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(Review)

Review of Reduced Gravity Boiling Heat Transfer: Japanese Research

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Abstract

To introduce the advance in the researches on boiling and two-phase flow in reduced gravity fields and the change in the situation surrounding them in Japan, a short review is focused on the individual research subjects, i.e., pool boiling, flow boiling, and unheated two-phase flow including their major topics. Representative results obtained so far are introduced. Future direction of researches on the present discipline is proposed and the activity to enhance the opportunity to use facilities with longer reduced gravity duration is explained.

1. Introduction

Recent increase in the size of space platforms requires the management of increased waste heat, which requires the transportation of a large amount of heat to the radiator across the platforms of enlarged size. For the reduction of size and weight is required for the utmost utilization of the platforms and for the reduction of the launch weight. Boiling heat transfer realizes the high-performance heat exchange due to latent heat transportation also in space. Cold plate areas are seriously reduced if high heat transfer coefficients are associated with the boiling phenomena, and the amount of mass flow rate and thus the power of mechanical pump are markedly reduced by the application of two-phase flow when the transportation of the same amount of heat is concerned.

The knowledge of boiling heat transfer is required for the safe operation of existing single-phase systems in case of accidental increase of heat generation rate. But the number of existing researches on flow boiling is very limited. This is partly due to incorrect knowledge that the gravity effect on the liquid-vapor behavior and the heat transfer is negligible in the presence of bulk flow in flow boiling. Of course this is not true when the inertia, surface tension and viscous forces are weak compared to the body force due to gravity. The boiling under reduced gravity conditions gives powerful means for the clarification of the phenomena encountered on ground since it simplifies the phenomena. In addition to the shortage of experimental data on boiling and two-phase flow, there is so often no coherency in the existing data obtained from different experiments because of the severe restriction in the specification of test apparatus, the difficulty of strict prescription of experimental conditions and no enough chance to repeat the experiments for the confirmation of the reproducibility. No answer is given precisely for a simple and the most fundamental question whether the heat transfer due to boiling is enhanced or deteriorated in comparison with that on ground. Two opposite results were obtained depending on the experiments by different researchers or under different experimental conditions.

In the present article, existing researches on the three subjects, i.e., pool boiling, flow boiling, and unheated two phase flow are reviewed in brief, and the future direction of researches and the activity to enhance the opportunity to realize the experiments under reduced gravity conditions are indicated reflecting the author's opinion.

2. History of Japanese Research on Reduced Gravity Boiling/Two-phase Flow and Development of Experimental Facilities

Researches on boiling heat transfer under reduced gravity conditions (usually referred to as ''microgravity'' conditions independent of the actual gravity level realized by the facilities) was started in the end of the 1950s in USA and a paper was found already in 1959 (Siegel and Usiskin[1]). In the early age of the research in the 1960s, the experiments were conducted by using drop towers of small scale installed individually in their laboratories while the aircraft was already available for these purposes even in the early days. Much effort was made to obtain steady-state results in a short reduced gravity duration of 1s or a little bit longer. The representative results of the experiments are summarized by Siegel[2] and Merte[3].

In Japan, pool boiling research was conducted in

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Univ. Tokyo by Kotake[4]. By using a small scale drop tower with gravity level of 0.082 G, the experiments were conducted both on the bubble behaviors and on the heat transfer. Bubble growth and departure insensitive to gravity was reported. The reduction of gravity promotes the bubble coalescence, but the heat transfer is unaffected under the conditions that the coalesced and single bubbles are coexisted on the heating surface. Despite of its early study, it already clarified some of essential characteristics well known in the present time. After this work almost no researches concerning the reduced gravity boiling/two-phase was started in Japan till a group of ETL (Electrotechnical laboratory) and Keio University started pool boiling experiments at the end of the 1980s by using Caravelle aircraft available in France. In the meanwhile, various facilities for the reduced gravity experiments were developed in the world after a pause of the research activities in this field in the 1970s. Also in Japan, a domestic facility for aircraft experiments using MU-300 small jet airplane was operated by Mitsubishi Heavy Industry in 1988 and succeeded by DAS (Diamond Air Service) from 1990. Nagoya airport is used for this flight campaign. Two or three experimental apparatus are installed in the cabin so that the users requirements concerning, for example, the interval of succeeding parabolic flights utilized for the adjustment of experimental conditions and the length in period of hyper-gravity are reflected enough. In 1991, well-known drop shaft JAMIC (Japan Microgravity Center) in Hokkaido island became available. The company was organized under the direction of MITI (Ministry of International Trade and Industry). The duration of 10s with reduced gravity level 10^{-5} G was the top of the world in both the quantity and quality. A structure of double capsules realizes such a low gravity level with minimized G-jitter. The drag force exerted by the air in the shaft is cancelled by an air jet from the rear end of the capsule not to make collision between the capsules. Usually drops were performed two or three times in a day. Despite of great specification which all researcher in the world agree, the operation of the facility was suspended at the end of fiscal year 2002 because of the financial reason. All of Japanese researchers in this field desires the restart of the facilities but the possibility seems to be infinitesimally small. In the middle of 1990s, another drop shaft MGLAB (Micro-Gravity Laboratory of Japan) directed by STA (Science and Technology Agency) was constructed. The duration is 4.5 s and might be short for most of boiling and two-phase flow experiments. From the latter half of the 1980s the number of researches in reduced gravity science and technology was increased in the world. This is also true in Japan. Researches not only in pool boiling but flow boiling and adiabatic two-phase flow were started. From 1991, TR-1A ballistic rocket became available to make possible the experiments which require longer reduced gravity duration. The rocket was launched from TNSC (NASDA Tanegashima Space Center in Kagoshima prefecture, Kyushu). The reduced gravity duration was 6 min and 10^{-4} G could be possible provided that there is no disturbance source of vibration in the payloads. The rocket system was operated 7 times till 1998 in almost every year, but was discontinued. Despite of extraordinary high experimental cost, the technology for the preparation of test apparatus for reduced gravity experiments was markedly improved. This is partly due to the fact that the tele-operation system was not available and the operation sequence should be completely fixed in prior to the launch on the basis of the prediction of the possible phenomena. In Japan, a chance of space shuttle experiments has not been given so far to the researches on boiling and two-phase flow except that for the development of two-phase flow loop TPFLEX (Two-Phase Fluid Loop Experiment) by the collaboration of NASDA and Toshiba Co. directed by Furukawa[5], where operation of two-phase flow loop by a mechanical pump was tested. In the 1990s, the reduced gravity experiments in Japan covers all three major categories, i.e., pool boiling, flow boiling, and unheated two-phase flow, and many researchers including the present author started the experiments encouraged by the development of new facilities described above. Specification of the facilities in Japan are summarized in **Table 1** including those already discontinued.

