27H01

# 微小重力実験用小型ダストプラズマ実験装置の実験的研究

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# Experimental Investigation of Small Apparatus for Complex Plasmas Experiments in Microgravity

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## 1. Introduction

A big issue of complex plasmas experiments in microgravity is void formation. The void is a region where number density of micro-particles is almost zero. This makes an observation area smaller, especially very small in a high power region. Therefore, we have investigated both mechanisms of the void formation and a small apparatus being suitable for the microgravity experiments. The current status of experimental investigation of the apparatus is reported.

## 2. Apparatus

The apparatus must be mounted on a rack. The rack having enough flexibility and room for users, which is installed on the 'Kibo' pressurized module, is the Multipurpose Small Payload Rack (MSPR). The MSPR has a user space named Work Volume, of which dimensions are 600 mm high, 900 mm wide, and 700 mm long. This may not be a sufficient room for our experiment because our apparatus should have a plasma chamber, a power supply for plasma formation, plasma diagnostics, video cameras, sheet laser lighting, and electronics boxes such as a controller and a data acquisition device at minimum. Some gas bottles accompanying with tubes and valves may be also required for high purity gas supplies but these are optional at present.

It is not easy work to design an apparatus optimized for microgravity experiments from scratch, that is, small and lightweight one which has sufficient performance. Fortunately, we have an excellent reference, PK-3 Plus [1)]. PK-3 Plus was launched in December 2005 by a Russian Progress cargo spacecraft. The operation was started in January 2006 and was terminated in June 2013. The long operation period of more than seven years proves the reliability and robustness, which are indispensable factors in microgravity experiments. Thus we decided the maximum dimension of the apparatus should be similar to that of PK-3 Plus.

Another issue is void formation in microgravity. The void is a region almost without micro-particles. The void is one of the most difficult issues to be solved in microgravity experiments. Since the void reduces observation area, it is difficult to observe phenomena requiring larger area such as the critical phenomena. In addition, the void formation mechanisms may interact with other mechanisms in which we are interested. Therefore, the void region must be reduced as much as possible. To suppress the void formation, it is expected that a flat potential profile in radial direction is helpful though it is difficult to obtain such a profile. As a starting point, a similar way of supplying RF current to our larger apparatus is applied since the flat potential area seems to be obtained near RF electrodes except for near edges.

The first apparatus is designed as shown in **Fig. 1**. The outside dimensions are almost the same as PK-3 Plus. Two RF electrodes are set at the places near top and bottom flanges. Each electrode has two feedthroughs so that RF current can flow from one feedthrough to the other. This should be one of the key techniques to achieve a flatter profile. Unfortunately, influence of glass wall is not avoidable due to its small size.

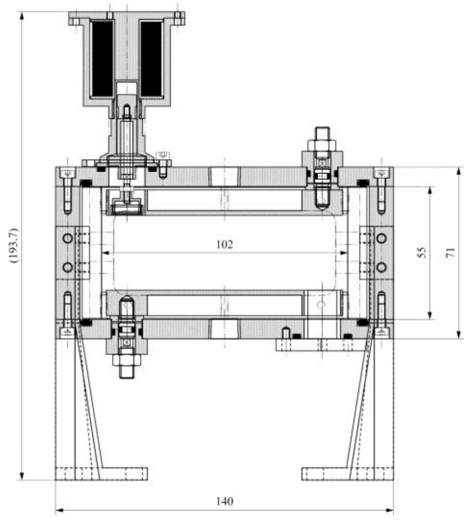


**Fig. 1** Schematic view of small apparatus

## Acknowledgment

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27H02

# PK-4J における円筒状ダストプラズマ：理論・シミュレーション

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## Study of Cylindrical Dusty Plasmas in PK-4J; Theory and Simulations[1)]

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### 1. Introduction

In the investigations of fundamental properties of strongly coupled Coulomb and Coulomb-like systems, dust (fine) particles of micron size in plasmas have been very useful.[2,3)] The only weakness of these particles is the strong response to the gravitational field. In order to avoid the effect, experiments of the project PK-3 Plus[4)] have been successfully performed on the International Space Station (ISS).

After PK-3 Plus, the project PK-4 is now in progress[5)] and the experimental apparatus is planned to be launched October 2014. We have constructed the similar apparatus PK-4J and studied the behavior of (dust) particles to propose interesting experiments in PK-4. Structures of these apparatus are shown in Fig.1.

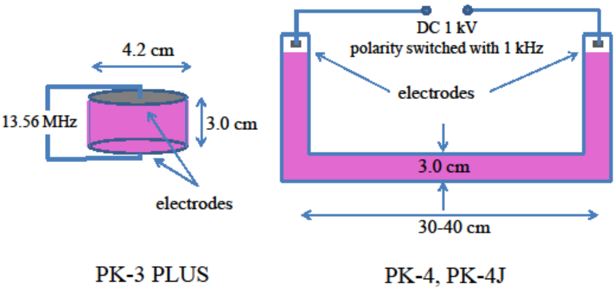


**Fig.1** In PK-3 PLUS (left), plasma is generated by rf discharge. In PK-4 and PK-4J (right), dc discharge with polarity switching generates plasma and behavior of dust particles is observed in the central straight part which is a long cylinder.

We consider the system of (dust) particles in a plasma (composed of electrons and ions) with the cylindrical symmetry and analyze their behavior first on the basis of the drift-diffusion equations. We then analyze the effect of discreteness of dust particles, correlation and structure formations, by numerical simulations. Our system is composed of plasma (electrons and ions) and dust particles.

### 2. Analysis Based on Drift-Diffusion Equations

Typical examples of distributions obtained by drift-diffusion equations are shown in Fig.2 where the net charge density and the electrostatic potential are also plotted. We observe, in the domain where particles exist, (a) the enhanced charge neutrality, (b) almost flat electron distribution, and (c) compensation of the change in the particle charge density by that of ion charge.

Under some condition, there appears the central region where we have no particles or the 'void'. An example is given in Fig.3. We have analyzed the condition for the void formation and details will be discussed in the presentation.

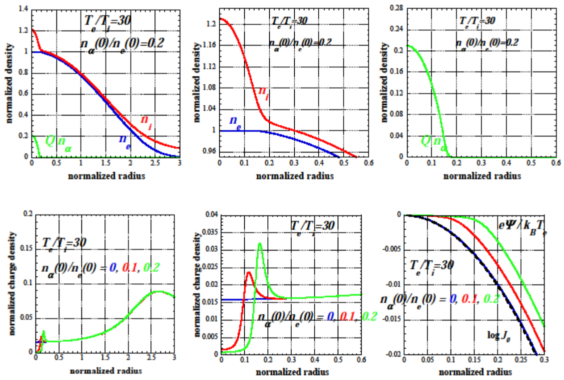


**Fig.2** Distribution of electrons, ions, and particles (top), charge density (bottom left and center), and electrostatic potential (bottom right)

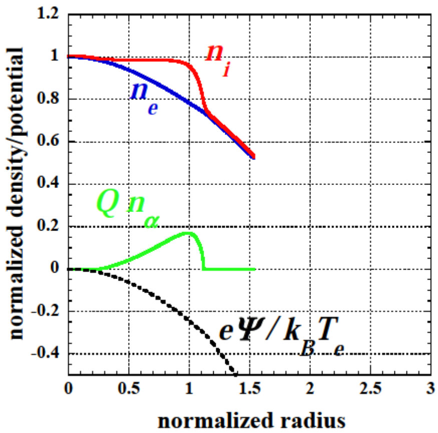


**Fig.3.** Distribution with void

### 3. Simulations of Particle Model

We then numerically simulate the behavior of particles following the trajectory of each particle. Typical examples of particle distribution are shown in Figs.4 and 5: Particles are organized into shells and a triangular lattice with defects is formed on each shell.

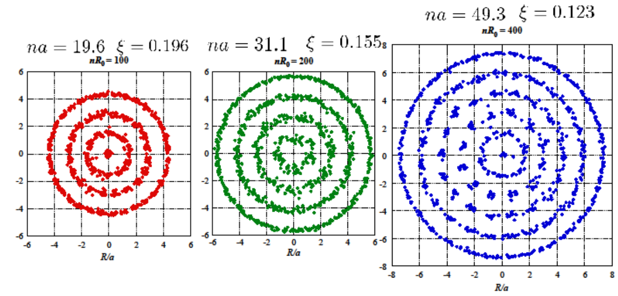


**Fig.4.** Examples of shell structures in uniform cylinder (projection onto cross section)

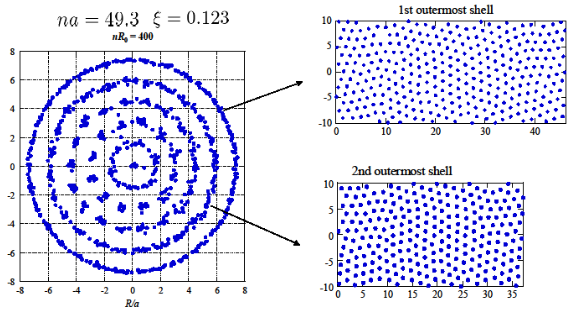


**Fig.5.** Example of configuration within shells (cylinders cut-out into planes)

When ions flow along the axis, we have an anisotropic part in the mutual interaction between particles. This part has the dipolar nature directed along the axis and has an effect which tends to align particles along the axis. An example of such effect is shown in Fig.6 where the tendency is observed in distributions within shells.

The effect of the gravitational field has been also investigated by simulations in the simplest case where the gravitation works perpendicularly to the symmetry axis. Examples of results are shown in Fig.7. The circular distribution is compressed along the direction of the gravity and is moved downward as a whole. When particles with different radii are included, they are separated by the mass difference.

#### 4. Concluding Remarks

Results of theoretical analysis and numerical simulations are presented. They will be also discussed in comparison with those of parabolic flight experiments.[6)]

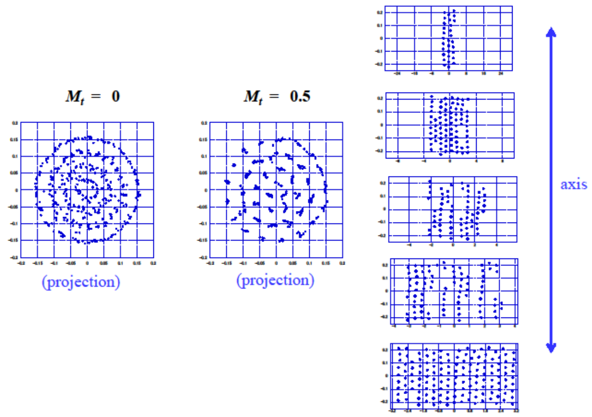


**Fig.6.** Example of effect of anisotropic interaction. Cross sectional projection without anisotropic interaction (left), the one with anisotropic interaction (center), and cylinders (shells) cut-out into planes (right).

### Acknowledgements

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27H03

# 国際協力による微小重力実験を目指した航空機による実験条件検討

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# Experimental Investigation for Collaborative Microgravity Experiments by Parabolic Flights

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Hiroo TOTSUJI (JAXA→Okayama Univ.)

## 1. Introduction

The next generation apparatus for complex plasmas experiments in microgravity, PK-4, will be launched this year. We have carried out parabolic flight experiments in order to propose new ideas with high scientific-significance to the PK-4 international science team. To verify feasibility of the ideas, we prepared a PK-4-like apparatus for the parabolic flight experiments. Unfortunately, directions and strength of gravity vary during the parabolic flight. Therefore, we continue modifying our apparatus to adapt it to the gravity condition. The present apparatus and major changes are reported.

## 2. Apparatus and Results

The original PK-4 for microgravity experiments was developed by the Max-Planck Institute for Extraterrestrial Physics [1)]. PK-4 has a long tube of 350 mm in length and 30 mm in inner diameter. As a result, cylindrical plasma is formed. This may bring us new experimental results since the configuration quite differs from the past apparatuses.

To propose new ideas to the international science team, we began the parabolic flight experiments. As the first step, an apparatus, which is very similar to PK-4, was prepared. This apparatus is relatively large as compared with the rack size on the airplane. Therefore, it was not easy to integrate the experimental rack. In addition, we found that the micro-particles moved along the longitudinal axis when the airplane attitude varied. It was difficult to stabilize the particle location. We also found, however, the cylindrical complex plasmas seemed to have no void. This was excellent news if the void was not formed. Therefore, we began to investigate the void formation mechanisms.

The modified PK-4-like apparatus was prepared for the next parabolic flights. The length was reduced to 300 mm to make the rack integration easier. In addition, the apparatus was divided into several parts to obtain more flexibility. In the experiments, we tried to stabilize the particle location by controlling the discharge more precisely but did not succeed so much. The void suppression was also investigated. A new equipment to obtain three-dimensional coordinates of particles was developed. Further improvement was needed to obtain the precise coordinates.

By considering those results, we decided the longitudinal axes of the apparatus and airplane were made perpendicular to each other though the longitudinal length was decreased. It was expected that the particles were held by floating potential on the wall and were stabilized when the airplane attitude changed. The current apparatus is schematically shown in **Fig. 1**. Although the longitudinal length is decreased to 175 mm, the plasma should be considered to be still cylindrical due to the ratio of the length to the radius (15 mm). Our latest experiment was carried out two years ago. In the experiments, the particle location was well stabilized as expected. In addition, the three-dimensional particle coordinates were successfully obtained. From the coordinate data, it was confirmed that the void was fully eliminated.

