Transport-Mechanisms During Boiling in Microgravity Environment

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Abstract

Pool boiling experiments in microgravity performed during the past 3 decades demonstrate unanimously that up to a medium heat flux the overall heat transfer is nearly independent from gravity. So far it was assumed that buoyancy plays the essential roll for heat and mass transport expressed in the empirical correlations for technical applications. We refer in this paper on results of experiments performed with various liquids and heaters, using different carriers which provide low gravity like TEXUS rockets, aircraft KC135, and drops in the tower of ZARM and shaft of JAMIC, and as highlights, experiments during space lab missions. Beside the measurements of the experimental parameters like the liquid state, temperature and pressure, heat fluxes, and heater temperature, we observed the boiling process itself with movie films and videos. From these records we learned about the bubble dynamics, the mechanisms of heat and mass transport without gravity only generated by the bubbles themselves, and details about the boiling process itself not recognized up to this day. These findings are essential for a better understanding of the complex physical process, and are important for the formulation of empirical equations, and in future for numerical solutions to predict the heat transfer for technical applications.

1. Introduction

The boiling process consists in sequences of nucleation at boiling onset, afterwards bubble activation, followed by bubble growth, detachment, departure, and the transport of the bubbles respectively the vapour away from the heater. Under terrestrial conditions these processes depend more or less on buoyancy effects caused by gravity, and it is generally assumed that their interaction is responsible for the overall heat transfer expressed in the used empirical correlations for pool boiling. In contrast to these assumptions it was surprising that in the experiments performed at microgravity the heat transfer didn’t immediately collapse, and that the equations for pool boiling heat transfer fail completely extrapolated to the actual low gravity conditions. On the contrary up to about 50 percent of the critical heat flux at 1g the heat transfer coefficients are nearly identical compared with the terrestrial values. At lower heat fluxes they are even higher up to 15 percent as under terrestrial conditions and show a slow decrease by increasing heat fluxes. The agreement of the heat transfer between the gravitational and terrestrial data indicates that the basic mechanisms in both cases must be identical and more or less independent from gravity. Today there is general agreement that the evaporation at the liquid/vapour interface on the bubble base is the dominating process for the heat transfer especially at the contact line of the three phases – solid, liquid, and vapour. But just as important is the bubble and vapour transport away from the heater.

Therefore still the questions raise how the bubbles detach, depart and move away without gravity or other external forces, and what are the mechanisms able to replace buoyancy? We concentrated our research on pool boiling only, without applying any external forces\(^1\), to find out what are the transport mechanisms the bubbles developing by themselves. At the beginning the objective of our research was to answer the questions: Is boiling an appropriate mechanism of heat transfers in space applications, and how do heat transfer and bubble dynamics behave without buoyancy, shear or electrical field forces? Is bubble dynamics itself being able to maintain heat transfer during boiling? The correlations used today to calculate heat transfer coefficients for practical applications in pool boiling are more or less based on the assumption that buoyancy detaches the bubbles from the heating surface and carry the vapour with hot liquid away. According to this model heat transfer would break down in microgravity, because rapidly a vapour layer would be formed and would isolate the heater. That’s why microgravity itself is an outstanding environment to study boiling in order to gain a better understanding of the complex interrelated physical mechanisms for application in space but rather at earth too. Flow boiling under microgravity has been studied by H. Ohta\(^2\), we recommend his paper.

2. Experiments

Various carrier systems that allow the simulation of microgravity could be used, such as the Drop Tower ZARM, Drop Shaft JAMIC, parabolic trajec-Tories with NASA’s aircraft KC-135, ballistic rockets TEXUS, and as highlight finally three Space Shuttle missions. As far as the possibilities of the respective mission allowed, a systematic research program was developed, which was always adjusted to the possibilities of the carrier system, and the mission, and it was continuously updated to the findings, former results, and to new experimental
parameters. Likewise appropriate experimental facilities were developed, designed and adopted to the carriers to obtain optimal results. The mean features of the experimental facilities consisted in the liquid cell with control of the temperature, and the fluid pressure with bellows by counter pressure with gas from a pressure vessel, in order to change the saturation pressure of the liquid and the sub cooling conditions. Various heaters were used like wirers with 0.05 and 0.2 mm diameter, small thermistors of 0.3 to 1.4 mm diameter, and a flat gold coated surface of 20 x 40 mm² in order to study the influence of geometry. These heaters could be employed simultaneously both for power control and as resistance thermometers to achieve an average temperature of the heater. Moreover the facilities contained special electronics for control, data recording, film and video cameras.