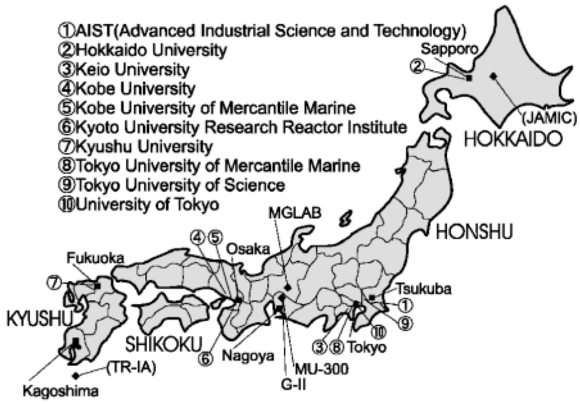

Fig. 1 Locations of reduced gravity facilities and research organizations for the present field in Japan.

3. Pool Boiling

3.1 Bubble behaviors

The bubble structure is to be clarified before the discussion on the heat transfer mechanisms. The structure of a single isolated bubble is similar to that on ground. Abe and Iwasaki[6] conducted pool boiling experiments for n-pentane by TR-1A No. 1. They developed a transparent heater made of glass to observe the bubble behavior also from underneath. The surface

Table 1 Specification of reduced gravity facilities in Japan including those already discontinued

	Balistic Rocket	Aircraft	Aircraft	Drop Shaft	Drop Shaft
Facility	NASDA (TR–IA)	NASDA/DAS or DAS MU–300	NASDA/DAS or DAS Gulfstream-II (G-II)	(JAMIC)	MGLAB
Location	Kagoshima	Nagoya	Nagoya	Hokkaido	Gifu
Duration	6 min	20–25 s	20–25 s	10 s	4.5 s
g-level	10^{-4} G	3×10^{-2} G	10^{-2} G	10^{-5} G	10^{-5} G
Payload	750 kg usually divided into 5 or 6 components	100 kg/rack total 200 kg max	rack A: 50 kg max rack B: 150 kg max total 250 kg max	1 rack 500 kg 1/2 rack 250 kg	200 kg (400 kg max)
Size restriction	$\phi720\times2520$ usually divided into 5 or 6 components	700 W × 450 D × 900 H	rack A: W665 × D565 × H530 rack B: W665 × D565 × H1125	1 rack 870 W × 870 D × 918 H 1/2 rack 870 W × 870 D × 443 H 1/2 rack 870 W × 425 D × 918 H 1/4 rack 870 W × 425 D × 443 H 1/4 rack 425 W × 425 D × 918 H	$\phi720\times885$ (2 or 3 columns dividable)
Power supply	DC28V, 10AH	AC 100 V (60 Hz), 1.5 kVA DC 28 V, 25 A × 2 Option: AC 100 V (60 Hz), 0.5 kVA	AC 100 V (60 Hz), 7 kVA max DC 28 V, 160 A	AC 100 V (50 Hz), 8 A Option: AC 100 V (50 Hz), 6 A DC 28 V, 40 A DC 28 V, 20 A × 10 min	AC 100 V (60 Hz), 12 A DC 24 V, 40 A
Remarks	Discontinued			Discontinued	

has artificial cavities to promote the nucleation on such a smooth surface, and is heated by ITO transparent film used as a electric resistance. The Fezeau interferometer was introduced for the detailed observation under attached bubbles. They confirmed the existence of stationary microlayer at low heat flux. Bubble coalescence is occurred also in reduced gravity as confirmed later by most investigators. It is well known that a large single bubble is surrounded by a small bubble and hovered by small bubbles (Straub[7]). Oka et al.[8] confirmed that primary bubbles newly formed under a coalesced bubble were successively swallowed into the coalesced bubble resulting its further growth. To clarify the structure, another attempt was made by the present author (Ohta et al.[9]). A transparent surface with a large heating diameter of 50 mm was developed. A cylindrical boiling vessel with 120 mm inner diameter was used and a coalesced bubble finally grew to become the same diameter as that of the vessel for saturated water at 0.1 MPa and heat flux $q=3\times10^5$ W/m^2 under reduced gravity conditions created by MU–300. By the attachment of a coalesce bubble to the inner wall of the vessel, the liquid-vapor behaviors underneath a large coalesced bubble was observed directly. There existed a macrolayer of 10^{-4} m-order thickness and small primary bubbles generated from the surface and collapsed on the surface of the macrolayer. The generation of primary bubbles was also confirmed by the observation from underneath. There was nothing to be called as ''vapor stems'' (Gaertner[10]) in the macrolayer but primary bubbles. The confirmation of the structure of a coalesced bubble was attempted by Tanaka-Nishio[12] using a narrow vertical gap to make the phenomena from three-dimensional to two-dimensional. Another experiments by Ohta et al.[13] reports the bubble structure for saturated ethanol at 0.01 MPa obtained by TR–1A No. 5 experiment. A coalesced bubble grows to become a diameter of around 100 mm, where primary bubbles with a maximum diameter of 10 to 30 mm were existed. The size of primary bubbles becomes one or two-order larger than the thickness of the macrolayer observed around the primary bubbles. It is important that the existence of microlayer and the extension of dry patch were observed at the base of individual primary bubbles, and the compound structure of a coalesced bubble was confirmed also in reduced gravity.

Bubble detachment in reduced gravity is one of the important phenomena. It is sometimes very difficult to distinguish the presence of bubble detachment from those due to residual gravity or g-jitter inherent in the facility employed. Oka et al.[8] reported the existence of two cases concerning the bubble detachment from the experiments on board Caravelle operated by CNES, i.e., bubbles ware attached on the surface for organic fluids of n-pentane and CFC11 with a large contact area, while the water bubbles lift off from the surface due to a slight contact. The bubble detachment is one of the basic mechanisms for the liquid supply to the heating surface and, in turn, for the heat transfer.

It is of practical interest whether steady-state heat transfer is possible or not during nucleate boiling in reduced gravity. As a result, under subcooled liquid conditions bubbles cannot grow beyond a certain size but stays on the heating surface balancing the rates of evaporation with that of condensation. The conditions to realize steady-state heat transfer in reduced gravity are represented by a relation between heat flux and liquid subcooling (Ohta et al.[13]).

3.2 Heat transfer coefficient and critical heat flux

It is well known that the heat transfer due to nucleate boiling is affected by many parameters, e.g., thermo-physical properties, heat flux, surface conditions and liquid wettability, concentration of additives, while effect of gravity is not well clarified and no coherent results were obtained despite of many researches working on this subject.

Oka et al.[14] found small difference in heat transfer between reduced gravity and normal gravity despite of great differences in both the bubble size and the bubble population density from the Caravelle experiments using n-pentane at subcooling $\Delta T_{sub} = 7$ to 32 K and heat flux $q = 1.1 \times 10^3$–4.2×10^4 W/m^2. They also reported the effect of gravity on nucleate boiling heat transfer. The heat transfer for water was deteriorated in the entire region of nucleate boiling, while such a deterioration for organic fluids of n-pentane and CFC113 is observed only at high heat flux and the reduction of CHF as much as 40% was obtained. They pointed out the importance of the contacting characteristics between the bubbles and heating surface for the reason of observed deterioration. The present author (Ohta et al.[15]) confirmed the both cases of the heat transfer enhancement and the deterioration for nucleate boiling of CFC113 and obtained almost steady state heat transfer during the reduced gravity duration created by MU–300 aircraft under small subcooled conditions. In both cases, bubbles were detached at very low frequency due to residual gravity or G-jitter, and the possibility to realize the almost steady state heat transfer is strongly depending on the bubble detachment. In the case of very low gravity level realized by TR–1A, a coalesced bubble stays and grows on the heating surface and the heat transfer in reduced gravity one-order higher than that in normal gravity. The situation was maintained only 15 seconds and suddenly changed to result in the heat deterioration and burnout (Ohta et al.[16]. The results by Tanaka-Nishio[12] supported the present trends. They indicated that the values of CHF under the reduced gravity conditions are influenced by the time of heating.