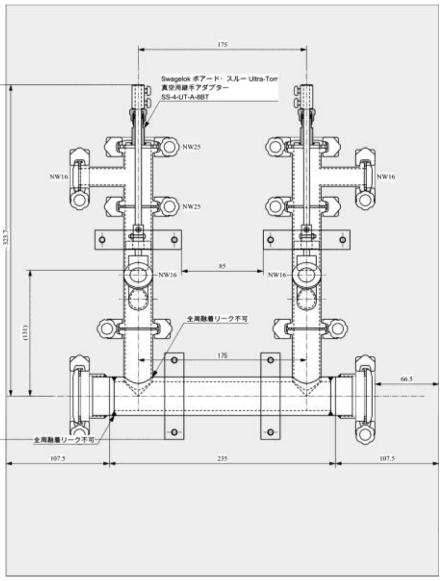


**Fig. 1**　Schematic view of PK-4-like apparatus (PK-4J)

## Acknowledgment

This work was supported by the Steering Committee on Space-Environment Utilization at ISAS/JAXA.

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27H04

# 荷電コロイド分散系の分子モデルによる分子動力学シミュレーション

○片岡洋右（法政大生命科学）

# Molecular Dynamics Simulation on Molecular Model for the Charged Colloidal Dispersion

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## 1. Introduction

The structure in the charged colloidal dispersion is analyzed by DLVO[1) 2)] or Sogami model[3)]. These theories assume low concentration of ion in the statistical mechanical calculations. This work presents a molecular model to be used in molecular dynamics (MD) simulations for the thermal average.

## 2. Large particle and small ion

The large particle must have large charge compared to small ion. We assume that the size and mass of large particle are comparable to that of small ion.

The large particle has 25e (e = charge unit) and mass and size are the same with those of Rn. The small ion has -e and mass and size are the same with those of Kr. The dielectric constant of the solvent is 100.

## 3. 2-particle system

The interaction energy between the large particles in the solution $u_{int}(r)$ is calculated by the 2-particle system by *NTV* MD.

$$u_{\text{int}}(r) = E_2(r) - 2E_1 \tag{1}$$

Here $E_2(r)$ is the average potential energy of 2-particle system of the large particle with the separation *r*, where 50 small ions move at temperature 1K.

The result on $E_2(r)$ is plotted in Fig. 1. Attractive interaction is observed around *r* = 1 e-9 m, with the depth 7 e-20 J.

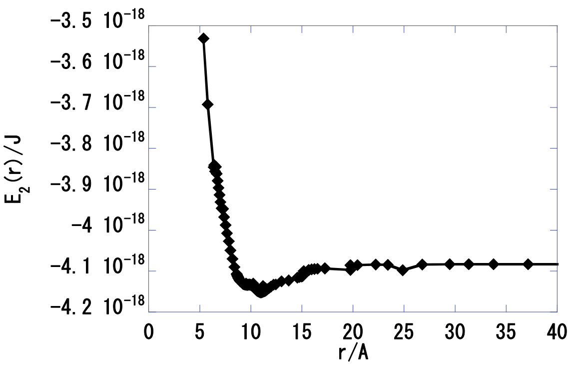


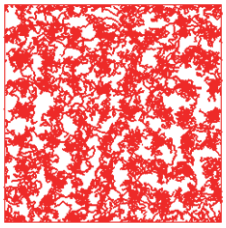

**Fig.1** The average potential energy of 2-particle system of the large particle with the separation *r*

## 4. Density dependence of structure

### 4.1 Trajectory of large particle

Molecular dynamics simulations are performed at many densities and temperatures. The structure is analyzed by the trajectory, the pair correlation function and pressure. The number of the large particle is 256 in the basic cell.

At low density (*d*), the solution is like gas phase. At the intermediate density, it has liquid structure like Fig. 2. The FCC solid (Fig.3) is observed at high density at T=290K.



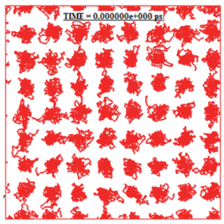


**Fig. 2** *d* = 1.5 g/cm$^3$, T=290K **Fig.3** *d* = 1.8 g/cm$^3$, T=290K

### 4.2 pressure at several temperatures

The pressure is shown in Fig. 4 as functions of density at several temperatures.

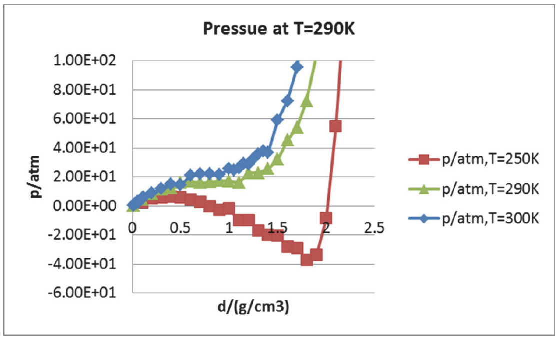



**Fig.4** The pressure at *T*=250K, 290K and *T*=300K as functions of density *d*.

Figure 4 shows the system at *T* = 290K and *d*=1 g/cm$^3$ is close to the critical point of liquid-gas transition if system is treated as the mixture of large particles and small ones.

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27H05

# シリカーラテックス混合分散液におけるコロイド結晶の fcc-bcc 相図

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# Fcc-bcc Phase Diagram in Silica-Latax Mixed System

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Kensaku ITO (University of Toyama), Junpei YAMANAKA (Nagoya City University)

## 1. Introduction

Hachisu and Yoshimura [1] have investigated colloidal crystals in charge-stabilized binary systems of latex particles with different sizes by metallurgical microscopic observation and succeeded to photograph images of the perfect structures of alloy crystals. General studies, however, have not yet been fully made for the colloidal crystals in mixed dispersions consisting of different species of particles. Therefore, it is worth to investigate the processes of phase transitions of colloidal crystals in mixed systems. In this research, we pursue structure changes of the colloidal crystals in the mixed dispersions of the silica and latex particles by using the Kikuchi-Kossel (K-K) diffraction method [2].

In the previous study [3], we investigated mixed systems of polystyrene-based latex particles (diameter: $D$ = 55.8nm) and silica particles ($D$ = 170nm). In the single-component dispersions prior to the mixing, the silica particles formed body-centered-cubic (bcc) crystals and the latex particles did not crystallize. In the binary mixtures of these particles, formation of crystals with face-centered-cubic (fcc) structures was verified by the analysis of the recorded images of K-K diffraction. Crystal growth in the specimens at low latex fractions took place with bcc structures and then changed to fcc structures.

In this research, we prepared the specimens for experiments by mixing the silica particles KE-E10 with each one of three kinds of latex particles (N558, N775 and N870) which have different sizes and surface charges and observed the processes of crystal growth in each of them for 30 days. The observed structure (bcc or fcc) of colloidal crystals varied according to the mixing rate, the elapsed time and the observation positions with different heights. The silica particles KE-E10 have the smaller size than the particles used in the previous study [3]. The colloid crystals in the single-component dispersion of the silica particle was confirmed to have only the bcc structure for the volume fraction of the range of 0.01-0.03.

## 2. Experiment

The colloid particles used in the study were silica Seahoster KE-E10 [4] produced by Nippon Shokubai Co., Ltd. (Osaka, Japan) and polystyrene-based latex N558, N775, N870 produced by Sekisui Chemical Co. (Osaka, Japan) which have average diameters $D$ of 130nm, 55.8nm, 77.5nm and 87.0nm, respectively. The latex N558 is the same particle used in the previous experiment [3]. The particle size distributions were about $\sigma/D$ ～5% for the KE-E10 and $\sigma/D$ = 8.78% (5.16% and 10.92%) for the N558 (N775 and N870), where $\sigma$ denotes the standard deviation of the particle diameter distribution. The ethylene glycol which was used as a solvent for KE-E10 was replaced with ultra-pure water completely to perform thorough ultrafiltration. After purification with Milli-Q water and deionization by ion-exchange resin particles, the effective surface charge densities $\sigma_{eff}$ of the colloidal particles were determined to be 0.12μC/cm$^2$ for the silica particles and 0.63μC/cm$^2$ (0.91μC/cm$^2$ and 0.59μC/cm$^2$) for the latex particles N558 (N775 and N870). The properties of the colloidal particles used in this experiment are summarized in **Table 1**.

**Table 1** The properties of the colloidal particles

| Particles | Diameters | $\sigma/D$ | $\sigma_{eff}$ |
|---|---|---|---|
| KE-E10 (Silica) | 130nm | ～5% | 0.12μC/cm$^2$ |
| N558 (Latex) | 55.8nm | 8.78% | 0.63μC/cm$^2$ |
| N775 (Latex) | 77.5nm | 5.16% | 0.91μC/cm$^2$ |
| N870 (Latex) | 87.0nm | 10.92% | 0.59μC/cm$^2$ |

To exclude the influence of any ionic strength distribution (caused by relatively slow deionization processes by the ion-exchange resins) among several samples, to minimize impurity ions from outside, and to avoid evaporation of the liquids inside, all the dispersion samples were introduced into hermetically sealed quartz cuvettes (height 45mm; width 10mm; inner thickness 1mm) with an air-tight lid. Ion-exchange resins were not added in the cuvette. The dispersions began to show iridescence proving the formation of microcrystals after their introduction into the cuvettes. The speeds of crystal growth varied from specimen to specimen. The cuvettes were kept standing vertically, and the temperature was held at room temperature.

We analyzed the colloid crystal structure formed in the cuvette by using the K-K diffraction method. In the K-K experiment, the laser beams enter perpendicularly to the wide surface of the cuvette. We used an Ar laser with wavelength 488nm.

## 3. Results and Conclusion

For preparation of the specimens, we took out several milliliters from the dispersion of the latex particle (N558, N775 and N870) and mixed them with the dispersion of the silica particle KE-E10 at various ratios. The single-component dispersions of the latex particles (N558, N775 and N870) were confirmed not to crystallize.

We observed the structure of the colloidal crystal in each specimen for 30 days by using Kikuchi-Kossel line apparatus and confirmed that the phase transitions (bcc→fcc or fcc→bcc) take place in many specimens. We recorded the position of the container at which the structural change of the colloidal crystal was observed. The colloid crystal in the single dispersion of silica particle KE-E10 was confirmed to take only bcc for the volume fraction of the range of 0.01-0.03. As discussed in the previous report [3)], we assume here also that the colloidal crystal did not form the alloy crystal of the silica particles and the latex particles and interpret that the colloidal crystals of silica particles changed their structures from bcc to fcc.

The structural changes of the colloidal crystals to the volume fractions of the silica and latex particles are shown in **Figs. 1, 2 and 3**. Observation of the crystal structure was performed every several days. The graphs drawn in **Figs. I**-(a), (b) and (c) ( I = 1, 2 and 3) are the phase diagrams observed, respectively, around several hours, 10 days and 30 days after the preparation of the specimens. As seen from the phase diagrams, the bcc to fcc transitions take place depending mainly on the volume fraction of the latex particle rather than that of the silica particle (in the range of 0.01-0.03). The volume fractions that the fcc phase begins to appear in the dispersions with N558, N775 and N870 are, respectively, about 0.0005, 0.0001 and 0.0003. These fractions correspond to the particle number $5.5\times10^{12}$, $4.1\times10^{11}$ and $8.7\times10^{11}$ per $1cm^3$, respectively.

Let us compare the results for the mixed dispersions with the latex particles N558 and N870 which have nearly the same surface charge. The bcc-fcc transition is favored to take place in the dispersion with N870. This is because N870 has the large diameter. Although the diameters of N775 and N870 are not different so much, the former has higher charge density than the latter. The bcc-fcc phase transition tends to take place favorably in the dispersion with N775.

When the surface charge of the particle is large in the colloidal crystal of the single dispersion, the tendency to take fcc structure is enhanced. Similarly, if the total electric charge of the latex particle is large in the mixed dispersion, the colloidal crystal tends to transform to fcc. When the fraction of the latex particle becomes increases, the vacant space for the silica particle decreases. As a result, it is inferred that fcc structure tend to dominate. To clarify the influence of the latex particles in detail, however, we have to make further quantitative analyses of these experimental results.

We will report the data concerning the position dependence of phase diagrams which show the effects of gravitation in a future communication.