3. Onset of boiling

According to the nucleation theory the onset of boiling doesn’t depend on gravity. However, the temperature and the nucleate sites along heater surface determine the onset of the boiling process, which locally starts and spreads out over the heater surface. Incipience of boiling depends on the local temperature and heat flux which are influenced by convection at 1g. It was observed that incipience of boiling occurs at μg at a lower heat flux than at 1g but at about the same temperature. At 1g the buoyancy driven convection cool the heater according to convection patterns not evenly, and nucleation occurs when locally the temperature which provoke nucleation is reached. In Fig. 1 the temperature course versus time at μg after power on is compared with 1g under the same experimental conditions: (platinum wire 0,05 mm diameter, power 69 kW/m², liquid R134a at saturation, p/p_c = 0.21). In both cases the temperature increase follows first according to conduction. At about 57 °C onset of boiling occurs at μg, followed by the rapid temperature drop to 45 °C within 0.6 sec. At 1g the temperature of the onset of boiling is roughly the same, but then the temperature slowly drops within 3 sec. to reach then the same value than at μg. In the further course both temperatures remain constant which means, that at the same heat flux the same heat transfer coefficients are adapted in both cases. The slow decrease of the heater temperature at 1g compared to μg indicates that a large part of the wire is cooled by buoyancy convection which avoid the spontaneous nucleation over the whole wire.

4. Bubble growth

The bubble growth rate depends from the temperature at the interface. We may assume that in boiling the temperature at the interface is nearly at saturation small deviation lead to strong evaporation. From our observation we suppose that the mean parts of the evaporation results from the thin liquid layer at the microwedge at the bubble base in direct contact with the solid heater, in these place high temperatures are calculated at the interface. As far as the bubble interface is in direct contact with the superheated boundary layer additional evaporation come along. This boundary layer is gravity dependent, and has so far influence on the growth rate, but this part is very small compared with the total evaporation rate; its influence is hard to ascertain.

5. Detachment and departure

Of course steady state heat transfer described before is only possible if mechanisms exist for bubble detachment and departure from heater, mechanisms, which replace gravity and buoyancy. It is important to understand these mechanisms able to detach and transport the bubbles without buoyancy. After nucleation and during growth static and dynamic forces hold the bubbles attached at the heater wall, and there are forces which provide them a first push to detach and depart the bubbles. We will describe some observations without consisting on completeness.

5.1 Inertia forces

In the videos we can observe a swarm of very tiny bubbles shooting from the heater short after incipience of boiling on wirers. The first nucleated bubbles are growing in the very high superheated liquid boundary layer at the heater; due to the high superheat they grow very fast, and push liquid away. The inertia forces of this liquid detach and carry the bubbles along. But this happens only during the first event of boiling onset.

5.2 Ripening

The heat for evaporation during bubble growth is mainly taken from the small, thin circular area at the bubble base, where it is attached at the wall. In the centre of it a dry spot is formed, as recent numerical and experimental studies demonstrate. It is often observed that the temperature below a bubble oscillates with the period of bubble generation and departure. The strong evaporation at the circle of the three phase line -solid-liquid-vapour- at the bubble base produces a recoil force, which deforms and holds the bubble at the solid surface and forms an obvious wetting angle. This evaporation process consumes the heat from the solid
wall, and reduces that way the local wall temperature. Also a very thin slice of the solid wall is affected the heat recovery by conduction is a slow process compared with the spontaneous evaporation. Therefore temperature oscillation is caused. At the low temperature of the circle process further evaporation is reduced and stopped, and just as the recoil force tends to zero. The bubble reforms to spherical shape, the dry spot below the bubble is rewetted by liquid. The bubble lifts him by the formation to sphere and the inertia of the following liquid pushes it off. This departure mechanism is confirmed by the observation at all our boiling experiments at microgravity, when the power was switched off all bubbles depart immediately from the heater surface and the liquid wets immediately. I called that process “ripening” because it can be compared with an apple at a tree, when the apple is getting ripe the sap (heat flux) to the apple is interrupted, the apple falls down.