The effect of gravity on critical heat flux is one of the most important subjects but very few results were obtained because of the difficulties to obtain the data under the limited duration of reduced gravity. conditions. Suzuki et al.[17] conducted the systematic experiments onboard Gulfstream II to clarify the effect of gravity on CHF for water at $P = 0.1$ MPa under subcooled liquid conditions $\Delta T_{sub} = 10$–40 K. They employed thin stainless steel plate of 20 mm × 5 mm. The values of CHF in reduced gravity is quite smaller than those in normal gravity, but they are larger by 200 to 400% than the calculated by Zuber's equation (Zuber[18]). The trend on the effect of liquid subccooling on CHF is similar to those in normal gravity (e.g. Ivey-Moris[19]) and CHF increases with liquid subcooling also in reduced gravity. In the later report based on the ground experiments using a horizontal heating surface of the same size but with a cover plate to reproduce the similar bubble behaviors to those under reduced gravity, the CHF values decrease with the reduction in the rate of increasing heat flux (Suzuki et al.[20,21]). In addition, it seems to be very difficult to compare the measured CHF values with the existing correlation because of the fluctuation of gravity, for example, from 0.01 to 0.03 g during the parabolic flight. Suzuki et al.[22] introduced a transparent heaters to observe the bubble behaviors from underneath. The experiments were conducted in JAMIC. Heating was started 10 s before the drop. Under high subcooling and high heat flux conditions for water, the bubble contact area instantaneously increased when the drop was started, but generated bubbles were detached from the surface to form coalesced bubbles just above the heating surface resulting almost constant bubble contact area during the drop of 10 s. The reduction of CHF values in reduced gravity was deduced also by the shapes of boiling curves (Oka et al.[8]). It is noteworthy that MEB (Micro-bubble emission boiling) is observed also under reduced gravity conditions provided that liquid subcooling is high. Because of the importance to apply MEB for the development of high-performance heat exchangers including those used in space, Suzuki et al.[23,24] performed detailed experiments on this subject recently.

3.3 Heat transfer mechanisms

Nucleate boiling heat transfer is characterized by the evaporation of microlayer underneath isolated bubbles or primary bubbles underneath a coalesced bubble. The behavior of primary bubbles is restricted by the existence of the macrolayer, and the boiling at a low liquid level dominates and characterizes the heat transfer, and the coalesced bubble influences the heat transfer indirectly via the behavior of macrolayer. The present author measured the macrolayer thickness by the sensors directly coated on the transparent substrate of the heating surface (Ohta et al.[9]). To evaluate the liquid film thickness from the measured electric resistance, water was selected as test liquid. The experiments onboard MU–300, the macrolayer thickness decreases with the increase of the heat flux also in reduced gravity. The trend is similar to those on ground (Baht et al.[25], Gaertner[10]). The heat transfer due to conduction across the macrolayer is limited to 30% even at heat flux just near the burnout $q = 2.7 \times 10^5$ W/m^2, $\Delta T_{sub} = 0$ K, at $P = 0.1$ MPa. The reminder part of the heat flux is transferred by the nucleate boiling in macrolayer. This indicates the dominant role of tiny primary bubbles for the heat transfer at high heat flux. In also TR-1A No. 5 experiment, liquid film thickness was measured for ethanol at $\Delta T_{sub} = 0$ K, $P = 0.01$ MPa. Because of large size of primary bubble, most of the obtained data of film thickness was those for microlayers underneath the primary bubbles. Based on the transition of the film thickness with time, the location of local dryout becomes clear, and transition of local heat flux is predicted by the transient conduction across the microlayer. The values are agrees well the local heat flux evaluated from the conduction across the heating surface substrate (Ohta et al.[26]).

To supply the liquid to the microlayer underneath a single bubble or a primary bubble in macrolayer, Marangoni effect due to the surface tension gradient along the surface of macrolayer is useful means and the effect becomes emphasized in the absence of gravity. Abe et al.[27] tested ethanol-water mixture in the JAMIC drop experiments of 10 s reduced gravity duration. No-azeotropic concentrations of 11.3 wt% and 27.3 wt% ethanol were chosen. The mixture is ''positive'' with decreasing surface tension with increasing the concentration of more volatile component. From the experiments, the bubble detachment is promoted for the mixture. The structure of coalesced bubble was reported to be the same as that of pure liquid. The heat transfer is enhanced for the mixture with the reduction of gravity in the almost entire heat flux range. The reduction of CHF values for the mixture is only 20–40 % of the terrestrial values which are very small compared to that for pure liquids. Abe-Iwasaki[28] observed bubble growth of CFC12–CFC112 mixture by using two-wavelength interferometer to separate the effects of concentration and of temperature on the optical index. They concluded that the Marangoni effect due to temperature distribution along the interface is dominant for pure liquid of CFC113, while the effect due to concentration gradient is dominant for the mixture. A large thickness of temperature and concentration boundary layers nearly one-order of magnitude higher than those by thermal and mass diffusion shows the existence of flows around a bubble induced by Marangoni effect.

To investigate the effect of nucleation characteristics on the heat transfer in reduced gravity is of great interest because it can changes bubble population density under the same heat flux conditions. Haze et al.[29] in the group of Osakabe in Tokyo Univ. Mercantile Marine employed the heating elements of different surface conditions in JAMIC drop shaft experiments. For the boiling of water, bubbles stay around heated wires except the one with scale deposition. The boiling curve on the bare surface in reduced gravity is equal to that in normal gravity, and no difference in the effect of surface properties and surface finish on the nucleate boiling heat transfer is observed between both gravity levels. Also the papers (Motoya et al.[30], Fukada et al.[31]) includes the results related to the surface characteristics of heaters.

A part of works for pool boiling by Abe was reviewed in the paper[32].

4. Flow Boiling

4.1 Liquid-vapor behaviors

Misawa-Anghaie[33] introduced two different test sections for boiling experiments, i.e., a transparent square channel of pyrex glass with 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 by JAMIC were conducted for CFC113 flowing in vertical test sections. It was clarified that the slip ratio under reduced gravity is less than unity and the pressure drop is larger than the predicted values by the homogeneous model because of the enhanced contribution of acceleration resulted from the increase in void fraction. Kawaji et al.[34] observed flow patterns for flow boiling of subcooled CFC113 and saturated LN2 in both on ground and in reduced gravity, and reported marked difference in shapes of liquid droplets in the dispersed flow region. Saito et al.[35] has performed by using Caravelle aircraft the flow boiling experiments for water of subcooled and saturated conditions in a horizontal transparent duct with a concentric heater rod. Under reduced gravity conditions, 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. To observe liquid-vapor behaviors, Yamada et al.[36] employed a vertical annuli for flow boiling of HCHF123 heated by hot liquid, and observed the process of flow pattern transition from bubbly to annular flow at low mass flow rate and high heat flux. They reported the decrease in the pressure drop in the annular flow regime by the reduction of gravity.