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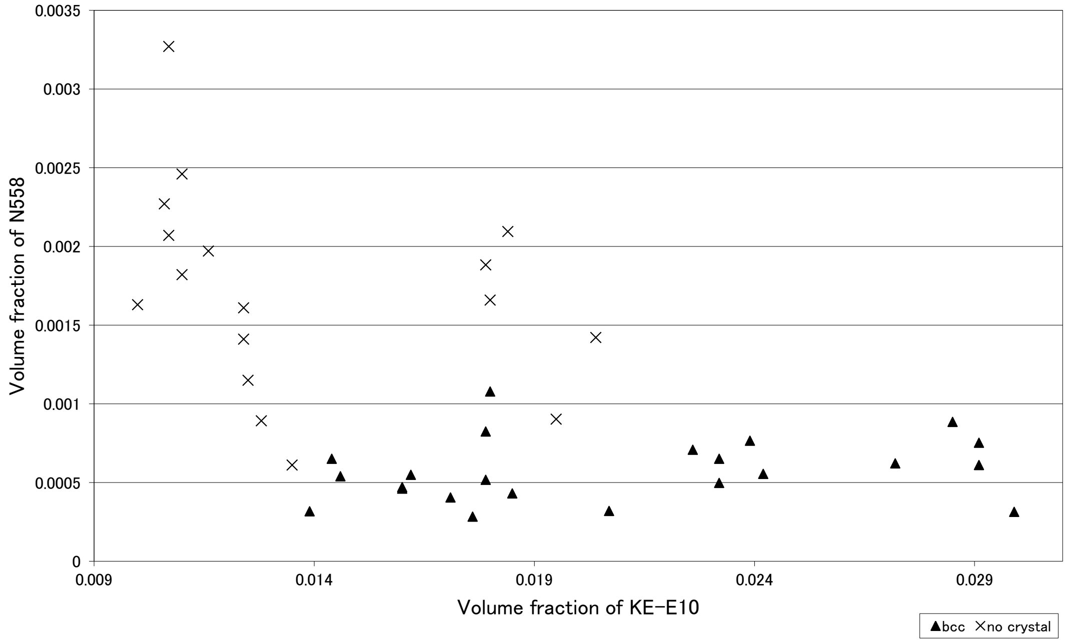