5.3. Coalescence mechanisms

Very strong transport mechanisms are coalescence processes. We observed during boiling vigorous lateral and vertical coalescence processes, which push the bubbles from the surface. There are three effects: i) even regarding only the steady state case before and after unification of bubbles, the centre of the joint bubbles moves away from the heater surface the released volume is replaced by following liquid, it’s inertia pushes off the bubbles; ii) after coalescence the bubble oscillates in lateral and vertical direction, in vertical direction it hits the wall and pushes itself off, iii) the momentum and inertia of the following liquid push the bubbles further off, see Fig. 2.

6. Vapour removal at saturation state

As described before the mechanisms of bubble detachment and departure are observed both for saturated and subcooled liquids. However, the mechanisms of bubble or vapour removal differ. In saturated liquids the removal is mainly caused by coalescence processes, and depends on the size of the coalesced bubbles. From videos we observed that the bubbles getting larger with distance from the heater. If two bubbles of same diameter coalesce free in liquid the centre of the joint bubble will be at the contact point when the oscillation comes to rest. The released surface energy caused by the reduced surface of the joint bubble is dissipated by oscillatory motion. If this coalescence happens parallel to the heater surface, the joint bubble will not move away. In saturated boiling the bubbles are hovering above the heater surface and new generated bubbles grow below, touch, and join them, and lift the bubble. If small bubbles contact larger ones, the vapour of the small bubble flows fast by the pressure difference due to Laplace equation into the larger bubble. This space is filled up by following liquid, which becomes accelerated and pushes by its inertia the large bubble. In Fig. 3 we observed in an experiment on the 0.2 mm Ø wire the bubble or vapour removal by coalescence processes. In the first row left two bubbles 1 and 2 are observed, which contact each other, following to the right the coalescence process between them begins. In the second row the united bubble 3 oscillates lengthwise and crosswise. If we follow the position of the two bubbles from the first row to the last picture we register a remarkably movement within the short period of 300 msec, the frame sequence is 20 msec. As we observed in the video, all bubbles grow with increasing distance to the heater by continuous coalescence processes, each coalescence push the joint bubbles by the inertia of the following liquid. These processes maintain the vapour transportation in microgravity.

7. Heat and vapour removal at subcooled state

In case of subcooled boiling the bubbles generate a strong convection as long as they are attached to the heater. This flow is perpendicular to the heater surface and causes a reaction force which presses the bubbles together with the recoil force towards the heater surface. However, as described before even at subcooled boiling bubbles detach from the heater by ripening and coalescence processes. Such detached bubbles move away along with the flow, and they become smaller with distance from the heater due to condensing in the subcooled liquid, Fig. 4. They are taken along by the inertia and shear of their own produced flow, and by the
flow generated from neighbouring bubbles.

This flow can be identified as a certain type of thermocapillary convection, caused by the bubbles themselves. The origin of this thermocapillary flow will be discussed below. In some distance from the heater these bubbles come to rest, condense, and disappear. Sometimes bubbles are observed Fig. 5 which stop in some distance from the heater and return to the heater, this may be due to the fact that this bubbles penetrate with her top into colder liquid, developing a thermocapillary flow which drift the bubbles backwards.

A further observation must be noted that at certain conditions of heat flux and liquid state on small plane circular heaters and on spherical thermistors large bubbles were generated, they are attached and remain at the heater with a size much larger, than the heater size, see Fig. 6. These bubbles produce a strong thermocapillary jet flow at the top. In these cases the energy and mass balance is covered by the evaporation at the base, the vapour flow through the bubble, the condensation of the vapour at the upper part, and the thermocapillary flow on the liquid side of the bubble, which takes heat and mass with it into the bulk liquid. If the power was changed these large bubbles adjust their size themselves till heat and mass transfer from bubble base to top is balanced. These bubbles act quasi as steady state adjustable heat pipes between the heaters and liquid.

8. Origin of thermocapillary convection

It must be emphasised that in the case of boiling in saturated liquids we could never observe any flow, however, at subcooled boiling we observed convection in all of our experiments. Up to now, it is not clear whether thermocapillary convection in the microwedge at the bubble base may occur or not. Indeed, there exist high temperature gradients along the interface due to the high evaporation rates there. However, the extension of this area is so small that either the convection doesn’t develop or could not be observed with present applicable optical methods. Therefore, we exclude the microwedge area from our further consideration.

We repeat the statement expressed before: no convection could be observed at saturated boiling, but a strong convection appears always at subcooled boiling, see Fig. 4, 5, 6. The first is understandable by the general experience that the interfacial heat and mass exchange is the dominating process, already small temperature differences lead immediate to a strong mass exchange either through evaporation or condensation, so that deviations from equilibrium are immediately balanced. This leads to nearly uniform temperature, so that no temperature gradients along the bubble interface appear, which are strong enough to generate thermocapillary convection.

