Pergamon

Int. J. Multiphase Flow Vol. 21, No. 6, pp. 1243–1252, 1995

0301-9322/95 $9.50 + 0.00

0301-9322(95)00050-X

BRIEF COMMUNICATION

AN EXPERIMENTAL STUDY ON THE MECHANISM OF GEYSERING IN A CLOSED TWO-PHASE THERMOSYPHON

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(Received 8 December 1994; in revised form 12 June 1995)

1. INTRODUCTION

Instabilities may make problems in maintaining smooth and safe operation of heat exchange systems for industrial applications such as boilers and other two-phase flow equipments. Geysering, as one of these instabilities, can be found in storage of cryogenic fluids (Hands 1988) or in applications in the missile industry since many rocket vehicles use cryogenic fluids as the vehicle propellant (Murphy 1965).

The term geysering in industry usually refers to a natural geysering phenomenon that is characterized by periodical rapid expulsions of a boiling liquid and its vapor from a vertical fluid column to a larger or open space. This may occur in a liquid-filled vertical tube subjected to a low heat flux. Boure *et al.* (1973) used the term geysering for periodic expulsion phenomena in a tube regardless of whether the tube is closed at the bottom. Others used the term chugging when the tube is open at the bottom so that a net flow can be recognized (Yadigaroglu 1981; Hands 1988). Geysering can be referred to as intermittent boiling in which the heat input is insufficient to maintain continuous boiling. However, this does not mean that intermittent boiling is always geysering. It is known that a geysering cycle can be divided into an incubation, an expulsion and a refilling period. However, these also occur in the intermittent boiling. Griffith (1962) proposed that if all bubbles disappear between fluctuations, the phenomenon can be called geysering even though only 20% of the liquid is blown out. In the present study, based on the natural geysering phenomenon, the term geysering is functionally adopted as a phenomenon characterized by cycles of a quiet condition and violent expulsion at the liquid surface level.

Further studies of geysering in large diameter tubes have been conducted by Murphy (1965) and Hands (1988). Murphy has carried out a series of experiments to produce the geyser–non-geyser correlation with water, R113, nitrogen and hydrogen as working fluids. However, the relation was found to be entirely inappropriate when compared to the data of water by Burkhalter *et al.* (1968), who also pointed out that the period of a geyser is directly proportional to the heat input.

The aim of this work is to study experimentally, by temperature and pressure measurements and/or visual observations, the mechanism of the geysering in a closed two-phase thermosyphon, in which the pressure of the liquid in the evaporator may increase during bubble expansion.

2. EXPERIMENTAL APPARATUS

The experimental apparatus is schematically shown in figure 1. It is a closed thermosyphon that can be divided functionally into three parts: an evaporator in the lower part, a condenser in the upper part and an adiabatic section in between them. The thermosyphon was made of glass to make visual observation possible. Using glass as the structural wall material and freon as the working fluid is known to result in nucleation at superheat conditions (Griffith 1962), which would not occur when using water as the working fluid. The evaporator part is a 1507 mm vertical tube of 18 mm i.d. and 22 mm o.d., corresponding to a volume of 383 ml. The condenser volume is 1178 ml, which is 3.1 times that of the evaporator volume. The outside wall of the evaporator is wound with a heater element to produce the desired heat fluxes by electricity. To reduce the heat loss from the heater, the outside wall of the evaporator is covered by an insulation layer made of ceramic fiber and glass wool, which can be partially removed or opened when visual observation is desired.

Temperatures were measured by C–A thermocouples at the 26 locations shown in figure 1. Data from these thermocouples were recorded intermittently every 1.5 s with a Yokogawa data acquisition system. Continuous monitoring with a pen recorder was also performed for both inside and outside wall temperatures at the bottom, middle and top of the evaporator. Fluid temperatures in the evaporator were directly measured by thermocouples inserted at the top end of the condenser and fixed along the center line. The temperatures in the condenser were similarly measured.

A pressure gage was installed at the top end of the condenser and was connected to the pen recorder. In the experiment, the system was first evacuated, and then the evaporator was filled from the bottom with 383 ml of the working fluid. This results in a volumetric filling percentage of 100% of the evaporator volume. R113 and water were used as working fluids. It is known (Boure *et al.* 1973) that for R113, bubble initiation occurs at high degrees of superheat; while for water, it occurs at saturated or even lower temperatures.