**Fig. 1(a)** Phase diagram for the mixed dispersion with N558 observed around several hours after the preparation

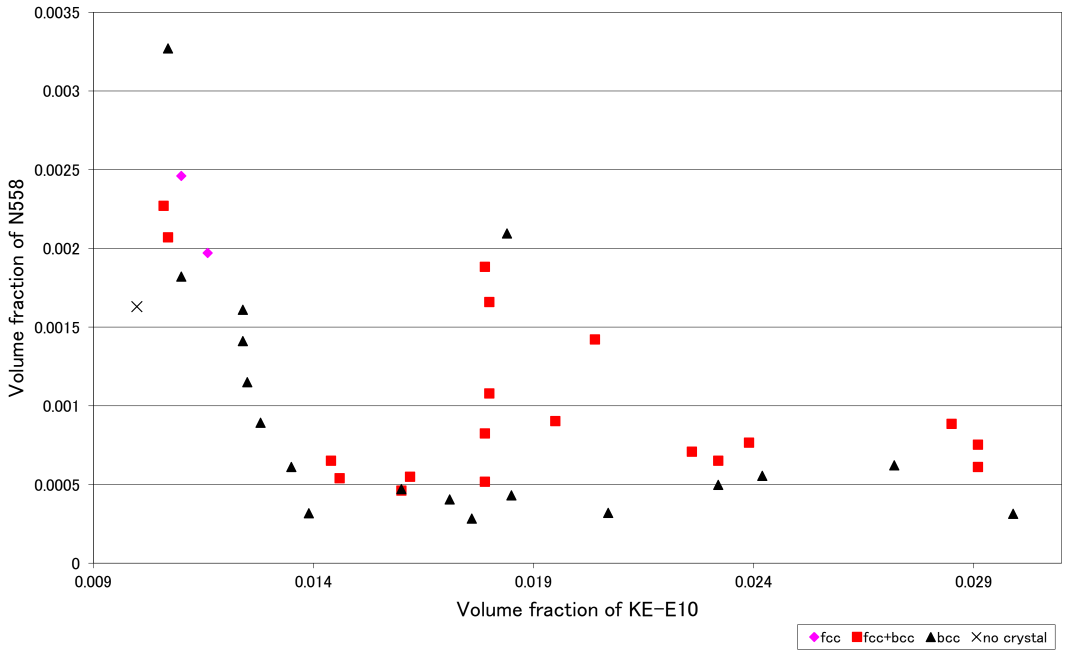



**Fig. 1(b)** Phase diagram for the mixed dispersion with N558 observed around 10 days after the preparation

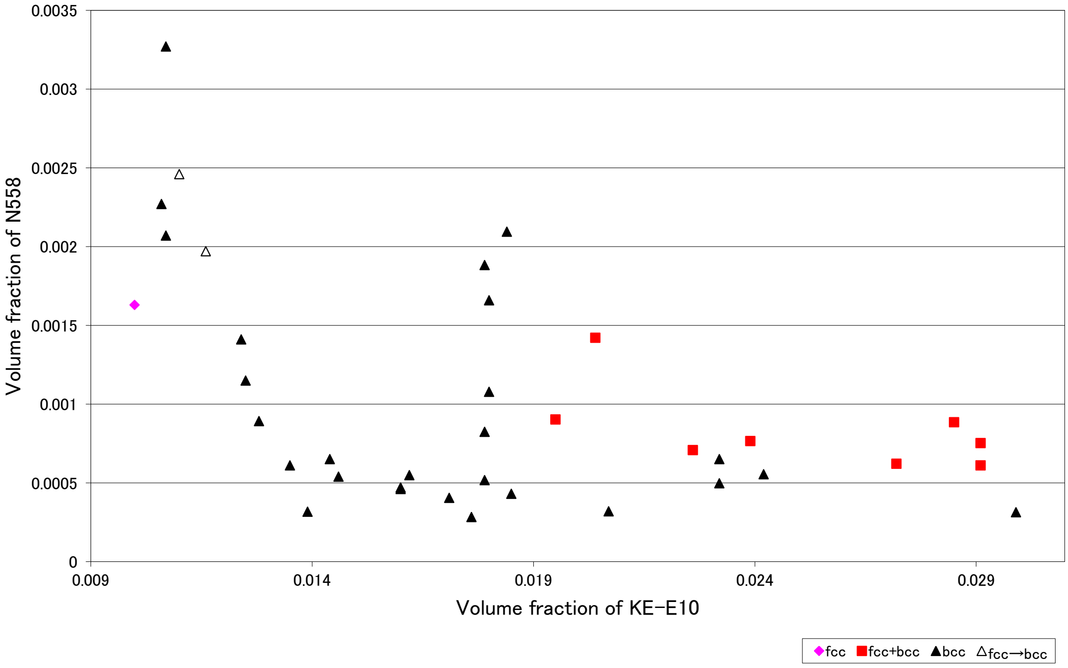



**Fig. 1(c)** Phase diagram for the mixed dispersion with N558 observed around 30 days after the preparation

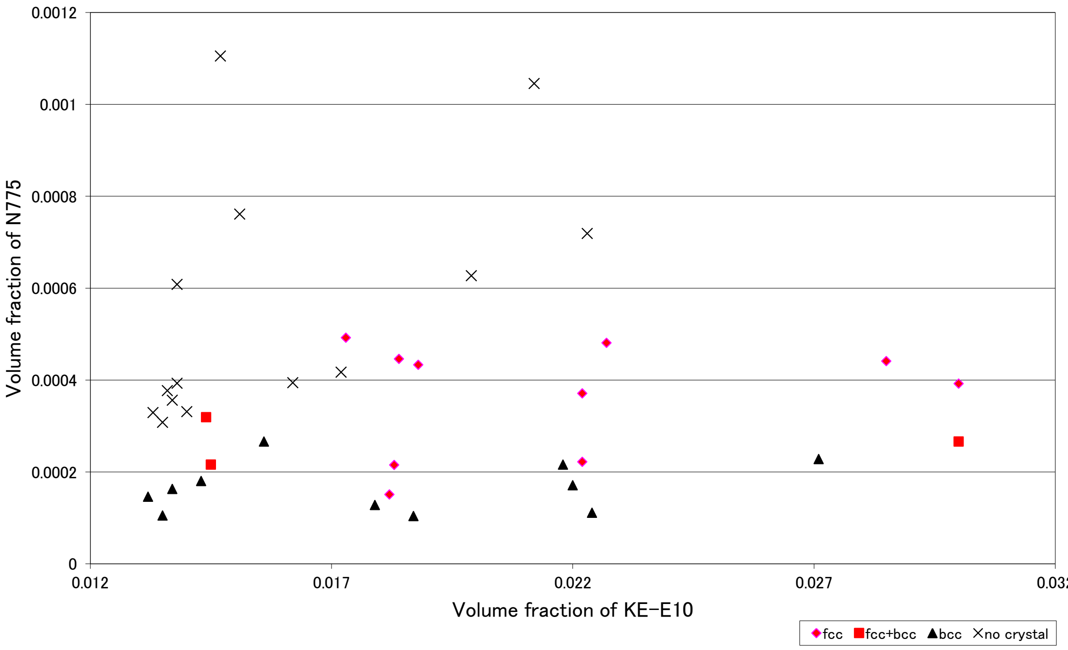



**Fig. 2(a)** Phase diagram for the mixed dispersion with N775 observed around several hours after the preparation

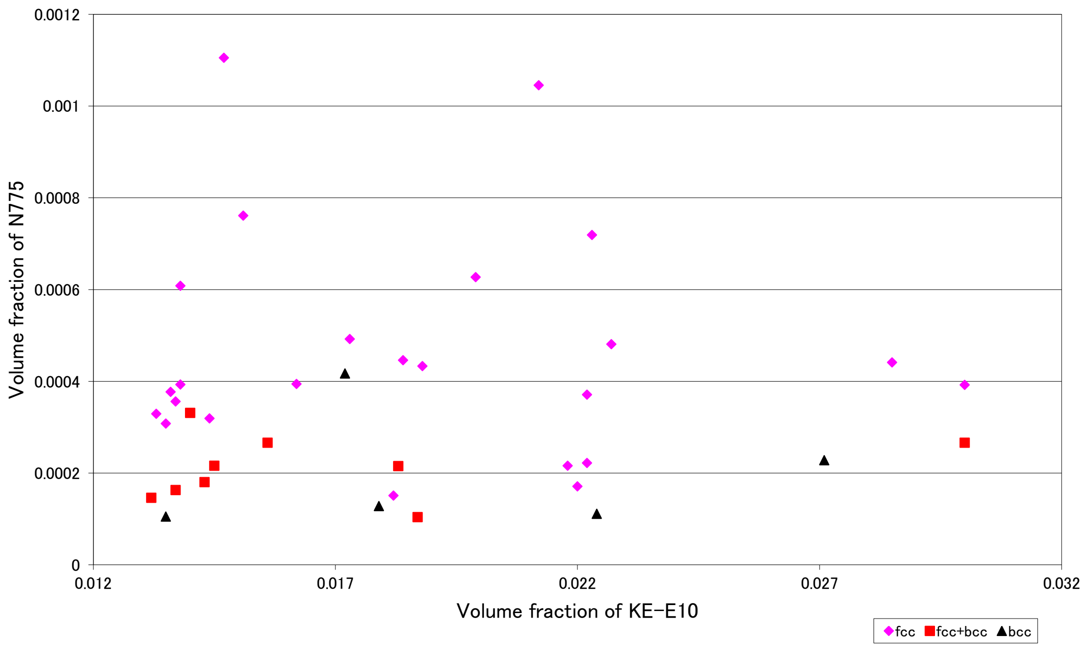



**Fig. 2(b)** Phase diagram for the mixed dispersion with N775 observed around 10 days after the preparation

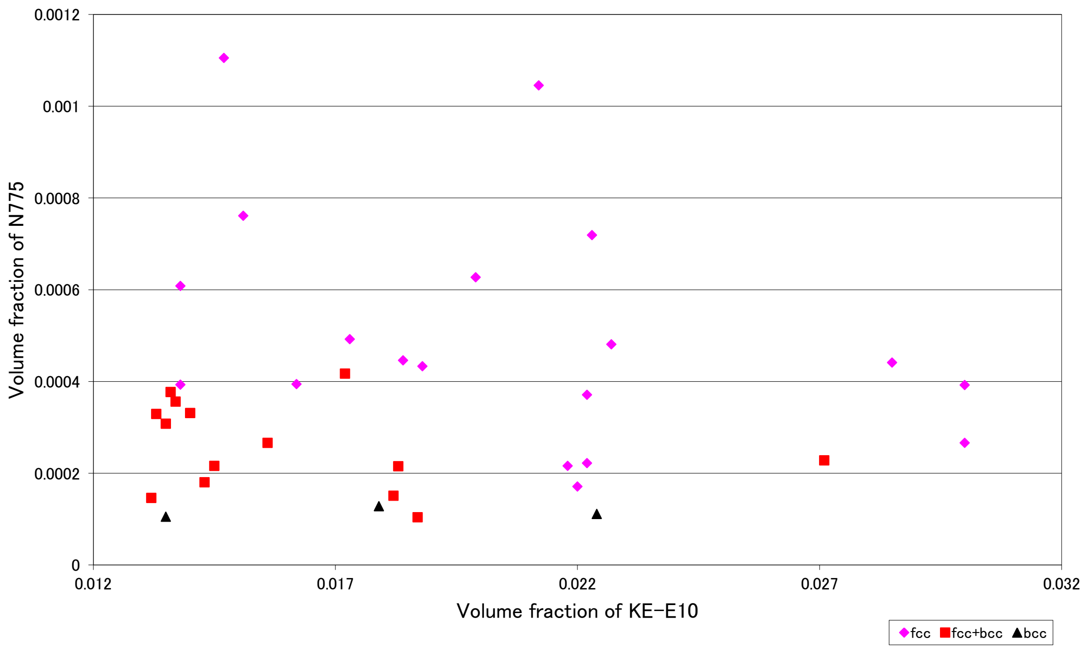



**Fig. 2(c)** Phase diagram for the mixed dispersion with N775 observed around 30 days after the preparation

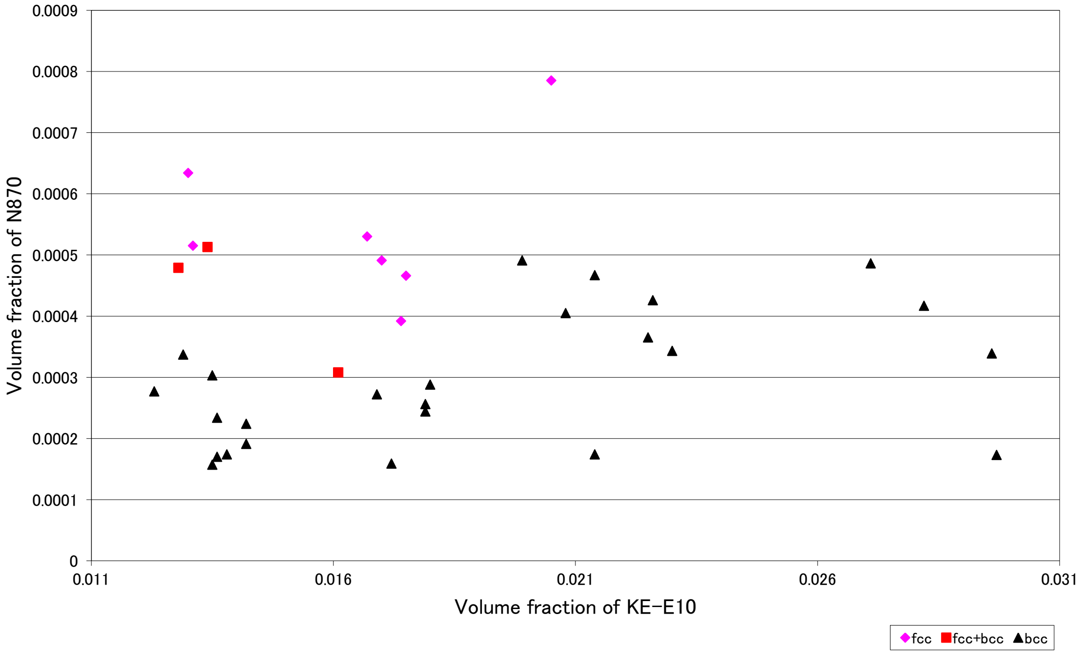



**Fig. 3(a)** Phase diagram for the mixed dispersion with N870 observed around several hours after the preparation

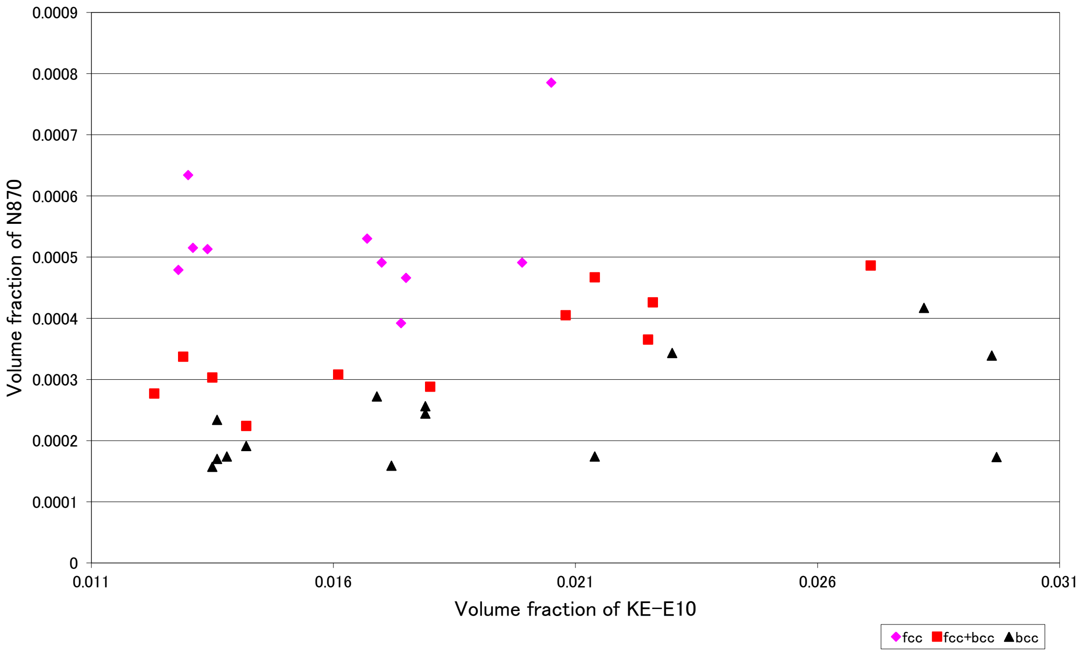



**Fig. 3(b)** Phase diagram for the mixed dispersion with N870 observed around 10 days after the preparation

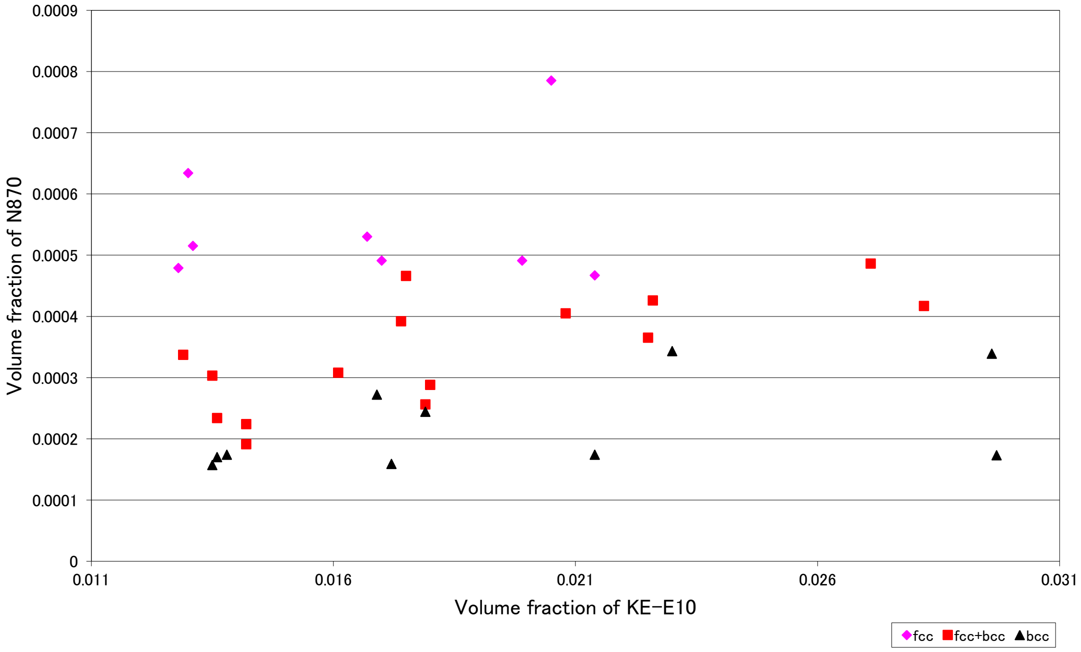



**Fig. 3(c)** Phase diagram for the mixed dispersion with N870 observed around 30 days after the preparation.

# 微小重力を利用した物理化学研究

○夏井坂誠（宇宙航空研究開発機構）

# Physical Chemistry Researches under Microgravity

○Makoto NATSUISAKA (Japan Aerospace Exploration Agency)

## 1. Physical Chemistry Researches under Microgravity

The presentation introduces physical chemistry researches under microgravity in Japan.

### 1.1 Honey Comb Film Formation under Microgravity

Masatsugu Shimomura (Tohoku University) etc. found that a dissipative structure where pores having a uniform diameter are regularly ordered ("honey comb film") can be obtained if steam is added to a casted polymer solution. Although the protocol is very simple, the uniformity and ordering of the pores are quite well (Fig. 1). The research team has tried to apply those to medical application and fabricated larger films. However, a kind of domain formation like a grain boundary in a polycrystalline is observed in some cases. The research team carried out parabolic flight experiments to reduce and/or avoid a natural convection considered to be a cause of this domain formation [1).

### 1.2 Photochemical Reactions in Super Critical $CO_2$

Yoshihisa Inoue (Osaka University) etc. revealed that an enantiodifferentiating photoisomerization affords chiral isomer and, when the photoisomerization is performed in supercritical $CO_2$, the enantiomeric excess shows a sudden leap in the near-critical density region, where the density fluctuation is known to maximize. This sudden leap is considered to arise from the difference in $CO_2$ clustering to the diastereomeric exciplex pair precursor to the enantiomeric products. The research team speculated that microgravity might stabilize density fluctuation in supercritical fluids and make the phenomenon described above enhanced and carried out parabolic flight experiments.

### 1.3 Colloid Research with Kikuchi Kossel Diffractometer

The research team organized by Ikuo Sogami (Kyoto Sangyo University) is interested in particle interactions in charged colloid dispersions. Crystal formations in those dispersions which occur when the salt concentrations are decreased were normally explained by DLVO (Derjaguin and Landau, Verwey and Overbeek) theory, but some observations like measurements of lattice spacing of the crystals, observation of gas-liquid coexistence state in colloid dispersions, and observation of void formations in colloid dispersions can not be explained by DLVO theory. Those suggest existence of a long range attractive interaction. The research team has prepared an ISS experiment by developing 'Kikuchi-Kossel' laser diffractometer (Fig. 2). Although this is simpler and more compact than small angle X-ray diffractometer, it can precisely measure crystal structures and lattice spacing.

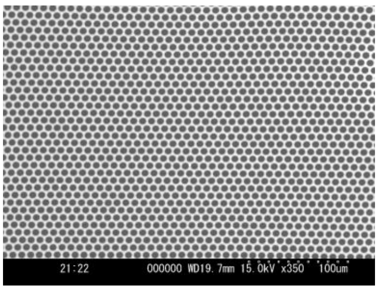



**Fig. 1** Honey comb film

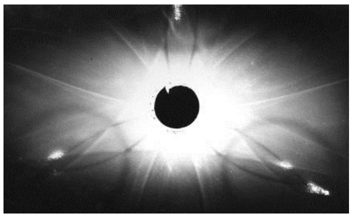


**Fig. 2** Kikuchi Kossel Diffraction

### 1.4 Exploration of Emulsion Stability under Microgravity

Kazutami Sakamoto (Chiba Institute of Science) etc. has tried to reveal basic mechanisms of emulsions' formation and those stabilities. Microgravity can make simplify those mechanisms by eliminating creaming and accordingly the research team plans to use microgravity environment. The research team has communicated with one of the European topical teams, PASTA (Particle Stabilized Emulsions and Foams) to establish a joint collaboration.

### 1.5 Impressionistic Physics of Bubbles, Drops and Foams under Microgravity

Ko Okumura (Ochanomizu University) etc. has investigated dynamics of bubbles, drops and foams via impressionistic physics which is a powerful way to find out simple laws from complex phenomena. Ko Okumura has started to attract considerable attention in the field through experiments performed with the Hele-Shaw cell (a quasi two-dimensional cell) so that he has been invited to join a number of topical teams of ESA; FOAM-C, PolarDrop and DOLFINE.

## References

1) Y. Hirai, M. Natsuisaka, T. Mashiko, M. Kanahara, Y. Saito, H. Yabu, M. Shimomura and K. Tsujii, Int. J. Microgravity Sci. Appl., **31**(2014), 3.

# 宇宙環境利用科学の将来展望と JASMA の役割

石川正道（日本マイクログラビティ応用学会会長）

# Current Issues of Promoting the Space-Environment-Utilization Science and the Role of JASMA

Masamichi ISHIKAWA (President, Japan Society of Microgravity Application)

## 1. Scope and purpose

JASMA has successfully boosted the science of space Environment utilization, especially in the field of material processing and physical science under the corporation of Japanese industry. The scientific outputs are comparable with those of Europe and USA, and contributing to the continuing execution of Japanese ISS program. Now, we are required to answer the next target and plan of microgravity program since the planned ISS experiments have gone favorably and the remaining number of experiments diminishes in the material and physical science, on the other hand the number of experiment concerning life/medical science is increasing.

In this session, the roadmap of microgravity applied science is overviewed by reviewing/discussing the outputs of ISS research, the emerging subjects of basic science, the educational aspects of microgravity utilization, the industrial enthusiasm in space tourism, etc. We are convincing that the JASMA's policy of using space environment to progress the science and technology of solving the societal problems is still active and the participation of society members is strongly anticipated in the panel discussion.

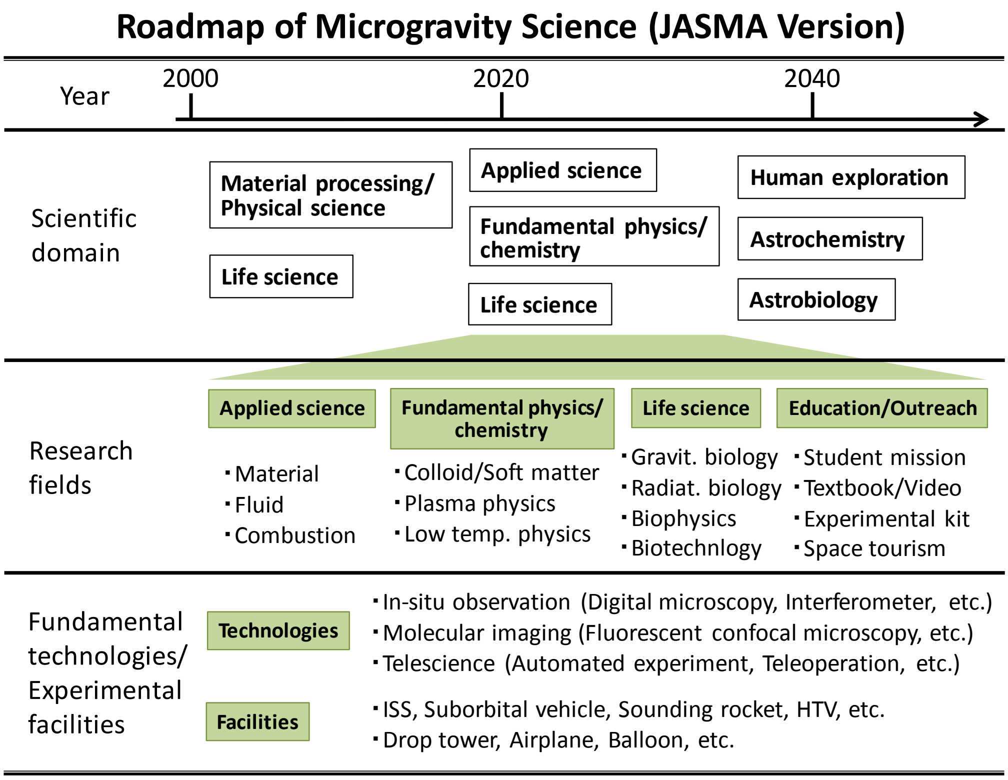
## 2. Issues to be addressed

(1) The present status and future plan of Marangoni convection research, as an example of the microgravity applied science. The discussion is put forward to the cases of crystal growth and combustion, etc.

