Advances in
HEAT TRANSFER

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PREFACE

For more than a third of a century, the serial publication *Advances in Heat Transfer* has filled the information gap between regularly published journals and university-level textbooks. The series presents review articles on topics of current interest. Each contribution starts from widely understood principles and brings the reader up to the forefront of the topic being addressed. The favorable response by the international scientific and engineering community to the 37 volumes published to date is an indication of the success of our authors in fulfilling this purpose.

In recent years, the editors have published topical volumes dedicated to specific fields of endeavor. Examples of such topical volumes are Volume 22 (Bioengineering Heat Transfer), Volume 28 (Transport Phenomena in Materials Processing) and Volume 29 (Heat Transfer in Nuclear Reactor Safety). As a result of the enthusiastic response of the readers, the editors intend to continue the practice of publishing topical volumes as well as the traditional general volumes in the future. Volume 32, a cumulative author and subject index for the first 32 volumes, has become a valuable guide for our readers to search the series for contributions relevant to their current research interests.

The editorial board expresses its appreciation to the contributing authors of Volume 37 who have maintained the high standards associated with *Advances in Heat Transfer*. Lastly, the editors would like to acknowledge the efforts of the staff at Elsevier who have maintained the attractive presentation of the volumes over the years.

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Microgravity Heat Transfer in Flow Boiling

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Abstract

To investigate flow boiling in microgravity, test sections of transparent heated tube and transparent heating surface were developed, and heat transfer characteristics were directly related to the liquid–vapor behaviors observed. The experiments were performed on board aircraft where the boiling system was exposed in series to normal, hyper and reduced gravity fields along a parabolic trajectory. In the experiments using a round tube and an analytical model, an important gravity effect on two-phase forced convective heat transfer where heat transfer is deteriorated in microgravity at low mass velocity was clarified. As regards the dryout phenomenon, measurement of critical heat flux was attempted in a short microgravity duration and the process of dryout was investigated for a moderate quality region based on the measured temperature fluctuation and corresponding liquid–vapor behaviors. Flow boiling in narrow channels was also investigated as one of the systems to be applied to space heat exchangers, and a few important characteristics were clarified concerning the gravity effect. Because of the limited opportunity for experiments and the short microgravity duration created by aircraft, the results obtained here could not cover all aspects of the phenomenon for the gravity effects on flow boiling for different systems and parameters, but the results are intended to become a powerful aid for further investigation in the present discipline utilizing longer microgravity periods in a new space platform to be realized soon.

I. Introduction

Recent increases in spacecraft size and power requirements for advanced satellites and other orbiting platforms have increased the demands for more effective thermal management and thermal control systems. Thermal systems utilizing boiling and two-phase flow are effective means for the development

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of high-performance, reliable and safe heat transport systems for future space missions. Boiling heat transfer offers high heat transfer rates associated with the transport of latent heat of vaporization and has the potential to significantly reduce the required size and weight of heat exchangers. The latent heat transport in two-phase flow reduces the flow rate of liquid circulated in the loop for the same amount of heat transport and, in turn, reduces the pump power requirement. Furthermore, two-phase fluids allow for precise adjustment of the fluid's temperature responding to the thermal load by simply pressurizing the system using an accumulator.

Despite their acknowledged importance, boiling and two-phase flow systems have not yet been fully implemented in new spacecraft except for small-scale heat pipes and a thermal transport loop planned in the Russian module of the International Space Station. This is partially attributed to the lack of a reliable database for the operation of such systems in microgravity. In addition, the uncertainty in the critical heat flux (CHF) conditions discourages space system designers from introducing such systems. Single-phase liquid cooling systems are favored despite the large mass penalty. But even with single-phase systems, boiling and two-phase flow would inevitably occur as a result of, for example, accidental increase in the heat generation rate, or a sudden system depressurization caused by valve operation.