The present author introduced a transparent heated tubes for flow boiling experiments (Ohta et al.[37]). The is made from a Pyrex tube of 8 mm inner diameter with small wall thickness of 1 mm to minimize the heat capacity for the effective use of short reduced gravity duration. The heated length is varied from 20 mm to 260 mm depending on the purposes of the experiments. The heater is made of a thin gold film and heating is conducted by the application of DC current directly to the film. The film has a thickness of 0.01 μm-order and it is transparent to allow the observation of liquid-vapor behavior through the tube wall. At the same time the film is operated as a resistance thermometer to evaluate the inner wall temperature averaged over the entire heated length.

From MU–300 aircraft experiments using a vertical tubes, followings were clarified (Ohta[38]). At low mass velocity $G=150$ kg/m^{2}s and low quality, the bubbles generated from the tube wall grows much larger in reduced gravity and begin to slide downwards and detach from the surface. The enlargement of the bubbles is caused by the reduction of buoyancy and it takes longer time before the detachment from the inner heated wall. The test loop was designed so that the static pressure by liquid column in the downstream does not influence the bubble behaviors. When mass velocity is increased to $G=600$ kg/m^{2}s, bubbles detach when they are still in a small size because of the increased shear force exerted by the bulk flow. At moderate quality, annular flow with smoother interface of the film is realized in reduced gravity. The reduction in the frequency and the length of disturbance waves are recognized. Under higher mass velocity or higher quality conditions, the effect of gravity is disappeared and the behavior of annular liquid film is dominated by the shear force exerted by the vapor core flow with higher velocity.

A narrow channel between the plates is one of the important system for flow boiling. The present author (Ohta et al.[38,40,41]) introduced a transparent heating surface with the temperature sensors for the evaluation of local heat transfer characteristics. The experiments were conducted for vertical channels at very low inlet liquid velocity onboard MU–300 aircraft. The gap size was varied from 0.7 mm to 10 mm for the boiling of water under the conditions of $P=0.1$ MPa, inlet liquid subcooling $\Delta T_{sub}=0$ to 10 K for a constant inlet liquid velocity of 0.06 m/s. At a larger gap size than that of bubble diameter in pool boiling in normal gravity, bubble size is increased and the coalescence is promoted in the downstream in reduced gravity. For a small gap, flattened bubbles with larger size covering almost entire heating surface of 30 mm × 50 mm in reduced gravity. For an extremely small gap size, increased growth rate of flattened bubbles eliminates the influence of gravity, and the vigorous exchange of generated bubbles and the bulk flow of liquid was observed on the entire part of local positions on the heating surface.

4.2 Heat transfer characteristics

There is very limited numbers of works for the measurement of heat transfer characteristics. Lui et al.[42] presented the experimental results on subcooled flow boiling in a horizontal tube, where the heat transfer coefficients due to nucleate boiling in reduced gravity increases up to 20% from those in normal gravity if subcooling is low.

The present author (Ohta[38]) found the gravity-dependent heat transfer in a vertical tube in the moderate quality region, where annular flow is realized. For CFC113, $P=0.1$ MPa, $G=150$ kg/m^{2}s, quality $x\approx 0.3$, the heat transfer coefficient due to two-phase forced convection deteriorates by 7% from the value in normal gravity, while it is enhanced by 25% at hyper-gravity 2 G. When mass velocity is increased the gravity effect disappears. The gravity effect on the heat transfer is not observed at low quality, where the heat transfer is dominated by nucleate boiling, despite the drastic change in the size of bubbles as mentioned above. At high mass velocity or high quality, no gravity effect is observed.

Acquisition of critical heat flux data was attempted in microgravity (Ohta et al.[43]) using short reduced gravity duration onboard MU–300. A partly due to the inferior accuracies in the experimental parameters which could be adjusted under the restriction in the cabin of aircraft, no appreciable difference in CHF values due to dryout is observed for R113, $P=0.1$ MPa, $x\approx 0.5$–0.9, while a quite different behaviors of inverted annular flow was observed under a CHF condition due to DNB at low quality.

In Japan, there is no experiment to heat gas-liquid two-component mixtures, the system adopted by Rite-Rezkallah[44,45], where they investigated the 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, including those not easily realized by the single-component system, provided that the differences between the single-component and binary systems in the interaction of liquid and vapor phases is took into consideration.

4.3 Heat transfer mechanisms

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. To obtain the velocity and temperature profiles in the annular liquid film a simple model was developed for the upward flow in a vertical tube as the first stage of the investigation (Ohta et al.[46]). One of the topics of interest might be the change of annular liquid film thickness under reduced gravity conditions. There are three different trends to be took into consideration; the decrease in liquid film thickness by the increase in the upward liquid velocity in the absence of gravity, the increase of film thickness by the reduction of interfacial shear force exerted by the vapor core flow, and the increase in annular film thickness because of the decrease in the liquid flow rate due to disturbance waves. As a result, the analysis indicated the increase in the annular liquid film in reduced gravity for given conditions. Heat transfer is influenced, in general, by two factors of the liquid film thickness and the turbulence in the liquid film. From the analysis the change of the annular film thickness has small influence on the heat transfer, while the reduction in the turbulence in the film reduces the heat transfer due to two-phase forced convention in microgravity. The analysis reproduces qualitatively well the trends of gravity effects on the heat transfer which varies with the mass velocity and quality. More detailed model concentrating on the periodical heat transfer due to the passage of disturbance waves is required to improve the knowledge on the phenomena.

Dryout mechanisms at moderate quality were investigated based on the comparison between the temperature fluctuations at heat fluxes just lower and higher than the critical value (Ohta et al.[47]). The temperature fluctuation is clarified to be synchronized with the passage of disturbance waves which supply the liquid to the dry patches extended between the passage of disturbance waves under such high heat flux conditions. Statistical nature of a longer interval of disturbance waves could become a trigger of temperature excursion.

The results by the present author on flow boiling under reduced gravity conditions are summarized in the article (Ohta[48]).

4.4 Heat transfer during quenching of tube with higher temperature

Kawaji et al.[34] investigated onboard 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 CFC113 was pumped into the tube. In reduced gravity, thicker vapor film is formed on the tube wall making the rewetting of the wall more difficult and resulting the reduction of heat transfer rate.