A series of experiments was started by supplying heating power through a regulator to the heating element in the evaporator, with the condenser being inactive. The heating power was first set at 19 W (223 W/m^2) and was increased step by step to 165 W (1936 W/m^2). When the condenser pressure reached the desired value (set pressure), the cooling system started to operate. The cooling water flow was controlled so that the minimum vapor pressure in the condenser between two expulsions, or the

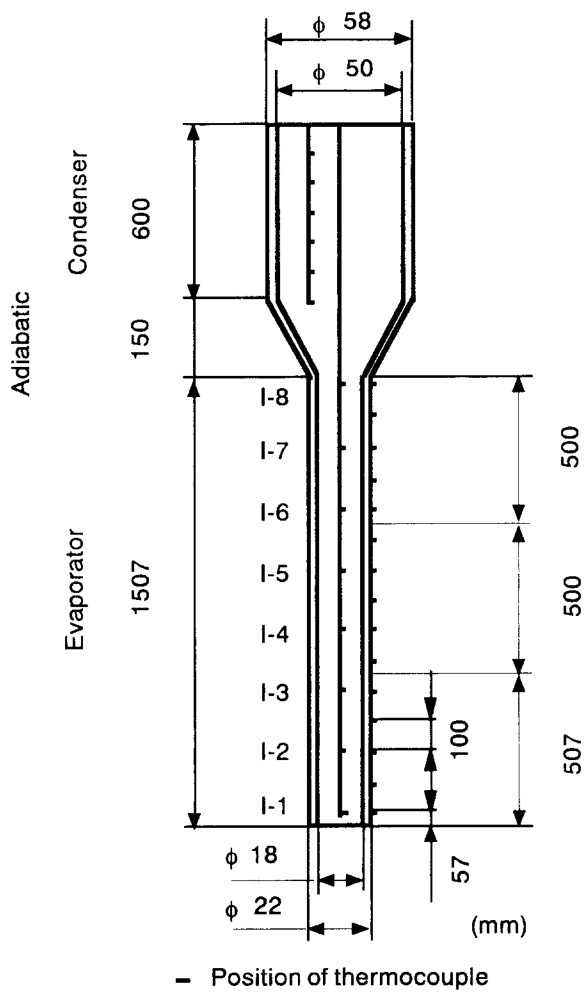

Figure 1. Experimental apparatus.

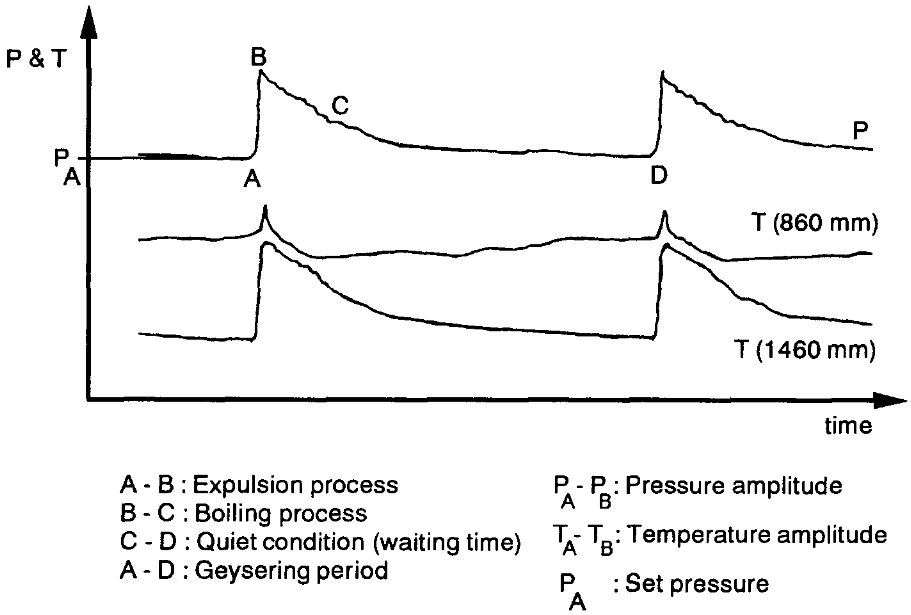

Figure 2. Geysering in one cycle.

base pressure, was kept at the set condenser pressure. This is shown in figure 2. The pressure fluctuation amplitude was defined as the difference between the set condenser pressure and the peak pressure during a geyser. The set pressure was varied from 36 to 88 kPa for R-113 and 3.4 to 47 kPa for water.

During measurement, the partially removable insulation layer was closed. It was opened to conduct visual observation after finishing the data recording.