The question arises: What generates the convection at subcooled boiling? We should assume following the arguments discussed above, that the interface in subcooled boiling is also near saturation temperature. Also a bubble at subcooled boiling is generated at the superheated heater wall, and grows within the superheated boundary layer, but if it grows beyond this boundary layer, and it’s top penetrates into the subcooled liquid, by that the interface may get only a
little below saturation temperature, and immediately the vapour molecules condense. At the liquid side the heat is transported into the subcooled liquid. However, inert, non condensable gases first dissolved in the liquid, are released on the bubble base with the evaporating molecules, transported with them, but when the vapour molecules condense, the non condensable molecules remain at the interface and accumulate there. The total pressure inside the bubble consists of the partial pressure of the accumulated gas and the partial pressure of the vapour can be assumed to be constant. At the top of the bubble interface where the inert gas is accumulated the partial vapour pressure is reduced and with it the saturation temperature. This partial vapour pressure determines the saturation temperature at the interface, which is lower at the top than at the bubble base; consequently at the interface a temperature gradient from top to base is established, which generates thermo capillary convection in opposite direction from base to top Fig. 7. Estimated calculations show that also very small impurities of inert gas in the liquid are sufficient to generate an inert (non condensible) gas layer thick enough to cause thermo capillary convection. By the shear force of the thermo capillary flow at the liquid side of the interface the accumulated inert gas together with the vapour inside the bubble is transported toward the bubble top and supports there the accumulation.

It must be emphasized that for our experiments we have used liquids as pure as available and we had them purified further by multiple distillations under vacuum conditions. Additionally it should be mentioned that the velocity of the thermocapillary convection, measured by PVI method during space experiments, decreases with increasing subcooling of the liquid. That’s why in this case the temperature gradient in the bulk liquid, generally used to describe thermo capillary convection by Marangoni number, can not be applied.

With the accumulation of inert gas for the first time a mechanism is described, which generates thermo capillary convection on bubbles without an observable temperature or concentration gradient in the liquid, but by a local change of the partial saturation pressure inside the bubbles.

9. Pumping at high subcooling, cavitation boiling

At high subcooling a high heat flux is necessary to raise the wall temperature up to nucleation temperature so that bubbles may be generated. Otherwise heat conduction at μg or convection at 1g is sufficient to cool the heater below nucleation temperature. If boiling occurs, the high superheat causes a rapid bubble growth, which consumes the surrounding superheat energy immediately. The bubble expands, the interface extends, and gets in touch with subcooled liquid, and then the vapour condenses immediately, the bubble collapse. The rapid periodic bubble expansion and collapse pump with high frequency the warm liquid away, boiling acts like apiston pushing the liquid. During the short period in which the interface exists, thermocapillary convection cannot be developed. Because of the microscopic size of the bubbles and the high frequency of this process the event could not be seen by direct observation, but by inspection with an interferometer a slow moving plume of warm liquid could be detected which is identified with the pumped liquid, whereas at 1g strong convection prevails and coverthe whole process.

10. Conclusion

During boiling experiments in microgravity it turned out that the most important mechanisms to maintain heat transfer are:

1. The evaporation at the bubble base, which determines the heat transfer, this process is up to a certain heat flux nearly identical at 1g and μg;
2. The bubble transport with detachment, departure, and vapour removal is due to the impulse and inertia generated by the bubbles themselves.

In this paper we deal with the 2. part, where we have discussed all the dynamics which the bubbles generate during their growth, their interactions with the heater wall, coalescent processes with neighboring bubbles, and finally with the origin of the flow induced by thermocapillary forces, which in case of subcooled boiling is due to accumulation of non condensable gases in the upper part of the bubbles in subcooled liquids. This conclusion results from the fact that in saturated boiling no such flow could be observed.

It is astonishing that the removal of the vapour either at 1g by gravity or at μg by the bubble dynamics has less influence on the heat transfer as generally assumed and even at flow boiling the heat transfer does not noticeably change at the conditions of microgravity.

We describe in this paper the physical processes and mechanisms of the complex boiling system which appear at μg and definitely as well at 1g, but in this case it is covert by convection. The knowledge of these mechanisms is important and essential for numerical studies, but even so for the formulation of empirical correlations with a wider range of validity as present correlation does.
References