It is safe to say that, to date, there is no cohesive database for microgravity boiling and two-phase flow (reduced gravity is referred to as microgravity or μg here). There is also a prevailing misconception that few differences actually exist between normal and microgravity heat transfer coefficients in flow boiling in the existence of bulk flow. But this is not true, as is shown in the following section when bulk flow is not so large. In addition to the clarification of phenomena in microgravity, the establishment of a coherent database for microgravity flow boiling and two-phase flow provides fundamental information for the development of large-scale two-phase thermal management systems for possible implementation in future spacecraft and earth orbiting satellites.

Research on microgravity boiling has a history of more than 40 years with a short pause in the 1970s and has been advanced with the development of various microgravity facilities and with increased experimental opportunities, especially in the last 15 years. Most boiling experiments in microgravity, however, have been conducted for pool boiling, while the data on flow boiling experiments are very limited except those for isothermal two-phase flow concerning the gravity-dependent flow pattern change and pressure drop. This is partially due to the practical difficulties in adapting the flow boiling apparatus with its various components to the microgravity facilities such as drop towers, aircraft, ballistic rockets and space shuttles with limited capacities in both integration volume and power supply.

Misawa and Anghaie [1] introduced two different test sections for boiling experiments, i.e. a transparent square channel of pyrex glass with a coating of transparent heating films for flow pattern observation and a copper tube with a nichrome coil on the outer surface for the pressure drop measurements. Drop experiments were conducted for Fron113 flowing in vertical test sections. It was clarified that the slip ratio under microgravity is less than unity and the pressure drop is larger than the values predicted by the homogeneous model because of the increased contribution of acceleration resulting from the increase of void fraction. Kawaji *et al.* [2] investigated on board KC-135 aircraft the behavior of two-phase flow and heat transfer during the quenching of a preheated quartz tube. The tube, heated externally by a spiral nichrome tape, was initially empty and Fron113 was pumped into it. In microgravity, a thicker vapor film is formed on the tube wall making the rewetting of the wall more difficult and resulting in the reduction of the heat transfer rate. They observed flow patterns for flow boiling of subcooled Fron113 and saturated LN2 both on the ground and in microgravity, and reported marked differences in the shapes of liquid droplets in the dispersed flow region [3]. Saito *et al.* [4], using Caravelle aircraft, performed flow boiling experiments for water under subcooled and saturated conditions in a horizontal transparent duct with a concentric heater rod. In microgravity, generated bubbles move along the heating rod without detachment and grow and coalesce to become large bubbles, while the local heat transfer coefficients along the periphery of the heater rod, however, are quite insensitive to gravity levels. Lui *et al.* [5] presented experimental results on subcooled flow boiling in a horizontal tube, where the heat transfer coefficients due to nucleate boiling in microgravity increase up to 20% from those in normal gravity if subcooling is low. Rite and Rezkallah [6,7] investigated heat transfer in bubbly to annular flow regimes of air–water two-phase flow. The method is useful for the investigation of heat transfer mechanisms for two-phase forced convection under various flow rate combinations of both phases, involving those not easily realized by the single-component system, if the differences between the single-component and binary systems in the interaction of liquid and vapor phases are taken into consideration.

To improve the approach for the clarification of phenomena in microgravity, the present author developed the observation technique, i.e. transparent heated tubes and transparent heating surfaces employed in the flow boiling using round tubes and narrow channels, respectively. In the experiments for flow boiling in a tube, the effect of gravity on the heat transfer was clarified by making reference to the observed liquid–vapor behaviors in a wide quality range covering the bubble to the annular flow regime. Gravity effects on heat transfer due to two-phase forced convection in the annular flow regime were analytically investigated to clarify the mechanisms relating to the gravity-dependent behaviors of annular liquid film. Acquisition of CHF data was attempted in microgravity and one of the major dryout mechanisms was investigated based on the temperature fluctuations obtained at heat fluxes just lower and higher than the critical value. For flow boiling in a narrow gap, a transparent flat heating surface was developed and integrated in a narrow channel, and some heat transfer characteristics inherent in microgravity conditions were clarified.