3. RESULTS AND DISCUSSION

In general, energy transfer of the thermosyphon can be described as follows. Thermal energy supplied through the wall of the evaporator is transferred to the liquid by conduction and convection. This energy serves as the resource required for the liquid-to-vapor phase change during the boiling process within the liquid, or for the evaporation process at the top surface of the liquid. In the condenser, part of internal energy of the vapor was released to the cooling water during condensation. The period of cycle depends on the energy input rate, the geometry of the apparatus and the physical properties of the working fluid. At a lower heat input, generation of vapor can be delayed until the saturation temperature, or the required temperature for the bubble initiation is reached. During the delay time, part of the energy is released from the top liquid surface, while the remaining part is collected by the fluid for increasing the internal energy to reach the critical temperature for the boiling process to start. This delay time is known as the waiting time (Niro & Baretta 1990). This critical temperature is dependent on the physical properties of the working fluid, the surface condition and other conditions of the system. Niro & Baretta (1990) found that in a uniformly superheated liquid, nucleation occurs at an active cavity when the liquid temperature reaches the critical superheat. The degree of superheat changes with pressure, with lower pressures usually resulting in a higher degree of superheat. Bubble initiation is dependent on the surface condition, the liquid–wall temperature difference and the fluid properties such as the surface tension. A smoother surface generally results in higher degrees of superheat. Since freon–R113 has near-zero contact angles, or good wettability, on engineering surfaces, the larger cavities may be flooded out; high superheat is therefore required for nucleation (Boure *et al.* 1973).

Typical temperature distributions just before the geysering are shown in figure 3 for the cases of water and R113. In a long tube with a small diameter, i.e. for a very small aspect ratio of diameter to length (D/L), circulation due to natural convection heat transfer is suppressed, conduction is therefore the dominating mode of heat transport. As seen in figure 3(a), for the case of R113, falling