Kawanami et al.[49] investigated the heat transfer during quenching of tubes by cryogenic fluids for the development of a system of fuel re-supply in orbit. Experiments were conducted in JAMIC using LN_2 as test fluid. A transparent tube (Ohta-Fujiyama[50]) was employed for the observation and the measurement of temperature transition. The test fluid is introduced from underneath to the tube to minimize the shear force in the counter direction exerted by the flow of generated vapor. They reported the quenching time shorter by around 1.2 times, and the maximum and the minimum heat fluxes larger by 1.4 and 1.2 times under reduced gravity conditions, respectively. The reduction of quenching time seems to be due to the increased velocity of quenching front under reduced gravity conditions.

5. Isothermal Two-phase Flow

5.1 Liquid-vapor behavior, flow regime transition

The establishment of flow regime map is needed for the investigation of gravity effects on various parameters. Fujii et al.[51] introduced a horizontal test tube onboard MU–300 and confirmed four flow patterns, i.e., bubbly, plug, semi-annular and annular flows for GN_2-water in reduced gravity. The transition from bubbly flow to plug flow in reduced gravity agrees well with the boundary by Rezkallah-Sim[52] for a vertical tube under normal gravity conditions. The boundary between plug flow to annular flow again agrees well with the results by Rezkallah-Sim for the transition from plug flow to churn flow, where the transition occurs at constant gas superficial velocity and the boundary is quite different from that by Dukler et al.[53] for reduced gravity data. Recently, Choi et al.[54] shows the systematic data obtained for air-water mixtures flowing in a horizontal test section with a diameter of 10 mm and a length of 600 mm onboard MU–300, where flow rates were varied in the ranges $j_G = 0.03$–21 m/s and $j_L = 0.1$–2.6 m/s under normal, hyper and reduced gravity conditions. From the figure plotted jL versus jG, the transition from bubbly flow to plug flow occurs at higher void fraction with the reduction of gravity, while the transition from plug flow to slug flow occurs at a constant j_G regardless of gravity levels. The transition from slug flow to semi-annular flow occurs at different boundaries depending on the gravity levels, while the transition from semi-annular flow to annular flow occurs at a constant void fraction 0.8 regardless of gravity level. The boundaries of the transition were compared with the correlation by Dukler et al.[53], Bousman[55] and Crowely-Izenson[56] developed for reduced gravity data.

5.2 Pressure drop

Fujii et al.[51] gives direct comparison of pressure gradient between a horizontal tube in normal gravity and that in reduced gravity. A few data in reduced gravity shows larger pressure gradient than those in normal gravity. They indicated that the effect of gravity is depending on the flow pattern rather than Martinelli parameter. The pressure drop in reduced gravity is well correlated by the Chisholm's correlation (3) (Chisholm[57]) with C = 16 in the relation between two-phase frictional multiplier Φ_L and Martinelli parameter X.

$$\Phi_L = [(dp/dz)_{TP}/(dp/dz)_L]^{0.5} \tag{1}$$
$$X = [(dp/dz)_L/(dp/dz)_G]^{0.5} \tag{2}$$
$$\Phi_L = [1 + C/X + 1/X^2]^{0.5} \tag{3}$$

where, $(dp/dz)_L$ and $(dp/dz)_G$: single-phase liquid and gas frictional pressure gradients evaluated using the liquid and gas flow rate alone. From the data by drop experiments, C = 14 is obtained and the multiplier in reduced gravity is larger by 5 to 10% than those in normal gravity where C = 12 for a laminar liquid and turbulent gas flow condition (Fujii et al.[58]). Choi et al.[54] shows the systematic pressure drop data in a wide ranges of flow rates for both phases. They compared the pressure gradients of reduced gravity and hyper gravity with that for normal gravity at constant values of Martinelli parameter. The ratios to those for normal gravity is up to 30% larger under reduced gravity conditions due to the difference between the flow patterns for both gravity levels. The gradient for hypergravity is again larger up to 45% because of the enhanced roughness on the air-water interfaces. They shows that the pressure drop data obtained in the entire rage of j_G and j_L are well correlated by C = 19, 17 and 19 for reduced, normal and hyper gravity conditions, respectively, within the error from 20 to 30%.

5.3 Two-phase flow structure

Fujii et al.[51] also measured void fraction for GN_2-water in reduced gravity. The data for both in normal gravity and in reduced gravity was compared with the drift flux model (Zuber-Findlay[59], Zuber et al.[60]) in the relation between the gas velocity j_G/α and gas-liquid mixture superficial velocity $j_G + j_L$.

$$j_G/\alpha = C_0(j_G + j_L) + V_{Gj} \tag{4}$$

where α is cross-section average void fraction. The data is correlated by the distribution parameter $C_0 = 1.15$ and zero drift velocity $V_{Gj} = 0$ m/s. Fujii et al.[58] correlated the data for nitrogen-water mixture from drop experiments by $C_0 = 1.33$ and $V_{Gj} = 0$ m/s, while they obtained $C_0 = 1.04$ and $V_{Gj} = 1.07$ m/s for the data in normal gravity. From this result, they indicated the decrease in void fraction, i.e., increase in the averaged thickness of annular liquid film under reduced gravity conditions. They pointed out that the maximum thickness of annular liquid film in reduced gravity is quite insensitive under the variation of Reynolds number, while the trend is quite different from that in normal gravity. The thickness of annular base film in reduced gravity is larger by 4 to 10 times and the average film thickness is larger by 2 to 5 times than those in normal gravity. They reported that the interfacial friction factor for gas flow in reduced gravity decreases to some extent in reduced gravity. Fujii et al.[61] shows non-zero drift velocity for both data of nitrogen-water mixture with and without sodium oleate obtained from drop shaft experiments. Since both data is correlated by nearly the same values, i.e., $C_0 = 1.03$, $V_{Gj} = 1.44$ m/s and $C_0 = 1.04$, $V_{Gj} = 1.41$ m/s with and without the surfactant, respectively, they concluded that the influence of surface tension on the averaged void fraction is small in the range $j_G = 3.7$–40 m/s and $j_L = 0.048$–0.44 m/s. The detailed measurement of time-dependent annular liquid film thickness and the analysis to simulate the liquid flow by using a correlation for interfacial friction factor by Reinarts[62], they reproduced the increase in the liquid film thickness under reduced gravity conditions. Choi et al.[54] investigated the slip ratio S based on the relation between the cross-section average void fraction α and volumetric fraction of gas phase $\beta(= j_G/(j_G + j_L))$.

$$\alpha = 1/(1 + S(1/\beta - 1)) \tag{5}$$

They found that the effect of gravity on the slip ratio gradually decreased with the increase of β, and for reduced gravity, the slip ratio is very small in the range of $0 < \beta < 0.5$. For bubbly flow and plug flow regimes, the values of C_0 in eq. (4) are 1.02, 1.11 and 1.27 for reduced, normal and hyper gravity conditions, respectively and the drift velocity is negligible for three gravity levels. The results suggest that the void fraction is larger in reduced gravity for the same mixture velocity $(j_G + j_L)$. In slug flow regime, the difference of distribution parameter becomes small and $C_0 \approx 1.30$ for three gravity levels.