II. Development of Transparent Heated Tube

A. Structure of Transparent Heated Tube

The heated tube is made from a pyrex tube of I.D. 8 mm with a wall thickness of 1 mm to minimize the heat capacity for the effective use of short microgravity duration. The heated length is varied from 17 mm to 260 mm depending on the purposes of individual experiments. The heater is made of a thin gold film and the heating is conducted by the application of DC electric current directly thorough it. The film has a thickness of the order of 0.01 μm and it is transparent to allow the observation of liquid–vapor behavior through the glass tube wall. At the same time the film is utilized as a resistance thermometer to evaluate directly the inner wall temperature averaged over the entire heated length. The gold film is coated uniformly along the heated length by the pulse magnetron spattering technique and therefore has sufficient mechanical toughness against the thermal stress caused by the difference in the linear expansion between the film and substrate glass. At both ends of the heated tube, silver films of quite large thickness are coated to be used as electrodes and are contacted to copper flanges as shown in Fig. 1. Several ring sheets made of aluminum foil are inserted between the tube and the copper flanges to remove additional electrical resistances and to solve the problem of thermal expansion. A test section consists of a heated tube and two unheated tubes of the same inner diameter connected at upstream and downstream locations as shown in the figure. The unheated tube in the upstream is used as an entrance section and its length is so decided that it takes the maximum under the restriction of apparatus height inherent in the microgravity facilities employed. The copper flanges are used for power supply and for the sealing of tubes by the aid of O-rings involved in them.

B. Electric Resistance of Thin Gold Film

For the evaluation of inner wall temperature, high accuracy is required in the measurement of electric resistance of the thin gold film coated there. The

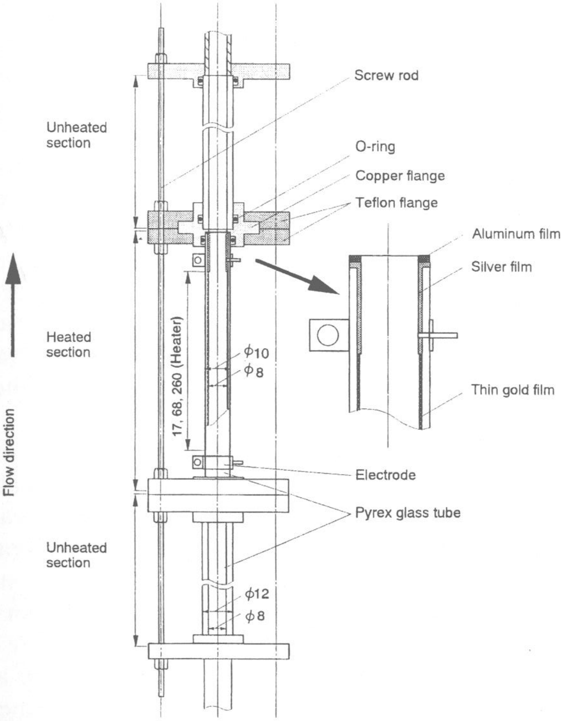

FIG. 1. Test section of transparent heated tube.

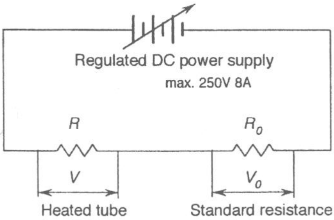

FIG. 2. Electric circuit for the measurement of heated tube resistance.

electric resistance R is directly calculated from $R=(V/V_o)R_o$ by using a simple circuit as shown in Fig. 2, where R_o is the value of standard resistance connected in series, and V and V_o are the voltages across the resistances R and R_o, respectively. The specific electric resistance of the thin metal film is, in general, higher than that of bulk metal and is less sensitive to the temperature change. Furthermore, in the present case, the resistance value is quite unstable and changes with repeated heating and cooling. To obtain the relation between the resistance R and temperature t, a very low electric current is applied so as not to increase the wall temperature, where the temperature of the film is assumed to be the same as that of the test liquid flowing in the tube. Annealing of the film at high temperature improves the stability of the resistance–temperature relation, but the level of resistance gradually decreases during a series of experiments as shown in Fig. 3. The figure indicates that the gradient of the resistance–temperature curve remains almost constant. The temperature coefficient of the film obtained from the figure is 5.7×10^{-4}/K which is about one-seventh of the value for bulk gold, 3.9×10^{-3}/K. Since the decrease in electric resistance depends not only on the time elapsed from the manufacturing and the history of the heating and cooling but is strongly dependent on the conditions of the coating process, the prediction of the transient nature of the resistance is impossible.