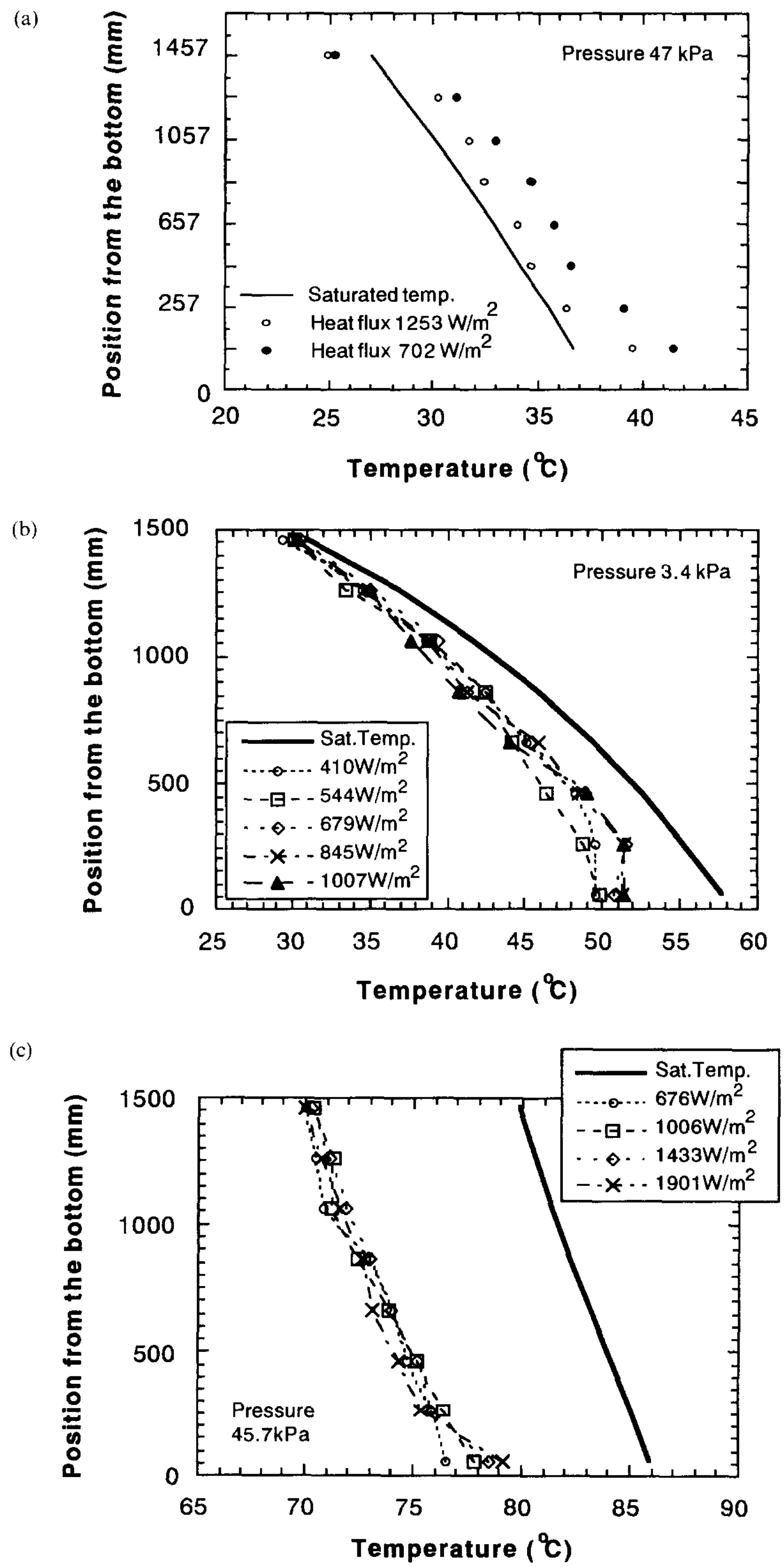

Figure 3. (a) Temperature distributions of R-113 just before geysering. (b) Temperature distributions of water just before geysering at a lower pressure. (c) Temperature distributions of water just before geysering at a higher pressure.

liquid from the condenser makes the temperature at the outlet of the evaporator lower than the corresponding saturated value. The temperatures at the lower locations are, however, higher than the saturated one, with the bottom having the highest degree of superheat. Usually the first bubble initiation comes from this area. As mentioned previously, higher pressures result in lower degrees of critical superheat.

Different results were obtained when water was used as the working fluid. As shown in figure 3(b) and (c), at all positions no superheat was observed. The first bubble initiation usually came from the upper part of the evaporator. The bubble generation then migrates downward in two possible ways: first, the bubble movements can dynamically enhance the bubble departure in the nearby positions; and second, the static pressure decreasing due to increasing void fraction can result in decreasing of saturated temperature and consequently more bubble generation. The temperature distribution or axial temperature gradient is dependent on the system pressure. The degree of subcooling at the upper part is lower at a lower system pressure than at a higher system pressure. The temperature distribution before geysering is strongly dependent on the thermal conductivity of the working fluid since the heat is mostly transported by conduction. The thermal conductivity of water in the range of the experimental conditions is about eight times higher than that of R113. This is the reason that the vertical temperature gradient in water is considerably smaller than in R113, which makes the mechanism of geysering in water different from that in R113.

The temperature at the bottom of the evaporator, just before geysering, is shown in figure 4 for various condenser pressures and heat fluxes. As seen in figure 4(a) for R113 at a lower pressure and a lower heat input, superheat was always reached before bubble initiation occurred. The degree of superheat decreases when the heat input increases. This affects the geysering periods as will be discussed later. As noted by Niro & Baretta (1990), the degree of superheat becomes smaller at higher pressures.

In the experiment with water as the working fluid, when the system pressure was high, however, bubble initiation was observed at the bottom imediately after the first bubble initiation at the outlet of the evaporator. At the outlet of the evaporator, circulation of the liquid is completed by evaporation at the top liquid surface, a falling liquid film from the condenser wall and a convective flow in the vicinity of the outlet of the evaporator. Increasing heat flux will enhance the evaporation at the top surface and increase the flow of the falling film along the condenser wall. Since the condenser pressure was kept unchanged, however, this increment cannot change the liquid temperature at the top surface. As a result, the temperature at 1460 mm was almost unchanged for various heat fluxes, as can be seen in figure 4(b). This is true for cases of both lower and higher pressures.

Figure 5(a) shows temperatures and the pressure fluctuations of R-113 recorded with the pen recorder for a heat flux of 702 W/m^2 and a system pressure of 47 kPa. Before the geysering began, the temperature at 460 mm from the bottom increased slowly with time, but when bubble initiation occurred at the lower part, the temperature spontaneously reached a small peak and then began to decrease. The small increase was caused by liquid flowing-up from the lower positions which had higher temperatures. The flowing-up of the liquid was caused by bubble expansion at the lower position. The decrease in temperature was caused by the fact that the thermocouple was surrounded by the expanding bubble in which the vapor temperature was lower than the surrounding superheated liquid. The bubble expanded as a long slug bubble, which pushed most of the liquid over it while moving from the lower part to the outlet. This caused the temperature at the upper part (e.g. 800 mm, 1460 mm) to increase. As a result, the higher the position, the larger the increment.