To clarify the flow mechanisms for bubbly flow, Takamasa et al.[63] (or Fukamachi et al.[64]) measured axial developments of one-dimensional void fraction, bubble number density, interfacial area concentration and Sauter mean diameter for nitrogen-water flow under reduced gravity conditions by using an image-processing method (Takamasa et al.[65]). The measurements were performed at four different axial locations in a range of $j_G = 0.0083$–0.022 m/s and $j_L = 0.073$–0.22 m/s. They indicated the importance of velocity-profile entrainment mechanisms in the bubble coalescence in reduced gravity, where large difference in the radial velocity distribution due to laminar flow is resulted from the decrease in the local slip between the phases and then from the decrease in the turbulence. The coalescence occurs due to the sweeping trailing bubbles near the channel center out preceding bubbles moving near the wall. The increase in Reynolds number decreases the effect and then the bubble coalescence because the turbulence makes the radial velocity profile flat. They indicated also the possibility of enhancement of bubble coalescence again at very high Reynolds number because the eddy with large energy enhances the axial bubble motion. Also they show that the interfacial area concentration profile in reduced gravity could be predicted by the transport equation by the wake entrained model developed for normal gravity.

Takamasa et al.[66] summarizes the difference in the gas velocity between those in reduced gravity and in normal gravity using the drift flux model. The gas velocity in reduced gravity is smaller than that in normal gravity at low mixture volumetric flow rate because the difference in the effect of local slip is pronounced. At high volumetric flow rate, the trend is reversed and the gas velocity in reduced gravity is larger because the effect of distribution parameter exceeds that of drift velocity because of non-peaking flat distribution of void fraction in reduced gravity. Hibiki et al.[67] developed a new drift flux model and evaluated using existing data base for reduced gravity conditions (Takamasa et al.[68]). The model reproduces well the levels of gas velocity for different gravity conditions and the trend that the values of gas velocities in reduced gravity and in normal gravity is reversed at a certain mixture volumetric flow rate.

6. Various Researches Concerning Boiling and Two-phase Flow

6.1 Bubble dynamics

Tomiyama et al.[69] developed a drag coefficient model for single bubbles by the balance of forces acting on the bubbles using existing correlation of terminal velocity. The model covers a wide range of properties, diameter and gravity level. The effect of frictional pressure gradient was taken into account by the introduction of a concept of an effective body acceleration in order to apply the model to the reduced gravity conditions. Tomiyama et al.[70] performed the numerical simulation of a single bubble motion, the most fundamental system for the direct analysis of bubbly flow, by using VOF method. Except the cases of spherical-cap and skirted, the method predicts well the transition of bubble shapes by assigning only eight cells to the bubble diameter. They indicated that the wobbling motion of bubble was caused by the velocity component normal to the interface, which was induced by the interaction of vortices. Sou et al.[71] simulated numerically the interaction of two bubbles in train. Both researches are powerful means for the analysis of bubble behavior in also flow boiling at low quality under reduced gravity conditions.

Takahira and Banerjee[72] simulated three-dimensional bubble growth and detachment in reduced gravity shear flow. They introduced the level set method to capture the liquid-gas interface. The shape of interface observed in the experiment was well reproduced numerically for a gas bubble from an orifice. The role of gravity and surface tension on the growth and the detachment was clarified. Takahira et al.[73] improve the method to reproduce the coalescence of bubbles and bursting of submerged gas bubbles at a free surface.

Tsuge et al.[74] investigated the behavior of a single bubble generated from an orifice submerged in quiescent liquid pool experimentally and theoretically. The influence of gas flow rate on the bubble detachment criteria and the volume of detached bubble were examined. They indicated the importance of pressure distribution at the bubble surface as a key factor affecting the bubble growth in a non-spherical shape.

For the bubble detachment in shear flow, Misawa et al.[75] investigated its mechanism using LN_2 gas bubble injected from an orifice to the flow of silicone oil and confirmed the role of drag force for the detachment under reduced gravity conditions onboard NASA DC–9. As regards the lateral migration and coalescence of single bubbles, there area few researches (Hamada et al.[76], Misawa et al.[77])

6.2 Heat pipe with binary mixtures

To realize wickless heat pipes applied to space machines, binary mixtures are selected as working fluids, where condensate is returned by Maragoni force due to concentration difference between the boiling and condensation sections (Kuramae and Suzuki[78]). The experiments were conducted in JAMIC by using ethanol-water mixtures of different concentrations. Marangoni convection was observed at the dilute solution of ethanol with 1 to 5% mole fraction and it prevents the complete evaporation of liquid in the boiling section. Kuramae[79] conducted the experiments of condensation using MGLAB drop facility. The difference in the shape and distributions of droplets with the reduction of gravity was reported.

6.3 Spray cooling

Spray cooling is one of promising methods applied to the heat management system in space. In general, the heat transfer, however, seems to be insensitive to the gravity. On the other hand, there is an evidence from the experiments that the phenomena is dependent on the surface orientation especially at high heat flux around the conditions of maximum and minimum heat fluxes. Kato et al.[80] investigated the effect of gravity on the spray cooling onboard MU–300. Decrease in CHF is observed for CFC113, while the trend is reversed for water. Heat transfer is enhanced for both liquids in the low heat flux region. In the transition boiling region, the boiling curve for CFC113 is shifted toward smaller surface superheat in reduced gravity. The effect of gravity disappears at high spray volume flux. Yoshida et al.[81] carried out the experiments by using water and FC72 onboard MU–300. Two different types of heaters were employed, i.e., a transparent glass heater for the observation from underneath and a copper block heater for the measurement of heat transfer data. At low spray volume flux, effect of gravity or of surface orientation in the terrestrial experiments was observed, while the significant influence of gravity or of the orientation was observed in the values of CHF and heat transfer in the transition region if spray volume flux is high and liquid film covers the heating surface. The heat transfer in film boiling region is deteriorated when gravity is reduced or the heater is facing downward at low Weber number less than 80.

6.4 Phase Separation Technique

Systematic researches on phase separation using T or Y-shape junction were started by a group in Kobe University (Fujii et al.[82]). An impacting T-junction was developed to separate liquid from the two-phase mixture (Fujii at al.[83]). The experiments were conducted on ground and by using MU–300. It was found that the inlet flow pattern and liquid velocity influences the phase separation and the separation is possible for the intermittent flow and is difficult for the inlet conditions of stratified or wavy flow in normal gravity. Under reduced gravity conditions, the data shows that the phase separation could be possible depending on the inlet volumetric flow rates of both phases provided that $j_{Gi} < 0.1$ m/s. Because the stratified flow and wavy flow disappear in reduced gravity, the method is recommended for a coarse separation of phases. Asano et al.[84,85] introduced Y-junction utilizing the difference of inertia force between gas and liquid phases. Air-water mixture was used and the angle of the junction was varied in 30, 60, and 90 degree. The experiments were conducted on ground and by using MU–300, where the separation was investigated in a horizontal plane. They reported that the phase separation performance was improved by the decreasing of the angle between the inlet and the side branch. The performance was higher in the order of slug, plug and annular flows, and 82% water was separated at $j_{Li} = 0.5$ m/s and $j_{Gi} = 7.0$ m/s. Under reduced gravity conditions, the performance of separation is improved when the tube diameter of gas ejection is decreased. They reported that the reduction of the performance was observed for bubbly flow in reduced gravity, and the performance was improved for a smaller junction angle. They reported that up to 60% liquid was separated in reduced gravity in the experimental range tested.

