論文の内容の要旨

論文題目　Highly subcooled boiling on heated elements with small thermal capacities
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Boiling is highly utilized in the industrial applications of large scale, such as nuclear power plant and steel industry due to its good heat transfer characteristics. In the past several decades, a large number of studies on boiling heat transfer have been carried out. However, because of complexity of boiling phenomenon, some mechanisms remain not clear. One of the recent major targets of the boiling heat transfer is the cooling of electronic devices such as CPUs. The recent rapid increase of the power consumption of electronic packages gives rise to the major issue of the cooling of that. The need for a miniaturization of cooling unit drives application of cooling by flow in small passages, which has large heat transfer coefficient even in single phase. Boiling heat transfer in small passages is expected to achieve higher heat flux than single phase heat transfer. Bubbles confined in a small passages, however, cause large pressure drop to flush them out and result in a dryout of the heated channel walls to damage the components.

In response to this, the author applied microbubble emission boiling to boiling in small passages. Microbubble emission boiling is a peculiar mode of boiling that is specific to highly subcooled boiling at high heat flux. In this mode, numerous microbubbles are injected from heat transfer surfaces due to violently rapid shrinkage of vapor bubbles with condensation. It leads not only to the fluctuation of bubble surface to generate microbubbles, but also to the good heat transfer characteristics by bringing cooler liquid above to the heat transfer surfaces. Experimentation of highly subcooled flow boiling in small channels was conducted to keep small pressure drop at the same level of single phase flow at up to high heat flux near 4.8 MW per square meter (Tange et al. (2004) and Tange et al. (2005)). The physics of flow boiling is more complex than that of pool boiling because boiling bubbles emerge in forced convective flow and phenomena in upstream affects those in downstream. Most of boiling experiments at high heat flux use copper blocks with large thermal capacities because of its toughness against of heating. In order to predict boiling in a small cooling packages, however, knowledge about boiling with small thermal capacities should be needed.

In order to survey the mechanisms and the occurrence condition of microbubble emission, the author conducted two series of experiment: (1) highly subcooled pool boiling on heated metal wires, and (2) highly subcooled pool boiling on artificial surfaces.

(1) Highly subcooled boiling on heated wires

A platinum wire with a diameter of 300 micron was submerged in a stagnant water pool in which liquid temperature was controlled and it was heated by direct electric current.
Heat flux and average temperature of the wire was estimated from power consumption and resistance. Boiling curves of various subcooling conditions was constructed, however, there is no clear jump of temperature between ordinary nucleate boiling regime and microbubble emission boiling as reported in the system of heater blocks with large thermal capacities. As the increase of the subcooling, critical heat flux increases

under low subcooling conditions and the tendency of the increase decreases over about 30 K.

From the photographic observation with high-speed video camera, it was found that primary bubbles on a wire did not depart from the wire and rapidly collapsed to generate several microbubbles with the deformation of the top of the primary bubbles under high subcooling condition.

Analysis of heat transfer was conducted to estimate the contribution of microbubble emission to the heat transfer qualitatively. Near saturated condition, boiling bubbles detached from the heat transfer surface and heat removed by the vapor bubble is not negligible. As the increase of the subcooling, maximum diameter of bubbles on the wire become small and heat transfer completes within a thin area around the wire.

Under more highly subcooled condition, however, it was found that heat transfer did not complete in the thin area. This indicates that emission of microbubbles and induced flows by collapses of the mother bubbles contribute the heat transfer.

(2) Highly subcooled boiling on artificial surfaces

Microbubbles came to the world with violently rapid deformation of a mother bubble on the heated surface in the heated wire experiment. According to the boiling experiment on a heated wire, maximum diameters of boiling bubbles depends on the position of nucleation sites even in the same heat flux and the same subcooling. Relatively large bubbles of more than 500 micron diameter deform largely, although smaller bubbles remain spherical during growth and shrinkage process. This indicates that the waiting time till the nucleation and the growth of thermal boundary layer varies according to the specification of the nucleation site. Steady heating experiment can not avoid the effect of preceding bubbles and adjacent bubbles on the motion of the bubble in question.

Subsequently, in order to examine the behavior of a single boiling bubble in an ideal situation imitating an actual boiling, careful experimentation was conducted. The objective of this experimentation is to generate a single vapor bubble in an ideal situation. Artificial surfaces were fabricated with MEMS technique to realize arbitrary thermal boundary layers and control the bubble nucleation. Nakabeppu and Wakasugi (2006) proposed new artificial surface fabricated with MEMS technique and performed an experiment on boiling bubbles generated at a single site with steady heating. This surface has miniature thermocouples and a hydrogen trigger for the nucleation. In this experimentation, the author employed the original Nakabeepu's surfaces and upgraded them by adding the thin film heater to make it possible to heat the surface transiently.

A new MEMS chip as artificial heat transfer surface is a silicon chip square in shape, 20 mm in height and width and 0.5 mm in thickness. It has seven thermocouples for temperature measurement and hydrogen trigger for control of bubble nucleation on a front side, and thin film heaters for transient heating on a back side. Each component on the chip was fabricated with sputtering and liftoff techniques.

A test section with the chip was submerged into stagnant pool in which test fluid, distilled and degassed water, is maintained at a desired temperature. The thin film heaters were heated by direct electric current to generate thermal boundary layer on the chip. Hydrogen trigger generated liquid-gas interface playing the role of the nucleus. It is the special feature of this chip that nucleation of a bubble is separated from heating of the surface. Temperature distribution and its time variation of the surface were measured by thermocouples.

At various heating time and heat flux, the bubble was generated and observed, and it was categorized into four patterns. Under the conditions of highly subcooled boiling at high heat flux, the growing bubbles largely deformed and generate tiny bubbles from the top part of it as same as that on heated wires.

Both on heated wires and on artificial surfaces, it was observed that microbubbles were produced from largely deformed mother bubble touched on the surfaces. And only relatively large bubble produced microbubbles. To employ microbubble emission boiling to boiling in small passages, height of the channel needs to be large enough to allow bubbles on the surface to grow and deform largely.

Although microbubbles emerged, boiling on heated elements with small thermal capacities did not reproduce the heat transfer characteristics of ordinary MEB, a stable regime in the temperature range of transitional boiling, as reported in the systems of heater blocks. This is because it is difficult for a small heated element to maintain the temperature in a range of transitional boiling once it partially dry out.

The main body of the thesis, which contains four chapters, treats the investigation on a single vapor bubble conducted against the background described above with experimental approaches. Chapter 1 introduces boiling phenomena in the context of applications and fundamentals and open problems on it in order to familiarize the reader with the terms in boiling research and to show the motivation of the investigation. Experimentation of subcooled boiling on heated wires is described in Chapter 2. Experimentation of subcooled boiling on artificial surfaces is described in Chapter 3. Conclusions and remarks are summarized in Chapter 4.