow resistance of the stagnant vapor. The stagnant vapor in the U-shaped bend grows in the upstream direction in the downcomer while absorbing the bubble influx, and then only vapor exits in the downcomer after the inlet velocity becomes zero. The increase in the flow rate of the bypass increases the differential pressure between the plenums, and perfect blockage occurs. The gravitational loss between the plenums is increased by the accumulation of vapor in the downcomer due to the growth of the slug therein and the increased gravitational loss corresponds to the frictional loss of the bypass. The flow rate of the boiling channel is not recovered but the dryout phenomenon is sure to occur on the heater rod if the heat input is not interrupted after flow excursion. It takes

Fig. 5 Typical results of static characteristic curve

Fig. 6 Typical measured result for perfect blockage type

a very long time to regain the flow rate of the boiling channel after shutdown of the heat input.

On the other hand, in the case of flow oscillation, shown in Fig. 7, flow excursion is caused by flow resistance due to the stagnant vapor and by the increase in gravitational loss, but this increase is less than that of frictional loss in the bypass caused by the increasing flow rate required for perfect blockage. Consequently, the flow rate of the boiling channel decreases to the condition where the frictional loss of the bypass corresponds to the increased gravitational loss of the boiling channel. The inlet velocity of the boiling channel periodically decreases with the growth of a slug in the downcomer and periodically increases with the diminution of gravitational loss with the efflux of the stagnant vapor into the exit riser. This is the reason flow oscillation occurs. From Fig. 7, the flow rate of the bypass oscillates with the same period and phase as the differential pressure between the plenums. This fact indicates that flow oscillation is not dynamic with the effect of fluid inertia but is quasi-static.

The stable flow limits obtained in two channels are shown as equilibrium quality versus inlet velocity before flow excursion in Fig. 8. The boundary,

Fig. 7 Typical measured result for oscillation type

whether perfect blockage or oscillation occurs, can be evaluated by the inlet velocity before flow excursion, and its value is 0.4 m/s in the present test section, that is, perfect blockage only occurs at velocities lower than 0.4 m/s and oscillation only appears at velocities higher than 0.4 m/s. From the figure, the stable flow limit obtained by increasing the heat input (q''_{up}) is far different from the one obtained by reducing it (q''_{down}) because there is the hysteresis of the stagnant state of vapor with the change of vaporization rate, as discussed in section 3.2. The difference between both of the stable flow limits dwindles as the inlet velocity increases.

From the comparison between Figs. 3 and 8, the stable flow limit roughly coincides with the transition point from bubbly flow to slug flow on the flow map at an inlet velocity less than 0.3 m/s, that is, flow excursion occurs as soon as a slug bubble is formed in the inverted U-shaped bend. On the other hand, the equilibrium quality of the stable flow limit exceeds that of the transition point at velocities greater than 0.3 m/s and the difference increases with increasing velocity. It indicates that the blockage of the flow by a slug needs a faster vaporization rate to stagnate and grow than to formulate, as the inlet velocity increases.

Fig. 8 Stable flow map

Fig. 9 Ratio of post-flow excursion equilibrium inlet velocity to pre-flow excursion inlet velocity

4.2 Characteristics of flow oscillation

The characteristics of flow oscillation were measured under various heat inputs. Figure 9 shows the ratio of the inlet equilibrium velocity after flow excursion to the inlet velocity before it in reference to the heat flux of the entrance riser. This ratio increases only with increasing heat flux, in spite of different inlet velocities, because the static characteristic has a negative slope and it shifts to the higher side of the inlet velocity as the heat input is increased (shown in Fig.5).

The period and amplitude ratio of the flow oscillation were characterized by the vapor flow rate, since the flow becomes the saturated boiling condition at the exit of the heated section after flow excursion. These results are illustrated in Figs. 10 and 11. The period can be characterized only by the vapor flow rate as shown in Fig. 10, is reduced with its enlargement, and almost coincides with the time when the lead of stagnant vapor travels from the inverted U-shaped bend to the U-shaped one. The increase in the vapor flow rate makes a smaller change in the bypass flow rate balance the variation in the differential pressure between the plenums because the frictional loss of the bypass is proportional to the square of the bypass velocity. Therefore, the amplitude ratio decreases with increasing both the vapor flow rate and the inlet velocity before flow excursion as shown in Figure 11.