Ishikawa[86] investigated the bubble separation from the mixtures using branching pipes with a branching angle of 90 degree under reduced gravity conditions created in JAMIC. According to the explanation in the paper, the separation characteristics were improved with the increase in the bubble diameter due to the larger pressure difference between the main and branching pipes. Concerning the phase separation for the establishment of on-orbit transfer technology for cryogenic fluids such as liquid helium, hydrogen and oxygen, there are many attempts also in Japanese industries and research organizations (e.g., Imai et al.[87], Kawanami et al.[88]).

7. Directions for Further Researches

7.1 Pool Boiling

Pool boiling under reduced gravity conditions is of great interest not only in the practical application but in its scientific aspects. From the observation of the structure of coalesced bubbles and of microlayer behaviors underneath a single or a primary bubble in reduced gravity, i.e., the essential part of liquid-vapor behaviors in pool boiling, the heat transfer mechanisms and presumably also the mechanism of burnout are the same independent of gravity level. In other words, elementary process of nucleate boiling heat transfer is not changed with the gravity but is varied quantitatively. Hence, the environment of reduced gravity, which enlarges the bubble size and delays or prevents the bubble detachment, provides a great condition for the clarification of the mechanisms of nucleate boiling heat transfer.

One of the major phenomena concentrating the interest of many researchers is the bubble detachment under reduced gravity conditions. It controls the interval of liquid supply to the heating surface and is a dominating motion affecting the burnout mechanisms. To find the criteria of bubble detachment through the experiments is quite difficult because of existing residual gravity or G-jitter inevitably encountered in the facilities. If a bubble is assumed to be detached even under reduced gravity conditions, the force lifting the bubble is to be identified. It might be a problem to handle a bubble as if it is a solid body to consider the forces acting on it, even though various forces including dynamic ones are taken into consideration. The criteria judged by the existence of possible interface proposed by Fritz[89] should be reminded again. From such an idea, the recent approach by the trance of interface locations numerically is correct, if the uncertainty in the accuracy of calculation and in given bold assumptions especially around the bubble base can be eliminated.

The microlayer behavior underneath a single isolated bubble or primary bubbles under a coalesced bubble plays an important role in nucleate boiling heat transfer. The distribution of its thickness is a key to evaluate the distribution of local heat transfer rate (Wayner[90]). To confirm a peak in the local heat transfer rate at an certain radial location inside a circle of bubble attachment, a heating surface with an array of fine sensors is to be employed in the experiments. The surface temperature measurement covering whole bubble attached area to evaluate exactly local heat fluxes is a quite difficult technological problem in reduced gravity because of its enlarged size of the area.

Effect of Marangoni force on nucleate boiling which is believed to be emphasized under reduced gravity conditions is one of unknown problems to be solved. The problem is divided into two points, i.e., the origin of such a strong interfacial force and its influence on the bubble behaviors and heat transfer. In the experiments, it is important to make attention to obtain pure fluids to eliminate the effect of incondensable gas (Straub[7]). It is a topic of great interest to enhance the liquid supply by self-wetting mixtures (Abe-Iwasaki[91]). The increase in CHF is expected by using such fluids with higher surface tension at higher temperature or with lower concentration of more volatile component.

Most of data in pool boiling experiments in reduced gravity are those for nucleate boiling, while the data of CHF, transition or film boiling is very limited in the present stage.

7.2 Flow Boiling

The number of fundamental researches for the clarification of the heat transfer characteristics is very limited despite the importance of practical application in space heat management systems. Effect of gravity on the heat transfer in the wide ranges of pressure, mass velocity and heat flux should be clarified systematically. But it requires long duration of reduced gravity and its repetition to confirm the reproducibility before the database is established, and the opportunity to realize the experiments on ISS is desired. As regards the critical heat flux data there is almost no existing fundamental works despite the importance for safe operation and for the clarification of the heat transfer limitation in the practical applications.

The system should not be concentrating on the flow boiling in a round tube but is to be extended to the confined channels between the flat plates or microchannels of various shapes. The most important subject in future investigations is the clarification of the flow and heating conditions where gravity effect is observed. This becomes possible to some extent by the comparison of three forces of inertia, buoyancy and surface tension dominating the behaviors of both phases and the heat transfer. The parameters including Weber, Froude and Bond numbers should be revised to find the boundary of dominating range of the forces. The accomplishment of this work could minimize the experiments to be performed by the limited opportunities for the use of facilities and enhance the data reliability for the practical application.

From the scientific interest, the mechanism of gravitational force affecting the heat transfer especially that in the annular flow regime is to be clarified in detail. The behavior of disturbance wave plays an important role when the quasi-steady phenomena is interpreted as the iteration of periodical ones with statistical nature characterized by the passage of disturbance waves. One more interest topic is the effect of gravity on the inverted annular flow in the case of DNB at low quality and high heat flux, where disturbance on the surface of liquid core flow is seriously influenced by the gravity (Ohta[48]).

7.3 Isothermal Two-phase Flow

The researches in this discipline are to be finally applied mostly to the heated systems, i.e., those of flow boiling, but the variation of flow rates for both phases in a wider range are useful for the clarification of mechanisms of two-phase flow structures. The effect of gravity on the distribution of void is widely investigated for the system with gas injection, while measurement or prediction is not tried enough for the bubble generated from the inner tube wall simulating the flow boiling conditions.

As was mentioned in the flow boiling section, to clarify the ranges of parameters where gravity effect is observed is important for the further investigation, and the experiments varying both the gravity and surface wettability becomes powerful means to solve the problem.

It is a serious problem for the design of two-phase loop used in space that there is no enough data for the pressure drop in reduced gravity and the pressure difference between the data for reduced gravity and for a vertical tube in normal gravity is unclear. It might be due to the difficulty to separate the frictional contribution from the total pressure drop in the case of the vertical tube.

8. Present Situation in Japan Surrounding the Researches on Reduced Gravity Utilization

The systematic support of reduced gravity experiments in the present field has already started at least in the beginning of the 1990s by the program by STA (Science and Technology Agency). From 1993 another powerful support with the name ''Space Utilization Frontiers Joint Research Projects'' by JSUP (Japan Space Utilization Promotion Center) including mainly the aircraft experiments by MU-300 and a part of TR-1A experiments has been started under the direction of NASDA. The opportunity to use these facilities was given to the researchers, and was technologically aided by a few leading manufacturers in the present research field. By such a strong support, the researchers were able to realize their planning in both hardware and software developed for a long time. The program, however, ended in 1997, and is succeeded by ''Ground Research Announcement for Space Utilization'' promoted by NASDA/JSF (Japan Space Forum). The program is ranked three to four different classes covering the researches from those of the early stage without the sufficient prospect of results to those interpreted as the preparation stages for the ISS experiments. As far as the present author knows, only several subjects were accepted in the present research field during a series of iterated announcement of opportunities in every fiscal year from 1997 to 2002. In this program, the researchers cannot obtain the direct support by the manufactures. But not only the aircraft experiments but also the drop shaft experiments are included in the program. Before the starting of JSF program, there were two more programs by one division of JSUP under the direction of NEDO (New Energy and Industrial Technology Development Organization) to utilize JAMIC drop shaft and by ISAS (Institute of Space and Astronautical Science), one of the research organizations of the Ministry of Education, with the name ''Fund for Basic Experiments Oriented to Space Station Utilization'' which was succeeded till 2001. In the latter program, researchers were supported financially but pay by themselves the cost for the use of facilities. The program was unified to that of JSF in 2002. Due to the reconstruction of three space organizations in Japan, i.e., NASDA, NAL and ISAS, to be planned in the autumn of 2003, research programs is not yet announced in the present stage (August in 2003).