In the present experiment the system pressure fluctuations or increment due to the bubble expansion was found to be higher than the pressure head between the bottom and the outlet of the evaporator when filled with the fluid. This suggests that the pressure in the evaporator was increased during a geyser. It is thus concluded that geysering may occur even though the evaporator pressure may increase. This does not agree with Griffith's (1962) argument that geysering occurs only when bubble expansion results in a decrease of the pressure in the evaporator.

Since water has better characteristics in boiling, subcooled boiling always dominated. If we compare the surface tensions of R113 and water, the value of R113 is three times higher than that of water. This is one reason why, unlike in R113, superheat is not needed for bubble initiation in water. Figure 5(b) shows the temperature and pressure fluctuations at a heat flux of 680 W/m^2 and

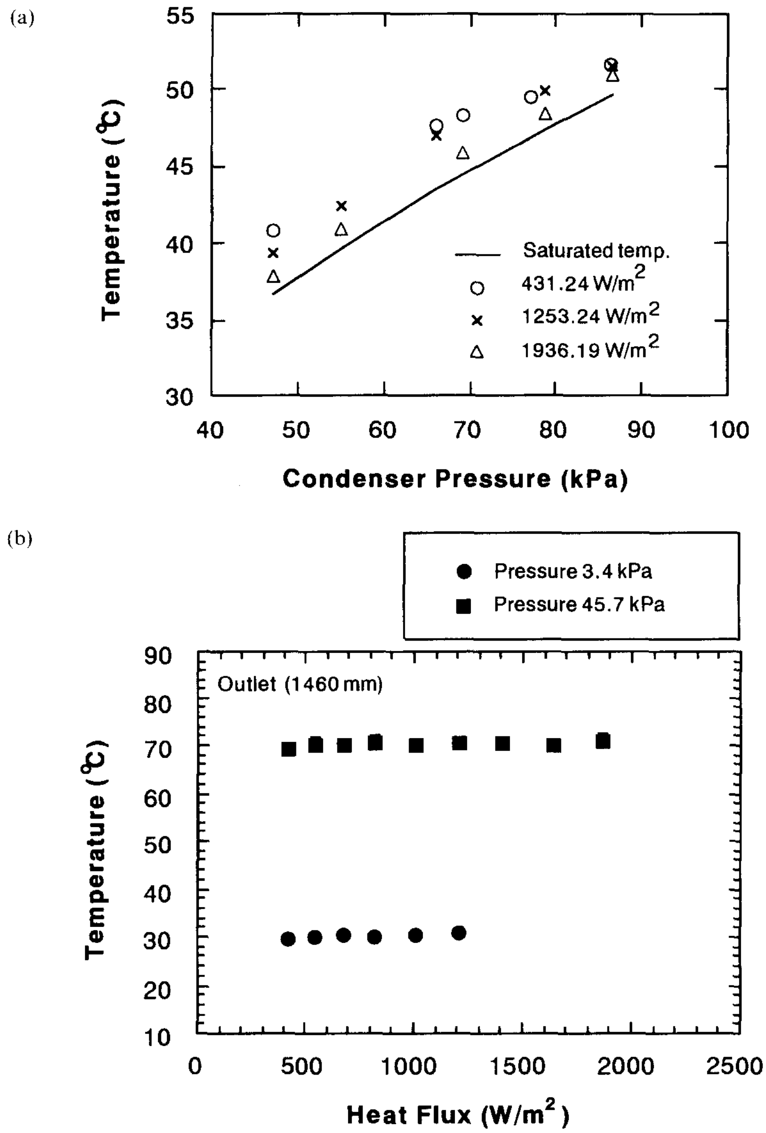

Figure 4. (a) Bottom temperature of R-113 just before geysering. (b) Evaporator outlet temperature of water just before geysering.

a condenser pressure of 3.4 kPa. The mechanism of geysering in water at low pressures was a propagation of boiling from the higher position to the lower positions. As shown in figure 5(b), the first increase in temperature occurred at the outlet (1460 mm) of the evaporator and simultaneously, the pressure in the condenser increased too.