Fig. 10 Period of flow oscillation

5. Comparison with Other Instabilities

5.1 Ledinegg type instability

Ledinegg type instability is exhibited as the instability caused by a negative slope on the static characteristic curve. In this case, flow excursion occurs, that is, the flow rate changes up to or down to the intersection of the static characteristic and the characteristic of external force such as a pump. Although the perfect blockage type is very similar to the Ledinegg one with regard to flow excursion, in the case of perfect blockage, it is different from the Ledinegg one in that the flow rate becomes zero because an increase in gravitational loss, which does not exist on the static characteristic curve, is generated by the vapor accumulation in the downcomer. Namely, the main difference between both instabilities is whether or not flow excursion occurs based on the static characteristic. The perfect blockage type is more dangerous in plants than the Ledinegg one because dryout phenomena would certainly be generated if it were not for interruption of the heat input.

Pressure drop oscillation, which is one Ledinegg type instability, may occur due to a negative slope on the static characteristic curve in the case where there is a compressible space, such as an accumulator, at the upstream of a heated section⁽⁷⁾. Although this instability is very similar to the oscillation type instability caused by stagnant vapor in that the flow oscillates regardless of fluid inertia, this oscillation is an alternative flow excursion between two positive slopes on the static characteristic curve. On the other hand, the

Fig. 11 Amplitude ratio of flow oscillation

oscillation type oscillates around the equilibrium velocity after flow excursion and both the processes of stagnation and growth of vapor and the efflux into the exit riser appear mutually and periodically. That is the main difference between the two instabilities.

5.2 Density wave instability

Density wave instability is cited as a representative instability in boiling two-phase flow. In boiling two-phase flow, void fraction and velocities of both phases fluctuate with time delays relative to the inlet velocity, so that a phase shift between oscillation of inlet velocity and oscillation of pressure drop in the two-phase region is brought about. The phase shift has an influence on the inlet velocity through an external restriction, so that a density wave instability occurs. Although the density wave instability apparently resembles the oscillation type instability caused by stagnant vapor, both instabilities differ essentially in that one is influenced by the fluid inertia but the other is not. Furthermore, the density wave instability has an inherent oscillatory system which depends only on the operating conditions but not on the operating history or on the nature of the disturbance⁽⁸⁾ but the oscillation type instability is affected by both, as shown in Fig. 7.

5.3 Slug excursion instability

When boiling occurs in downflow, the slug bubble generated near the exit of a downcomer, under a certain subcooled condition, does not flow out to a riser but grows toward the upstream while blocking the flow. Consequently, flow excursion may break out. The authors call this phenomenon 'slug excursion instability' (5). Slug excursion instability is different from what is caused by stagnant vapor in a bend as regards blocking the flow and reducing the flow rate, but both instabilities have many similar points: The flow rate of the bypass oscillates with the equiphase of the differential pressure between the inlet and outlet plenums and flow excursion is caused by increasing gravitational loss due to the accumulation of vapor in the downcomer. In the present test section, the downcomer is adiabatic, and vapor is supplied only from the entrance riser to the downcomer so that flow reversal is not caused by a slug rapidly growing toward the upstream. Therefore, it is considered that slug excursion instability is essentially classified as an instability caused by stagnant vapor in a bend.

6. Conclusions

Thermo-hydraulic instability has been investigated

experimentally in a boiling two-phase flow system composed of a vertical N-shaped boiling channel and an adiabatic bypass between inlet and outlet plenums using Freon 113, and the following are clarified:

- (1) A new type of flow instability exists. This instability is caused by flow resistance due to a stagnant slug in bends and by the increase in gravitational loss due to its growth in the downcomer.
- (2) There are two types of instabilities. One is the perfect blockage type where the inlet velocity becomes zero and is kept intact. The other is the oscillation type where the inlet velocity decreases to a certain value and oscillates around it. The boundary, where either of the two types occurs, is determined by the relation between the increases in the gravitational loss of the boiling channel and in the frictional loss of the bypass flow rate.
- (3) For the oscillation type instability, the period of flow oscillation depends only on the vapor flow rate and decreases with its increase. On the other hand, the amplitude ratio decreases as both the vapor flow rate and the inlet velocity, before flow excursion, increase.

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