(2) The search of new subjects in basic sciences (physics, chemistry and life science).

(3) The creation of education/outreach programs to disseminate the outcome of ISS research to the society.

(4) Panel discussion: the continuation of the existing research fields, the creation of new projects in the fields of basic sciences and education/outreach, and the JASMA's roadmap of microgravity applied science as shown in the Figure.



# マランゴニ対流研究を例とした宇宙実験の将来展望

○今石宣之（九州大学）

# Perspective of Future Space Experiments Based on Marangoni Flow Researches

○Nobuyuki IMAISHI (Kyushu Univ.)

## 1. Marangoni Flow Experiments In Space (MEIS)

From Aug. 20 2008 to Feb. 25 2013, five series of space experiments using large scale half zone liquid bridges of high Pr fluids were carried out in the FPEF (Fluid Physics Experimental Facility) onboard ISS Kibo to clear some ambiguities in Marangoni flow instabilities in liquid bridge. These series, MEIS1～MEIS5 (Marangoni Experiments In Space), were conducted by research groups headed by Profs. H. Kawamura and Nishino. MEIS project was first adopted in 1993 but its start fell largely behind schedule because of the delay in ISS construction. Recently, a quick review of MEIS 1 and MEIS2 was publishedl[1)]. The article reviewed Marangoni flow research activities and developments of experimental facilities.

Objectives of MEIS project can be summarized as follows:

1) Evaluation of the critical Marangoni number ($Ma_c$) for flow transition from a steady axisymmetric to 3-D oscillatory flow as function of liquid bridge size, aspect ratio, Pr number. and bridge shape (liquid volume).
2) Observation of the structure of the oscillatory flow by means of. 3D-PTV system, photo-chromic dye surface velocimetry and IR camera.
3) Observation of flow transition process from steady flow to periodic oscillatory flow and further to chaos/turbulent flow.
4) Possibility of Particle Accumulation Structure (PAS) in liquid bridge and semispherical hanging drop under μG condition.

These experiments can be done only in FPEF onboard ISS which allows large size liquid bridge (diameter up to 50mm and aspect ratio up to 2.0), large temperature difference and long evolution time for weak disturbances to grow up to detectable 3-D oscillatory flow state.

So far, published MEIS results suggest that the objectives of the program were successfully achieved. Results indicate that the size dependency of $Ma_c$ is much smaller than those of the previously reported $Ma_c$ obtained by short time μG experiments. This reveals that too fast temperature ramping rate causes significant delay the growth of the disturbances and increases the observed $Ma_c$ and also the hydrothermal wave instability is the main mechanism of the instability. However, more detailed works on the effects of aspect ratio, surface shape, Pr number and heat exchange with the ambient atmosphere on $Ma_c$ and flow modes are necessary. More results of MEIS will be reported as soon as the team finishes analyses of the huge data set sent/returned from space.

## 2. Marangoni flow experiment projects after MEIS

After MEIS program, Dynamic Surf. project (Dynamic Surface Deformation Effects in Transition to Oscillatory Thermo-capillary Flow in Liquid Bridge of High Prandtl Number Fluid) was adopted at the 1st IAO (2000) and it's experiments are now in progress on board ISS.

For the sake of effective use of FPEF, an ITT proposed JEREMI project (Japanese-European Research Project on Marangoni Instability) expecting launching a modified liquid bridge system, in which the ambient atmosphere is much better defined, in date of 2016. In these projects, the effects of the dynamic deformation of the liquid bridge surface and heat/momentum transfer through the liquid surface on $Ma_c$ and flow modes will be quantitatively evaluated.

## 3. Possible future works

MEIS experiments revealed that transition process from 2-D axisymmetric steady flow to oscillatory and further to chaos based on the local surface temperatures by using IR camera and thin thermocouples. Under large temperature differences, the flow may become turbulent. Analysis of such thermocapillarity-driven turbulent flow, if any, will open a quite unique field in fluid physics. Quantitative discussion on such turbulent flow requires correlations of local temperature and velocities in the bulk as well as on the surface. However, present FPEF has no such device to measure these local values. Under very large temperature difference, fluctuation of local temperature causes large distortion of image and optical path of laser-Doppler system and gives big noise for a hot-wire anemometer. Development of new velocity measurement system is essential. Such a velocity measurement system will be effectively applied to various fluid dynamics researches and also to crystal growth research.

Accomplishment of space experiments needs long-term collaboration and discussions in the project team made up of experts in various fields to develop new concept, new devices and highly sophisticated modeling and theoretical/numerical analyses.

## References

1) "Review of MEIS experiments", Int. J. Microgravity Sci. Appl., **31** Suppleme nt (2014).

# 宇宙環境利用科学ロードマップの策定に向けて

○稲富裕光，足立聡，橋本博文，石岡憲昭（ISAS/JAXA）

# Toward Establishment of Roadmap for Space Environment Utilization Science

○Yuko INATOMI, Satoshi ADACHI, Hirofumi HASHIMOTO and Noriaki ISHIOKA (ISAS/JAXA)

## Scope and purpose

The Global Exploration Roadmap shown in Fig. 1 is being developed by space agencies participating in the International Space Exploration Coordination Group (ISECG) [1]. The roadmap builds on the vision for coordinated human and robotic exploration of our solar system that was established in The Global Exploration Strategy: the Framework for Coordination (May 2007). The roadmap reflects a common long-range human exploration strategy that begins with the ISS and expands human presence into the solar system, leading to human missions on the surface of Mars. The ISS provides the opportunity for research and technology demonstrations which benefit from its unique location. It is also the foundation of exploration, advancing critical capabilities to take humans further into space and reducing the cost of human space flight.

Steering Committees for Space Science and for Space Engineering of ISAS/JAXA are now drawing up a roadmap for space science and exploration in Japan since June, 2013. In the framework of the roadmap future space experiment missions related to space environment utilization science will be mainly categorized as small-scale projects adopted by competitive environment in ISAS. It means that the competitors will be challenging missions of space science and space engineering.

On the other hand it is the fact that the concrete future plan that looked ahead to for ten years and 20 years later in Japan has not been discussed in the space environment utilization science. Figure 2 shows a draft idea of a future road map for space life science [2] for reference. However, even for the research field, clarification of the implement priority of the space mission will be strongly required in a limited budget of JAXA. For the breakthrough it goes without saying that the related research communities should work out a crossover and comprehensive plan for the future. In the present symposium the authors would like to discuss establishment of a road map for microgravity sciences with the members of JASMA.

## References


1) http://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf

2) N. Ishioka: J. Jpn. Soc. Microgravity Appl., **28** (2011) 124.

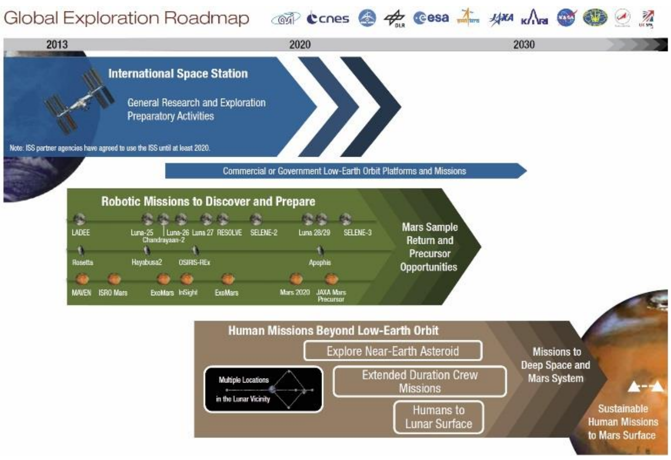




**Fig. 1** Global Exploration Roadmap [1].

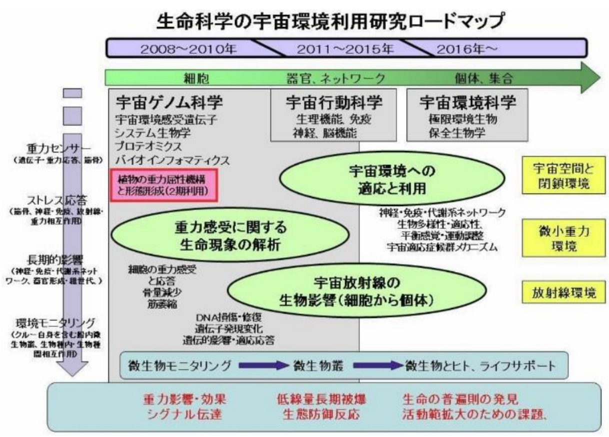



**Fig. 2** Future roadmap for space life science research [2].

# 技術と科学の共生：微小重力研究の教育的成果

○中村祐二（豊橋技科大）

# Co-operation of Engineering and Science: Educational Outcome brought by Microgravity Researches

○Yuji NAKAMURA (Toyohashi Univ. Tech.)

## 1. Introduction

When we talk about the "microgravity (-utilized) research", it contains at least two issues. Generally, one is pure science outcome and the other is technological/engineering supports to make the scientific outcome is effectively done. With this regards, these two issues always co-exists as *essential* items and they are "inter-dependent" pair. In other words, either of them cannot be self-stand and there is no superiority to grade them. Let us consider the effectivity this feature in education.

## 2. Interdependency of Science and Engineering

Fig. 1 summarizes how they are inter-dependent. In the left path in Fig.1, it is shown how to achieve pure scientific outcome assisted by engineering development (e.g., hardware, measurement system) as typical example. Similarity, we can find the right path such as the engineering problem should be solved under microgravity environment assisted with microgravity researches. This is demanded when manned mission or long-term stay in space is the target. As it is understood, any topic in space science (left path) as well as space engineering (right path) should need microgravity environment and interdependency of science and engineering. In this sense, space-utilization engineering (in Japanese, 宇宙環境利用工学) should stand separately to hold such interdependency feature.

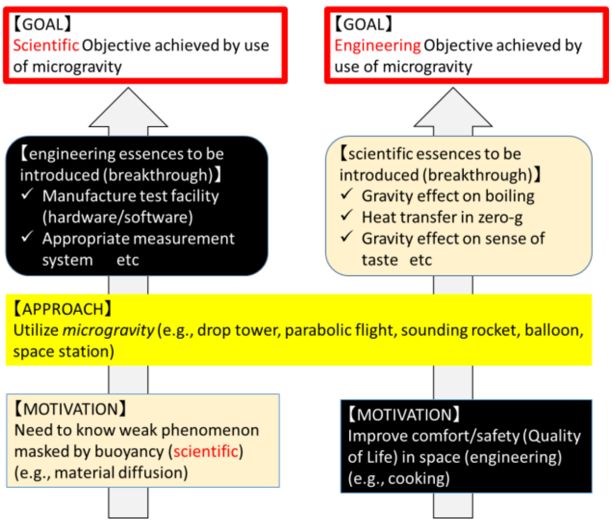



**Fig.1** Interdependent of science and engineering in microgravity-utilized research.

## 3. Impact in Education

Recently, Japanese Ministry of Education (MEXT) encourages engineering universities to develop the new educational program to develop "needs-oriented", not conventional "needs-oriented" type of graduates. To do so, it is necessary to have "sense" of back-tracing the problem (consider what is the necessary task to fulfill the goal deeply and pick the right essences to dig with). To do so, interdependent problem is a good example for training. In this sense, microgravity research (especially, engineering goal path) shall be considered as effective "tool" for future engineers' education.

Let me give one example for engineering problem in space; such as cooking. Fig.2 shows the illustration of cooking of egg (sunny-side-up). Under normal gravity, egg is pushed over the hot plate and large area is spread to receive the heat from the plate. Hot plate is heated by flames uniformly assisted by buoyancy-induced flow so that cooking performance is good and easy. Under microgravity, on the other hand, no force to push the egg toward the plate so that heated area should be much smaller. In addition, flame in reduced gravity does not good to heat up the plate uniformly. Obviously the same design/strategy of cooking might not work. To propose new design of cooking in space (as real "engineering" problem), we must know the heat transfer and boiling phenomena in reduced gravity as essential matter. Without the sufficient scientific knowledge, it would be impossible to make this happens.

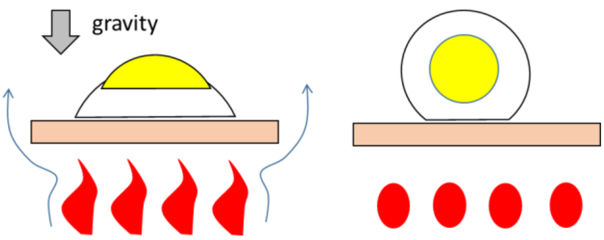



**Fig.2** Cooking eggs in normal gravity (left) and microgravity (right)

## 4. Remarks

Microgravity researches are basically inter-dependent problems of science and engineering, it must be unique as well as strong educational "tool" to train ones to be professional engineers. Appropriate scheme (educational program) utilized of microgravity research is welcome to propose.