The mechanism of geysering based on visual observations is shown schematically in figure 6. Griffith (1962) noted that two mechanisms could be responsible for the generation of large liquid superheat, which is the cause of geysering. The first is the delay in nucleation because of the absence of nucleation sites. The second is the decrease of the static pressure as a result of generation of voids. In this study, two kinds of geysering have been observed which are classified as follows. The first is geysering driven by the superheat of the liquid, and the second is geysering caused by a temperature distribution or the internal-energy storage pattern that will support nearly simultaneous bubble initiation along part or all elevations of the evaporator.

With R113 as the working fluid, during the waiting time, although the liquid at the outlet of the evaporator was at a saturated or even subcooled state, evaporation at the liquid surface always occurred to balance the falling film flow from the condenser wall. This was observed in all experiments except in the lower heat fluxes. The single bubble from the bottom flowed up while rapidly increasing its size due to evaporation from the surrounding liquid. This seems to be the basic mechanism of geysering in this case. This observation is different from that by Hands (1988) who claimed that the upward-flowing bubble enhanced the generation of more bubbles on its way to the top surface. Our observation seems to suggest that evaporation through the liquid–vapor interface of the bubble is an easier way to transport energy than initiating other bubbles at the wall, which require higher superheat. While the bubble hydrodynamically moved upward, expansion also occurred simultaneously due to a decrease in the static pressure. The bubble temperature was near the saturated one. The superheat of the surrounding liquid accelerates the bubble expansion by evaporation at the liquid–vapor interface. At the beginning of a geyser, the pressure increase caused by the bubble expansion was still small since the bubble volume was small compared with the evaporator volume. The accelerated bubble expansion due to the superheated surrounding liquid is a dominant mechanism at the beginning of the geyser. At the beginning of a geyser or immediately after the first bubble initiation, the degree of superheat of the liquid is high enough to considerably accelerate the expansion; as a result, bubble expansion becomes very fast. The bubble then expands to become a slug bubble, and pushes the liquid on top of the bubble upward, which makes the system pressure increase. The increase in system pressure will tend to increase the static pressure of the whole fluid column in the evaporator, while bubble generation will tend to decrease the static pressure of the liquid below the bubble. In the present experiment, the pressure of the liquid below the bubble also increased as a result of these two counteracting factors. The liquid above the bubble moves upward; as a result, a falling liquid film is developed around the bubble which receives heat from the wall