The present author should refer to the proposal for

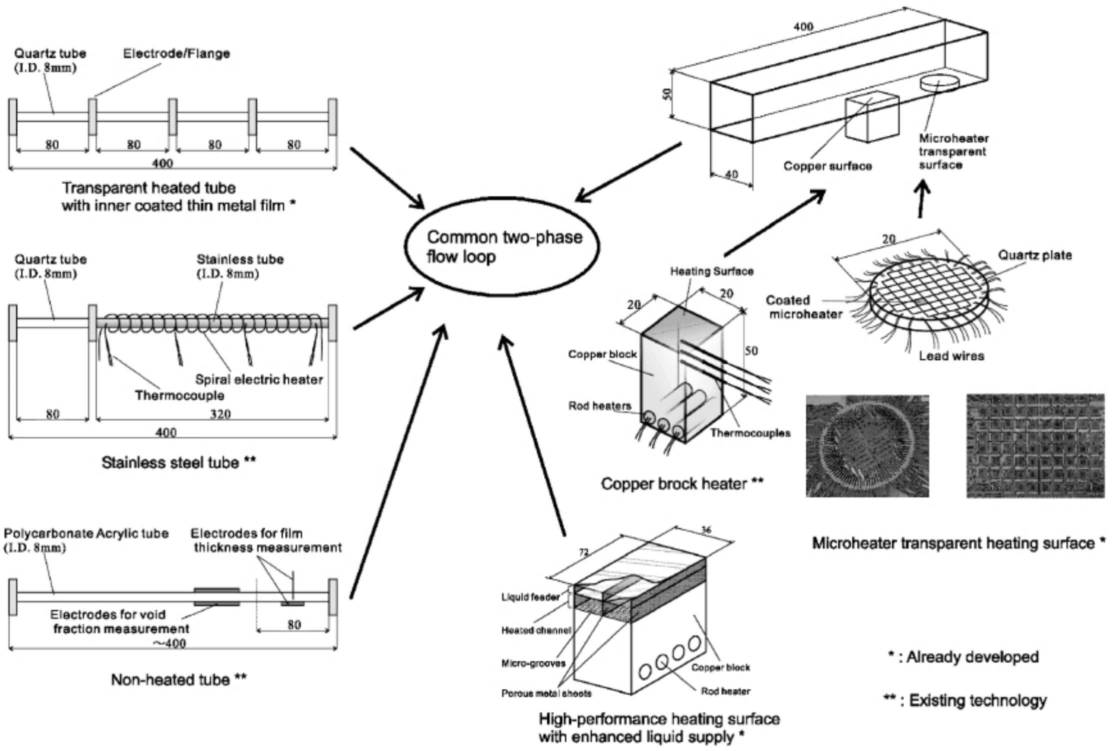

Fig. 2 Concept of interchangeable test sections connected one test loop which makes various experiments simultaneously possible utilizing a limited opportunity of long-term reduced gravity duration.

the ISS experiments. As is known widely, 1st international announcement of opportunity for ISS was made in the autumn of 2000. The researchers of five countries from Japan, USA, Canada, Italy and Germany collaborated to make a proposal, where a common test loop was used to conduct multiple experiments mainly on flow boiling by the interchangeable structure of test sections. The apparatus was planned to be in stalled on FPEF (Fluid Physics Experiments Facility) developed by NASDA. The FPEF is a unique facility to have capacities in the volume and power supply required for the experiments. Finally, the proposal was not accepted by reasons of unrealistic requirements in the development of test sections and of operating time included in the proposal. But it can be at least said that the process of application became a strong activity in the preset research field. As depicted in **Fig. 2**, the proposal has an idea to utilize one apparatus to realize various experiments to make utmost use of the limited opportunity. All the test sections have already been developed and tested or under testing to confirm their individual functions. To prove the possibility for the integration in FPEF, a mockup model was actually constructed as shown in **Fig. 3** to prepare for the desired next opportunity.

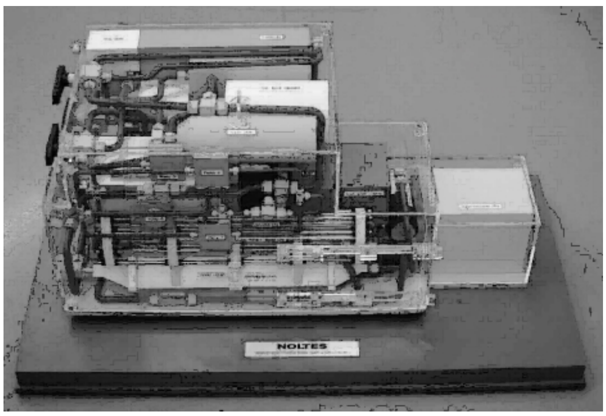

Fig. 3 An example for the integration of two-phase loop and test sections under an assumption to use FPEF (Supported by Office of Research and Development, NASDA).

9. Concluding Remarks

Outline of existing Japanese researches on boiling and two-phase flow under reduced gravity conditions are introduced and it is clear that the researches cover most of important topics in this field and have possibility for the consistent development also in future. It is noteworthy that a lot of new results with scientific and technological values were obtained in Japan concerning liquid-vapor behaviors and/or heat transfer in pool boiling, flow boiling and concerning adiabatic two-phase flow including the results for the special topics. Recently, the situation surrounding the researches became rapidly degraded because of the problem of foundation. The situation is not inherent only in

Japan but seems to be a common problem in the world. It is contradictory that the investigation cannot be advanced despite of its superior potential only if no opportunity to use the facility of reduced gravity is given. At least in Japan, the order of priority for the present research field has not been high among others, and there is no symptom for the improvement of the present situation in a short period. The phenomena of boiling and two-phase flow have many dominating parameters and the boundaries of parameters where the gravity effect is observed. The boundaries should be clarified by both the analysis and experiments of short reduced gravity duration in order to find the experimental conditions for desired long-term experiments. Powerful international collaboration is required for the proposal of the experiments by ISS to avoid the duplication of the contents in the proposed experiments for the effective use of very limited opportunity. The present author desires that this article could contribute to introduce Japanese researches for many investigators in the world and to become a motive for the international collaboration before the next A.O. for ISS.

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