# 微小重力実験の共同作業型課題としての活用範囲の広がり

○森義仁（お茶大）

# Widening Application of Microgravity Experiments to Teamwork-solved Subjects

○Yoshihito MORI (Ochanomizu University)

## 1. Teamwork to Solve Complicated Subjects

The subjects to be solved are becoming complicated in the academic and industrial worlds and the cooperative teamwork activity made by the group consisting of the members coming from the various areas is required to solve them. The members are expected to train in the suitable programs.

The teamwork training programs frequently appear in engineering education but less in science education. Then we try to think what kinds of the effective training programs can be prepared in science education. An idea is to employ microgravity experiments as the subjects and some tested example can be shown in the present talk.

## 2. The Related Examples in Education

### 2.1 Undergraduate Student Academic Activity

In science education, there is less teamwork activity programs because in the scientific research situation an individual research subject is typically given to a student.　Before 2014, a good opportunity was prepared as a teamwork-solved subject for undergraduate students. It's the microgravity experiment contest for Japanese and Asian students. There students meet together, show their ideas, discuss them each other to come to the single proposal. When the proposal is accepted they start to make an experimental instrument (Fig.1) and optimize the experimental conditions to get the goal by conducting expected experiments in a parabolic flight.

### 2.2 Campus Festival

A student campus festival is a traditional event in a university. In these years, more academic exhibitions have appeared there, for example the presentations of the researches about the worldwide environmental issues, the report about the aid activity for developing countries and so on. One of those was the ten-year history of the microgravity experiment contest (Fig.2). There the 60 accepted proposals in the ten years was showed and the 0.1-sec microgravity situation was demonstrated with the instrument, FUWATTO-KUN, which a 2-m drop tower. The movies and photographs relating to the microgravity experiments were projected. In particular, much attention was attracted by the collaborations between the microgravity experiments and art, which were the microgravity dance motivated by the ancient art and the sound sculpture of the floating particles. It generally seems that an opportunity of the microgravity experiments is available for undergraduate students in science and engineering but it actually opens to the other areas. The collaborations between the microgravity experiment and art make non-science and non-engineering students feel the microgravity experiment more familiar.

### 2.3 High School and University Collaboration

In these years, we can find richness of diversity in collaborations between high schools and universities to prepare the highly potential human resource to bring the developments in our country. There are many types of programs and an expected and potential program is group-working activity on the microgravity experiment. Figs.3 and 4 shows the program prepared for the high school student by the host university. The lecture of the parabolic flight microgravity experiments was given to the students and the student met the 60-year history of the microgravity experiment contest with the demonstration with the "FUWATTO-KUN". The high school student groups tried to make an original experiment proposal.

## 3. Perspectives

Although the microgravity experiment contest was stopped, we confirmed that there was the high effectiveness to motivate young undergraduate students. The two rest examples of the student campus festival and the high schools and universities collaborations can be expected as the good teamwork-solved subjects.

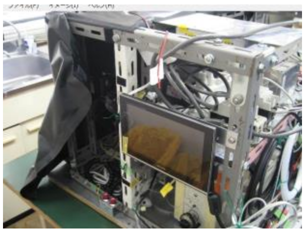


**Fig.1** Assembled machine

**Fig.2** Campus Festival

**Fig. 3** Group-working

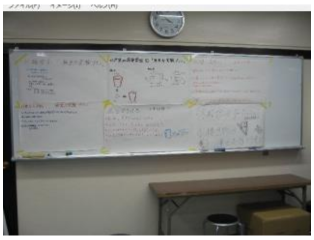


**Fig. 4** Proposals

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# ISS 利用 TPF 沸騰二相流実験
# その１．概要

○大田 治彦，新本康久，廣川 智己(九州大学)，浅野 等(神戸大学)，河南 治(兵庫県立大学)，
鈴木 康一(山口東京理科大学)，今井 良二(室蘭工業大学)，
岡 利春，友部 俊之，宇宿 功史郎，島田 雅喜(IHI エアロスペース)，
松本 聡，栗本 卓，高岡 秀充，坂本 道人，川崎 春夫，澤田 健一郎(宇宙航空研究開発機構)

# Experiments of Boiling and Two-phase Flow Onboard ISS: 1. Outline of Experiments

○Haruhiko OHTA, Yasuhisa SHINMOTO, Tomoki HIROKAWA (Kyushu Univ.),
Hitoshi ASANO (Kobe Univ.), Osamu KAWANAMI (Univ. of Hyogo),
Koichi SUZUKI (Tokyo Univ. of Science, Yamaguchi), Ryoji IMAI (Muroran Institute of Technology),
Toshiharu OKA, Toshiyuki TOMOBE, Koushiro USUKU, Masaki SHIMADA (IA),
Satoshi MATSUMOTO, Takashi KURIMOTO, Hidemitsu TAKAOKA, Michito SAKAMOTO,
Haruo KAWASAKI, Kenichiro SAWADA (JAXA)

## Abstract

Boling experiments under microgravity conditions are useful for understanding of interfacial phenomena and heat transfer under the terrestrial condition in addition to their application to the innovative two-phase thermal management systems for space development. To obtain the reliable and coherent data for the gravity effects on flow boiling, space experiments onboard ISS are to be performed. There are three targets: (i) To clarify gravity effects on heat transfer coefficients and critical heat fluxes in a wide range of flow and heating conditions, (ii) To clarify the mechanisms of heat transfer in various flow regimes under microgravity conditions, (iii) To establish a dominant force regime map by the clarification of exact boundaries between the buoyancy-, inertia- and surface tension- dominated regimes. The above subjects are schematically shown in Figs.1-4. Two heated sections of a metal tube or transparent tubes[1] is switched in orbit as shown in Fig.5. The former is prepared for the measurement of detailed heat transfer data and critical heat fluxes, while the latter is developed for the data acquisition with real-time interfacial observation under selected experimental conditions. In the downstream of both heated sections, non-heated test sections are connected for the detailed observation of interfacial behaviors by using high -speed cameras. Table 1 shows experimental conditions. An engineering model was already developed, and a flight model is under development. A series of experiments in orbit is scheduled in 2016.

## Acknowledgement

The authors express appreciation for the support of TPF project by JAMSS, JSF, and for the contribution by Prof. Kiyosumi Fujii in Nara Institute of Science and Technology moved from JAXA.

## Reference

1) H. OHTA, Microgravity Heat Transfer in Flow Boiling: Advances in Heat Transfer, **37**, 2003, 1.

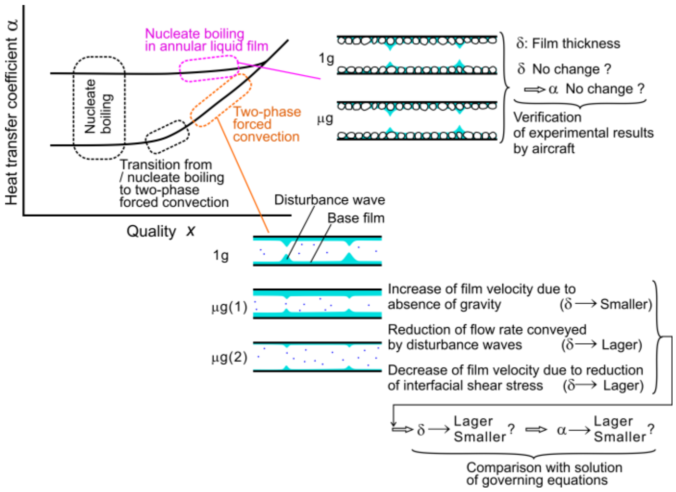


**Fig. 1** Effect of gravity on heat transfer (1/2).

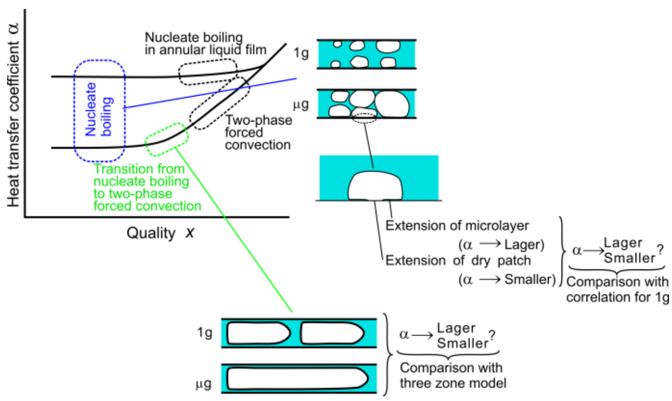


**Fig. 2** Effect of gravity on heat transfer (2/2).

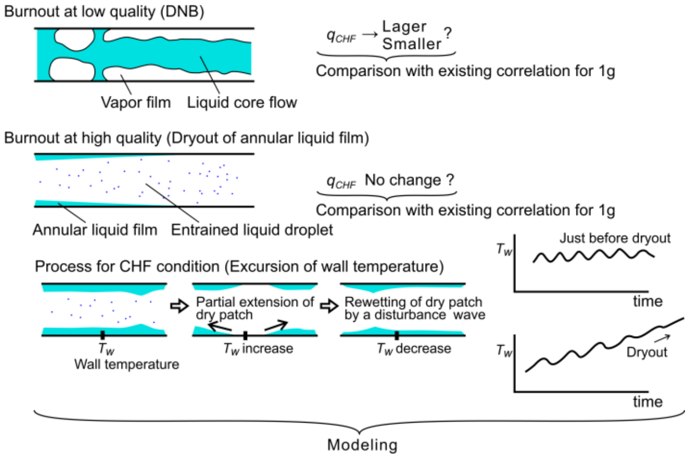


**Fig. 3** Critical Heat Flux conditions.

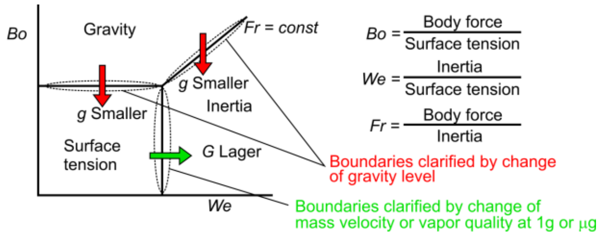


**Fig. 4** Dominant force regime map.

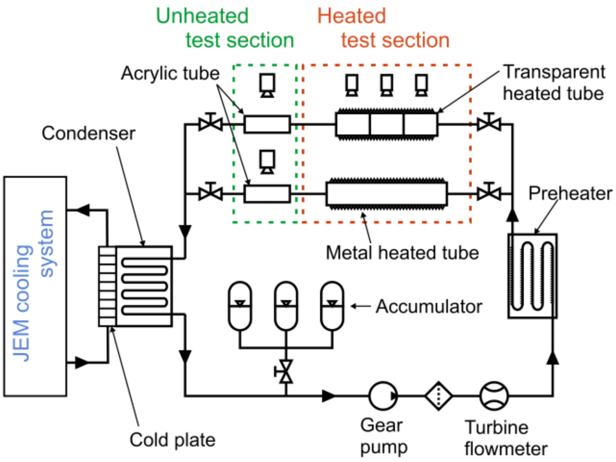


**Fig. 5** Outline of test loop for ISS flow boiling experiment "TPF".

**Table 1** Experimental condition for flow boiling onboard ISS.

| | |
|---|---|
| Power supply | 250 W |
| Test fluid | n-perfluorohexane |
| Inner diameter of heated tubes | $d_i$ = 4 mm |
| Heated length | $I$ = 50 mm × 2 and 5 mm × 1 for transparent heated tube<br>$I$ = 368 mm for copper heated tube |
| Mass velocity | $G$ = 30 – 600 kg/m$^2$s |
| Inlet liquid subcooling | $\Delta T_{sub}$ = 0 – 30 K |
| Vapor quality range | $x$ = 0 - 0.9 |
| Heat flux | $q$ = 1 – 400 kW/m$^2$ |

27A02

# ISS 利用 TPF 沸騰二相流実験　その２．実験装置の開発

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## Experiments of Boiling and Two-phase Flow Onboard ISS: 2. Development of the Experimental Equipment

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### 1. Introduction

Recently, because of increase in the space platform size and its power consumption, the amount of waste heat has become larger. Boiling and two-phase flow becomes powerful means for this system, because boiling is one of the most efficient modes of heat transfer due to phase change. Therefore, the experiment on boiling and two-phase flow under microgravity conditions is proposed and selected as a candidate subject of ISS experiments[1].

In this paper, the test results of the Engineering Model (EM) for the microgravity experiment in order to verify the performance and feasibility to be used in the International Space Station (ISS), and the some improvements in the Proto Fright Model (PFM) are reported.

### 2. Experimental Equipment

Two-Phase Flow Experiment Equipment (TPF-EE) is shown in Fig.1. The dimension is 500 x 800 x 650 mm and the mass is 140 kg. TPF-EE is accommodated in the Work Volume (WV) of the Multi-purpose Small Payload Rack (MSPR) onboard the ISS/Kibo.

The test loop has two different heated sections, i.e. transparent heated tube and metal heated tube, in which pure normal-perfluorohexane is used as test fluid. Using this apparatus, we intend to perform the experiment of the heat transfer with boiling flow. At the same time, we study the mechanism of liquid-vapor behaviors in two-phase flow under the microgravity conditions.

### 3. Results

Several tests using the EM revealed some problems. One of the problems was the pressure fluctuation in the circulated fluid. Figure 2 shows the pressure oscillation with the applied voltage to the pump. It reveals that the pressure oscilllation increases with applied voltage being more than 4V. Since the vibration of the pump has been identified as the cause, its axial alignment and material of the axial bearing were reviewed.

On the fabriation of the PFM, we have made some improvements in the parts of TPF-EE in order to satisfy the scientific and safety requirments.