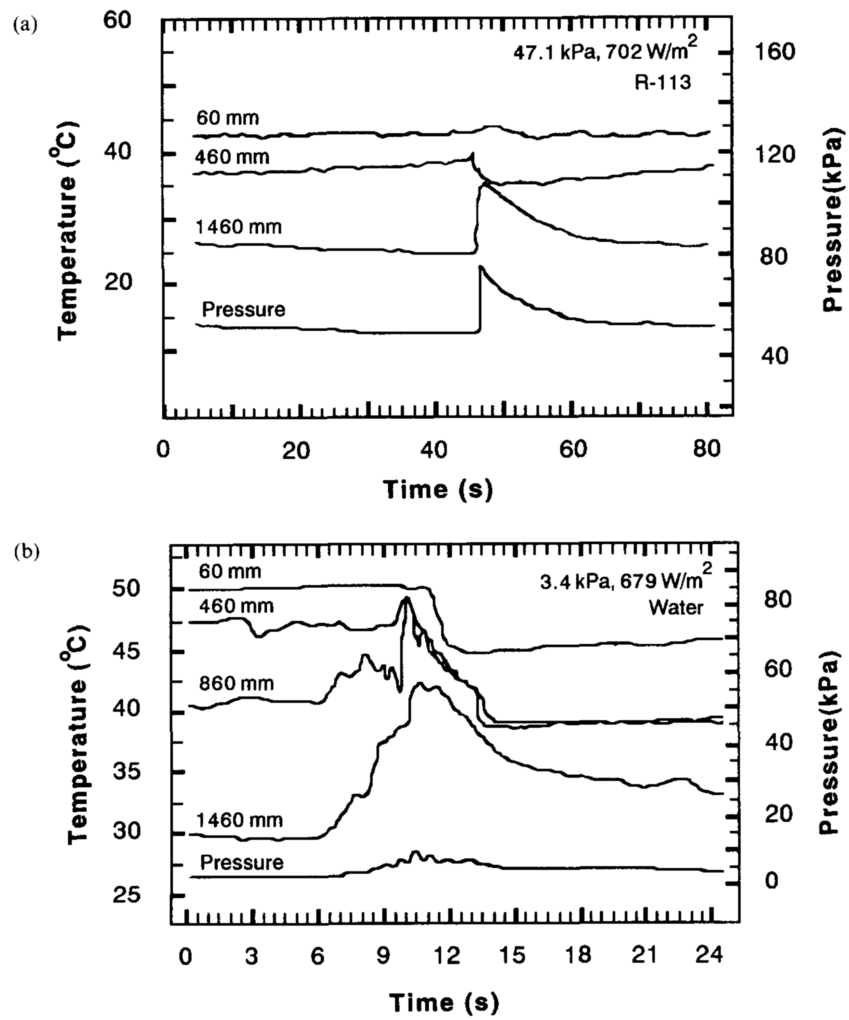

Figure 5. (a) Pressure and temperature fluctuation of R-113. (b) Pressure and temperature fluctuation of water at a lower pressure.

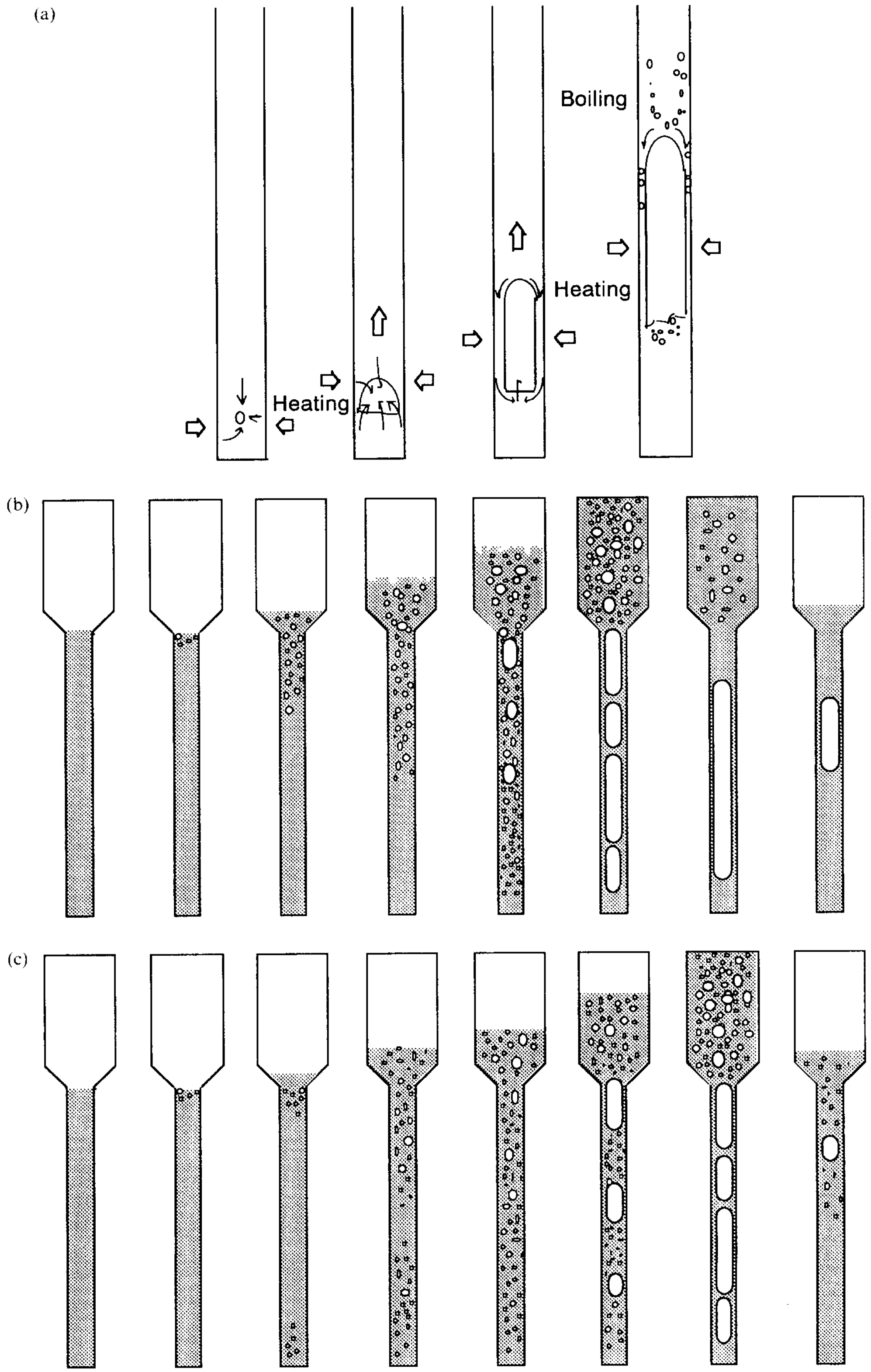

Figure 6. (a) Sketch of the geysering mechanism in R-113. (b) Sketch of the geysering mechanism in water at a lower pressure. (c) Sketch of the geysering mechanism in water at a higher pressure.