Another behavior is also recognized for the thin film. The value of electric resistance falls seriously just after the heating despite the wall temperature being still higher than that of the liquid. The resistance value gradually recovers to become a value corresponding to the liquid temperature. Figure 4 shows the unrealistic wall temperature calculated by the substitution of indicated transient resistance values into the relation between the resistance and temperature calibrated after 2 h has elapsed from the heating. The difference between the present superficial wall temperature and measured liquid temperature gradually reduces. In the aircraft experiments, however, the test runs at various heat flux levels are performed successively before the complete recovery of the film resistance. To confirm the validity of the measured wall temperature after the heating, heat flux was supplied in advance at $q_o = 4 \times 10^4\ \mathrm{W/m^2}$ for 30 min followed by 7 min pause, then heat flux at the prescribed level is supplied again. The temperature differences between the wall and the liquid ΔT_b before and after the aging are

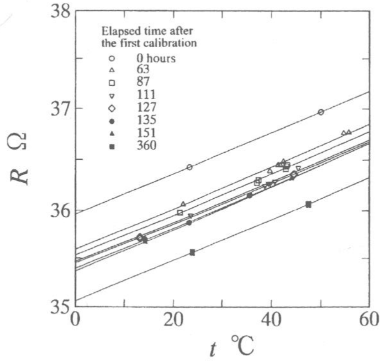

FIG. 3. An example of the change in the relation between resistance and temperature for thin gold film coated on the inner tube wall.

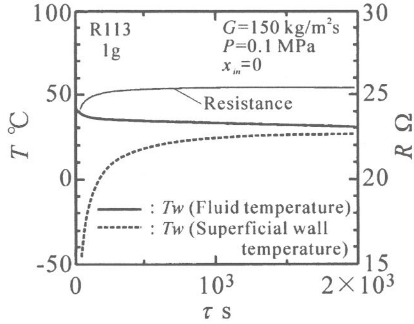

FIG. 4. Drop and recovery of thin gold film resistance after aging.

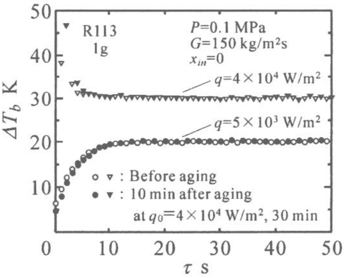

FIG. 5. Temperature difference between wall and bulk liquid at heat flux q before and after aging at q_0.

compared in Fig. 5, where the transient data for heating after the aging is plotted for single-phase forced convection at $q = 5 \times 10^3\,\mathrm{W/m^2}$ and for nucleate boiling at $q = 4 \times 10^4\,\mathrm{W/m^2}$. Fron113 in the saturation state was used and the test was conducted at mass velocity $G = 150\,\mathrm{kg/m^2}$ under atmospheric pressure $P = 0.01$ MPa. It is clear that no difference between the wall temperature data before and after the aging is observed for both heat flux levels. Hence, the transient nature of the value of the electric resistance can be eliminated even if heat flux is supplied successively in a series of experimental runs.

C. PERFORMANCE OF THIN GOLD FILM AS A TEMPERATURE THERMOMETER

In the aircraft experiments, the gravity level changes stepwise along a parabolic trajectory. The acquisition of steady state data at different gravity levels and of the data for rapid phenomena requires high response of the wall temperature. Figure 6 shows the transition of wall temperature t_o after