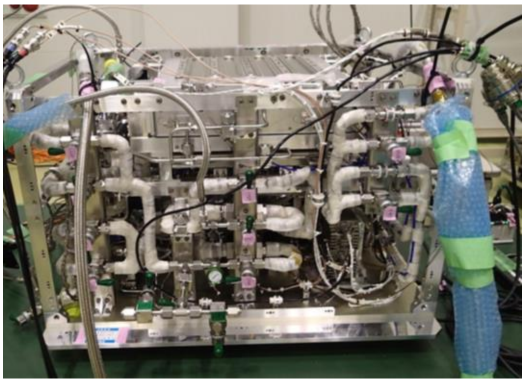

**Fig. 1**　Picture of the Engineering Model.

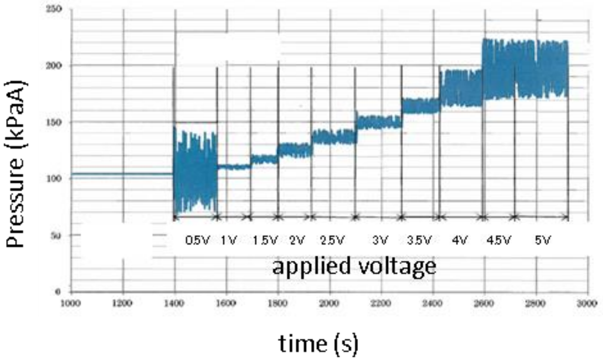


**Fig. 2**　Pressure fluctuation with applied voltage to the pump

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# ISS 利用 TPF 沸騰二相流実験
## その 3. 蒸発部の開発

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# Experiments of Boiling and Two-Phase Flow Onboard ISS:
## 3. Development of Evaporation Section

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Koushiro USUKU, Masaki SHIMADA (IA), Satoshi MATSUMOTO, Takashi KURIMOTO,
Hidemitsu TAKAOKA, Michito SAKAMOTO, Haruo KAWASAKI, Kenichiro SAWADA (JAXA)

## 1. Introduction

Boiling and two-phase flow loop system can be achieved high-performance heat exchange and heat transfer for the thermal management of space system. However, boiling phenomena in microgravity is unclear until now. Authors plan two-phase and flow boiling experiment as called “TPF”, onboard “KIBO”, which is Japanese Experimental Module in the International Space Station. Systematic experiments on flow boiling and two-phase flow will be performed by using long-term microgravity period in ISS for establishment reliable database, which is required for the design of the thermal management in the future space system.

Here, we report the evaporation sections in the TPF loop as shown in **Fig. 1**: the copper heated tube section and the transparent heated tube section will be illustrated.

## 2. Evaporation Sections

**Fig. 2** shows images of the copper heated section and the transparent heated section. The heated length of the copper tube is 363 mm, and inner diameter of the tube is 4 mm. The outer wall of the tube is covered by two metal heaters; main and sub heaters. 10 thermocouples are installed at 0.5 mm location from the inner-wall surface.

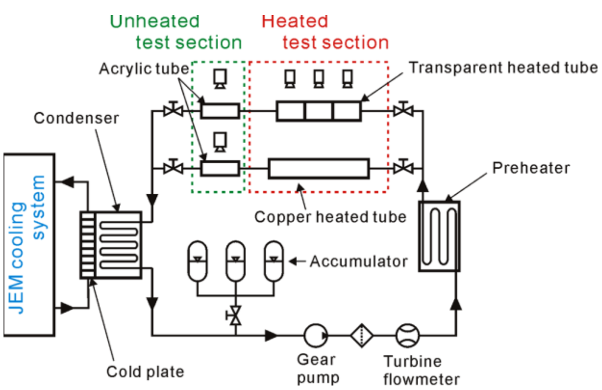


**Fig. 1** Outline of test loop for ISS flow boiling experiment.

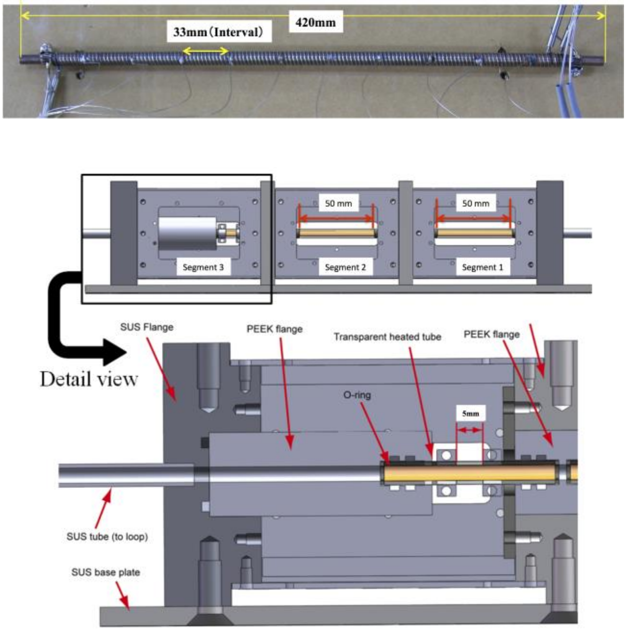


**Fig. 2** Images of the metal heated tube section (Top) and the transparent heated section (Bottom).

In the ISS experimental loop, three transparent heated tubes, segment 1, 2 and 3, are installed as an evaporating part. The heated lengths of each segment are 50 mm for segment 1 and 2 and 5 mm for segment 3. The inner diameter of all tube is 4 mm with 1 mm wall thickness, and the inner-wall of the tube is covered by extremely thin gold film as using not only a heater but also resistance thermometer, that is, the averaged inner-wall temperature entire heated length can be measured. At the same time, gas-liquid behavior of flow boiling can be observed through the gold film on the wall.

The single-phase heat transfer results of transparent heated section in the EM facility test shows in **Fig. 3**. In laminar and turbulent flow regions, the experimental results have a good

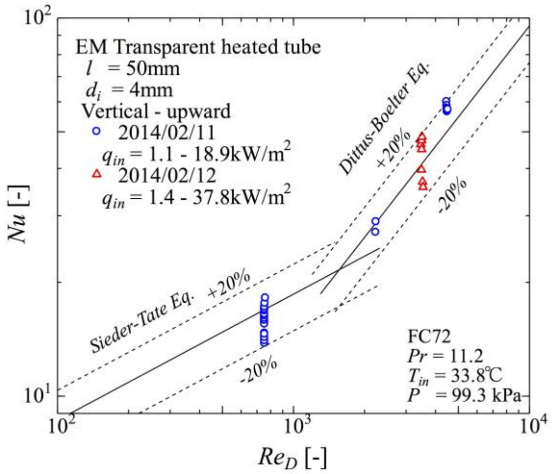


**Fig. 3** Single-phase heat transfer at Segment 1 in the transparent heated tube section.

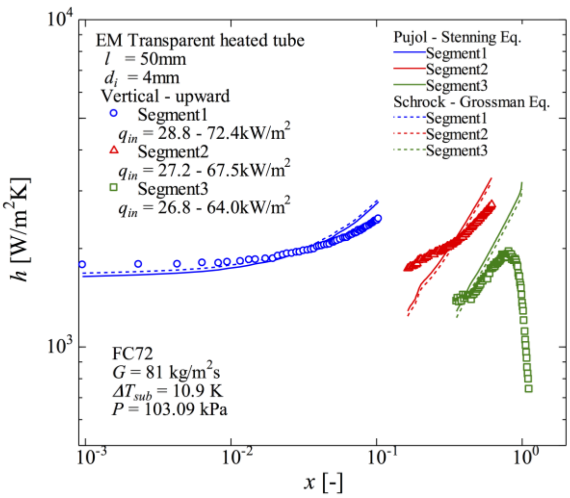


**Fig. 4** the relation between exit quality and heat transfer coefficients at each segment during flow boiling experiment by using transparent heated test section in EM facility.

agreement with Sieder-Tate and Dittus-Boelter equations.

**Fig. 4** shows the relation between exit quality and heat transfer coefficients at each segment during flow boiling experiment by using transparent heated test section in EM facility. At segment 3, the abrupt decrease of heat transfer coefficient caused by dryout could be found. The value of critical heat flux at segment 3 was 52 kW/m$^2$. It is coincide with 55.6 kW/m$^2$ derived from Katto's equation.


## Acknowledgement

The authors express appreciation for the support of TPF project by JAMSS, JSF, and for the contribution by Prof. Kiyosumi Fujii in Nara Institute of Science and Technology moved from JAXA.

27A04

# ISS 利用 TPF 沸騰二相流実験
# その４．観察部での気液界面構造の計測

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島田 雅喜（IHI エアロスペース），松本 聡，栗本 卓，高岡 秀充，坂本 道人，川崎 春夫，
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# Experiments of Boiling and Two-Phase Flow Onboard ISS
# 4. Measurements of Gas-Liquid Interface Structure at the Observation Section

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Osamu KAWANAMI (Uni. of Hyogo), Koich SUZUKI (Tokyo Univ. of Science, Yamaguchi),
Ryoji IMAI (Muroran Institute of Technology), Toshiharu OKA, Toshiyuki TOMOBE, Koushiro USUKU,
Masaki SHIMADA (IHI Aerospace), Satoshi MATSUMOTO, Takashi KURIMOTO, Hidemitsu TAKAOKA,
Michito SAKAMOTO, Haruo KAWASAKI, Kenichiro SAWADA (JAXA)

## Abstract

Flow visualization of vapor-liquid two-phase flows is important to understand heat and flow characteristics. In reduced gravity and low mass velocity condition, flow structure will be much different from that in the normal gravity condition. Two-phase flow observation sections are installed to visualize gas-liquid interface structure with high spatial and temporal resolution.

Observation test section is placed at the just downstream of each heating section as shown in **Fig. 1**. The channel diameter of the observation section is the same as the heating section at 4.0 mm, and the observation section is smoothly connected to the heating section. Requirements on the observation section are three-dimensional measurement of interface structures in two-phase flows, bubble velocity in intermittent flows, wave velocity in annular flows, void fraction, and pressure loss. For three-dimensional observation, a method of stereoscopic photography by which two images from two orthogonal directions can be photographed by one camera is applied. The optical system consists of one high frame rate video camera, four metal mirrors, two LED lighting for the back-lighting. The arrangement of the optical equipment is shown in **Fig. 2**. The test section was a square pole of transparent polycarbonate to avoid the refraction at the outside surface. A circular channel with 4 mm in diameter was drilled at the center of the square pole.

Examples of photographed images are shown in **Figs. 3 (a) and (b)**. These images were taken with the frame rate of 1000 fps. The size of image pixel was about 28 μm. The three-dimensional structure of vapor-liquid interface could be visualized well. In Fig. 2 (a), bubble positions and their shapes were clearly visualized. In Fig. 2 (b), liquid film structure, especially the difference in film thickness along the flow and circumferential directions, are clearly visualized.

To evaluate the accuracy in the measurement of sizes, such as liquid film thickness, bubble diameter, moving distance, two methods of the calibration were conducted. The first is a static method using a stainless steel rod with various diameters. The rod configuration is shown in **Fig. 4**. The rod was inserted in the tested tube filled with the liquid FC72 to form simulated liquid films as shown in **Fig. 5**. Measured values of the thickness from the image are compared with given thickness from the difference between the inner diameter and the rod diameter. The compared results is shown in **Fig. 6**. It can be seen that the actual size can be measured from the image with ± 4 % accuracy.

Next, measured results of time-average void fraction from the continuous images of two-phase flows were compared the values measured by a quick closing valve method. The compared results is shown in **Fig. 7**. It can be seen that the void fraction can be measured from the image with ± 5 % accuracy.

## Acknowledgement

The authors express appreciation for the support of TPF project by JAMSS, JSF, and for the contribution by Prof. Kiyosumi Fujii in Nara Institute of Science and Technology moved from JAXA.