and transports it to the bubble. Due to the decrease in static pressure with elevation, the bubble expands faster at the upper part. The result of this is an increase in the condensor or system pressure. This mechanism controls bubble expansion during the geysering. This kind of geysering process could be known as geysering driven by superheat of the liquid.

With water as the working fluid, superheat was not observed. It is found that the geyser is driven by another mechanism, i.e. by a certain temperature distribution or the internal-energy storage pattern which can induce fast propagation boiling or a spontaneous boiling. This propagation can be realized when the system pressure and heat input have a certain characteristic such that the temperatures along the wall and within the liquid reach critical values for bubble initiation so that the initiation can be continuous from one place to the next. On the other hand, spontaneous boiling can be induced when the temperatures of the liquid along the wall simultaneously reach the critical values for the initiation. This will make the liquid inside the evaporator be spontaneously expelled to the condenser or the upper space, which is known as spontaneous liquid expelling. This mechanism is closely related to the heat transfer process between the heated wall and the liquid. In a long tube with a small diameter, since the circulation flow due to natural convection is usually very weak, conduction or thermal diffusion are a more dominant mode of heat transfer process. Murphy (1965) found that the geometry ratio (the heated tube length divided by the tube inside diameter) can determine the geyser–non-geyser boundary, but this was found to be entirely inappropriate for the water data produced by Burkhalter *et al.* (1968). In the present experiment, it was found that the temperature distribution may play an important role in the mechanism of geysering. The occurrence of geysering is thus determined by the geometry ratio, the physical properties and the temperature distribution. From the temperature distribution shown in figure 3(b) and (c), together with the wall surface condition, we can estimate roughly where bubble initiation will begin and how the bubble will grow.

The mechanism of geysering in water is schematically shown in figure 6(b) and (c) for the cases of lower and higher system pressures, respectively. The first bubble initiation was observed at the outlet of the evaporator in both cases. The propagation or generation of other bubbles was, however, found to be different for the two cases. As was shown in figure 3(b), liquid at an upper position has a smaller degree of subcooling. When the system pressure is low, the initiation of the first bubble at the outlet was followed by propagation of boiling from the outlet of the evaporator downward to the bottom. The first bubble reduces the hydrostatic pressure at the lower positions and causes a reduction of the corresponding saturated temperature (Griffith 1962). This makes the next bubble initiation possible; this chain reaction continues until the bottom of the evaporator is reached. At the same time, the liquid expelled to the condenser is cooled and the vapor is condensed. This is followed by refilling of the evaporator and an increase in the static pressure in the evaporator due to void decrement. The increase in the static pressure affects the saturated temperature, making the bubbles in the evaporator condense or even vanish to reach the quiet or waiting state. When the last large bubble vanishes, a breaking sound is heard due to the water hammer phenomenon.

Figure 6(c) is a sketch of the mechanism of geysering in water for the case of a higher system pressure (47 kPa). As was shown in figure 3(c), saturated temperature distribution along the center of the tube is almost linear, but the measured liquid temperature distribution shows that the degree of subcooling decreases towards the bottom of the evaporator. When the first bubble initiation occurs at the outlet of the evaporator, it will be followed by bubble generation at the bottom where the liquid is less subcooled. The bubble from the bottom grows and pushes part of the upper liquid into the condenser space, making the pressure inside the evaporator decrease, and resulting in a lower saturated temperature so that the next initiation occurs. This process continues from the bottom to the top of the evaporator.

4. CONCLUSION

(1) It was found that temperature distribution or the internal-energy storage pattern may play an important role in initiating a geyser. Temperature distribution is dependent on the geometry of the system, the physical properties of the working fluid and the heat transfer process.

(2) When superheat is the driving force in producing a geyser, it was found that although during bubble generation the evaporator pressure may increase, geysering may still occur.

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