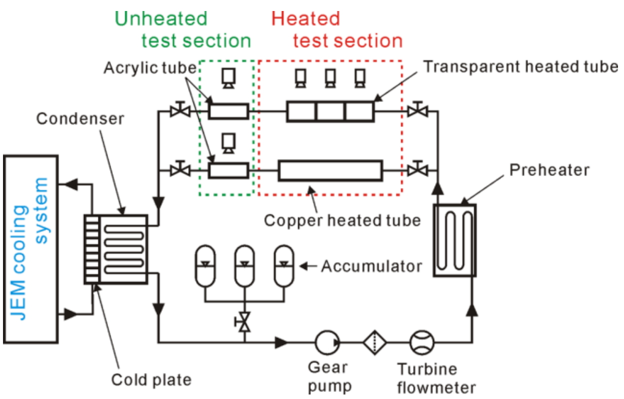



**Fig. 1** Outline of test loop for ISS flow boiling experiment.

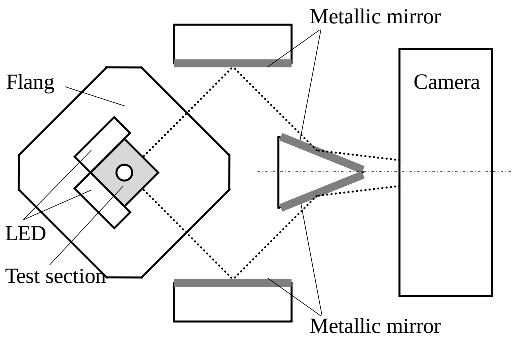
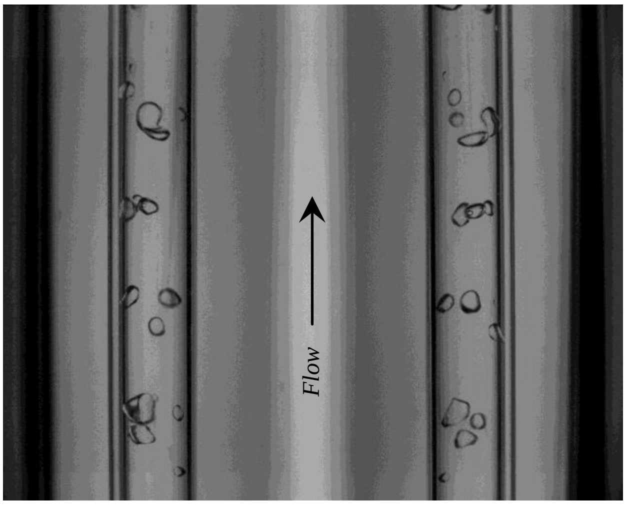
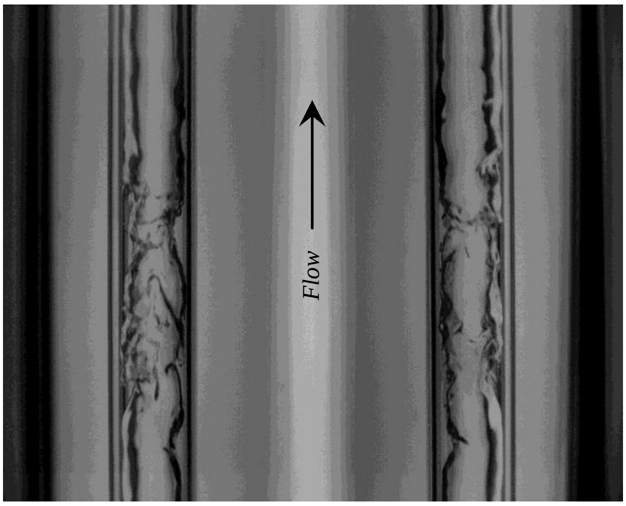



**Fig. 2** Arrangement of the optical system.




(a) Mass flux : 300 kg/(m$^2$s)




(b) Mass flux : 200 kg/(m$^2$s)

**Fig. 3** Examples of the photographed images.

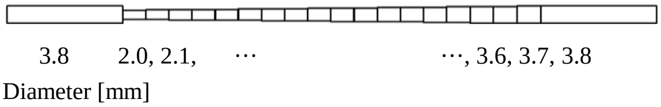



**Fig. 4** SUS rod with various diameter for calibration.

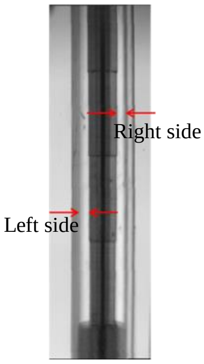



**Fig.5** Image of channel with calibration rod.

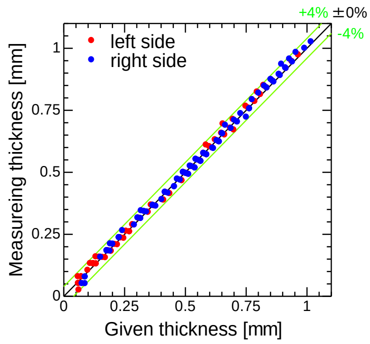



**Fig.6** Comparison of liquid thickness between measured result from image and given values using calibration rod.

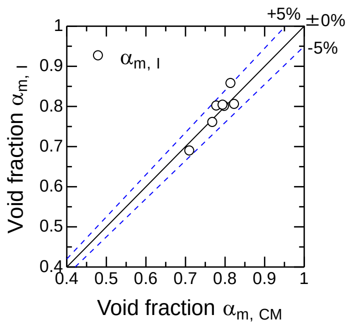



**Fig. 7** Comparison of average void fractions between the measured results from the observed images, $\alpha_{m,I}$, and the results by a quick closing valve method, $\alpha_{m,CM}$ .

## References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27A05

# ISS 利用 TPF 沸騰二相流実験　その 5．凝縮器の開発

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# Experiments of Boiling and Two-Phase Flow Onboard ISS: 5. Development of Condenser

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## 1. Introduction

On the manned spacecraft or facility, thermal management, such as heat transport and heat rejection is one of the essential technology to be established. Especially two phase thermal management technology utilizing latent heat transport is favorably effective for the application to a large scale spacecraft system in future since the high amount heat transport and rejection are practiced by less flow rate of working fluid.

The project on two-phase boiling flow experiments has been carried out as the so-called TPF “Two Phase Flow” promoted by JAXA for these several years. In this project, interfacial behaviors and heat transfer characteristics in boiling two-phase flow under microgravity condition will be investigated. The heat generation in the boiling test section including heat supplied into the working fluid must be transported to ISS thermal management system through the condenser assembled on this experimental test loop.

The present paper introduces the thermal design and the evaluation test for the condenser system.

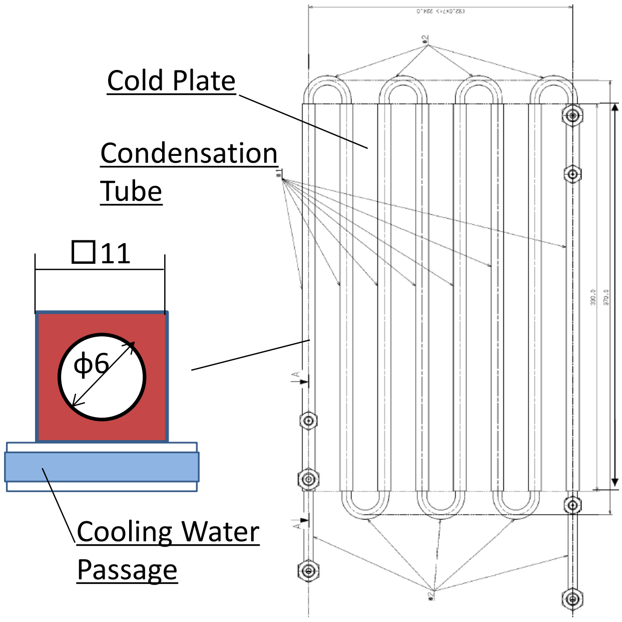



**Fig.1** Structure of condenser for TPF experimental fluid loop

## 2. Structure of condenser for TPF experimental loop

The condensing tube was assembled on a flat type cold plate which had employed for on-orbit system and high reliability in practice. Figure 1 shows structure of the condenser. The condenser is square rod of 11mm ×11mm with a circular flow path of 6mm in diameter. Each rod is connected by U-shape tube. The square tube is made of copper in order to realize less thermal resistance by the high thermal conductivity of wall section. High heat conductive adhesion is used for the joint surfaced between the condenser tube and the cold plate. In the condenser system, fluid temperature at inlet/outlet of hot side as well as tube wall are planned to be measured in order to obtain local and overall condensation heat transfer coefficient.

## 3. Arithmetic thermal model of condenser

Figure 2 shows an arithmetic thermal model for the condenser. It is considered that one dimensional thermal path is applied from fluid in the condenser tube to cold water in the cold plate through the condenser tube wall, the adhesion, and the cold plate wall to obtain thermal resistance by thermal conduction and heat transfer. The condensation heat transfer coefficient under microgravity condition is given as a half value from the empirical equations for the ground based condition. The half value is assumed from the fact that the condensation length under microgravity is twice as long as under 1-g condition by the numerical calculation[1]. Thermal resistance through condenser tube wall is calculated through two dimensional thermal conduction analysis. Fluid temperature, quality, and local pressure are calculated via above thermal resistances.

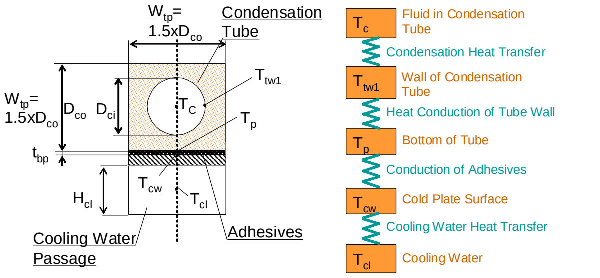



**Fig. 2** Arithmetic thermal model of condenser structure of condenser

Numerical calculation was conducted by the arithmetic thermal model on the following conditions shown in Table 1.

**Table 1** Data for numerical calculation

| | | |
|---|---|---|
| Fluid | Hot Side | FC-72 |
| | Cold Side | Water |
| Hot Side | Inlet Pressure | 0.103MPa |
| | Inlet Temperature | 55.7 C |
| | Inlet Quality | 1.0 |
| | Mass Flow Rate | 0.0042kg/s |
| Cold Side | Inlet Temperature | 23C |
| | Mass Flow Rate | 45kg/h |
| | Heat Transfer Coefficient | 2000 W/m2/K |
| Condenser Tube | Inner Diameter | ϕ6mm |
| | Length | 2m (ϕ6mm) |

We provided the additional following condition as required specification for the condenser;

Outlet sub-cool temperature is 10K at 400W for the equivalent mass flow rate. This condition was determined in consideration of measured suction performance of mechanical pump.

Figure 3 shows the distribution of thermal resistance on flow path. The thermal resistance by condensation increases toward downstream section since the condensation liquid film becomes thicker as shown in Figure 3. We can see that other major thermal resistance is achieved in the cold water passage, and that the resistance at the tube wall and the adhered portion between the condensation tube and the cold plate are sufficiently small. It is found that the thermal resistance on condensation side is dominant at the downstream.

Figure 4 shows distribution of fluid temperature and sub-cool temperature with tube length in the hot side passage. It is confirmed in the experiments that 9K in sub-cool temperature for the 6mm-tube and 14K for the 4mm-tube are obtained, which indicated achievement of our target. We had already confirmed that the cold plate had enough area to install the condensation tube with required length.

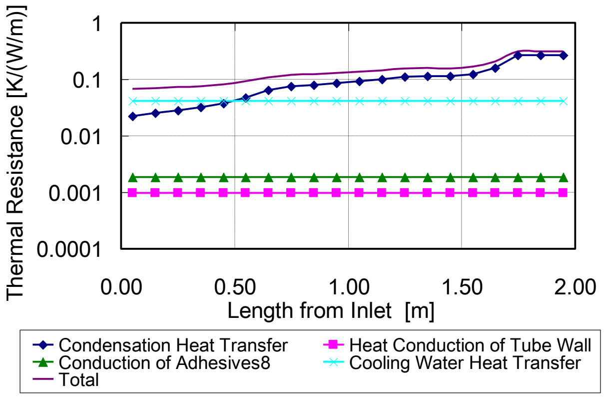
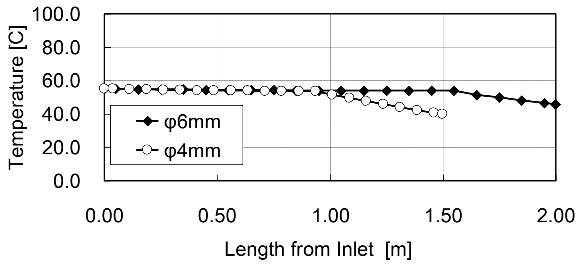
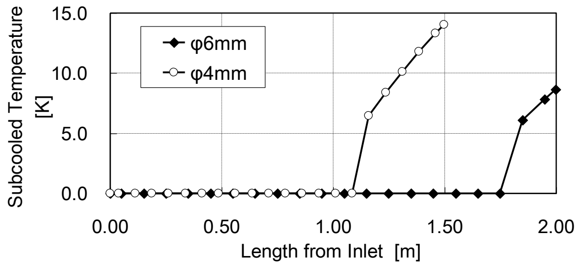



**Fig.3** Thermal resistance at local point




(a)Temperature in condensing tube




(b)Sub-cooled temperature in condensing tube

**Fig.4** Temperature and sub-cool temperature resistance at local point

## 4. Results of evaluation test for BBM condenser on ground based condition

BBM test on ground based condition was carried out to confirm performance of condenser.

Test loop for the condenser system is shown in Fig.5. Working fluid, FC72, circulates the condenser loop from a heating bath shown in Fig.5. Steam of FC72 is supplied into the condenser tube from a steam generator at a quality of 1.0. Cooling water of 23ºC flows into the cold plate and heat is exchanged between the cold plate and the condenser tube. Heat loss from the condenser tube is calculated the fluid flow rate and the temperature difference between inlet and exit of the tube. The working fluid is condensed completely and turns to liquid at the exit of condenser tube. Heat gain of the cold plate is also calculated by water flow rate and temperature difference between inlet and exit of the cold plate.

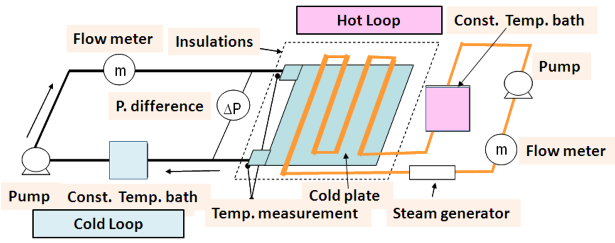



**Fig.5** Ground test loop of condenser system

Liquid subcooling at the condenser tube exit is shown for the flow rate of cooling water in the cold plate in Fig.6. According to the test results, the flow rate of test fluid, FC72, is given as 0.25kg/min in the present experiment on boiling for the maximum heat transport of 400W. Here, the subcooling of test fluid is 28K at the condenser tube exit for the flow rate of cooling water of 45kg/h (0.75L/min), and this satisfies sufficiently the requirements of ISS experiment. Pre-heating may need at the entry of boiling test section to keep the liquid subcooling of 10K at the tube exit. For the higher fluid flow rate, 0.51kg/min and 0.76kg/min for example, it is unable to condense completely in the condenser tube. So, the dry quality of the test fluid is estimated 0.46 and 0.20 at the tube inlet to flow out as liquid from the condenser tube, respectively, as shown in Fig.6.

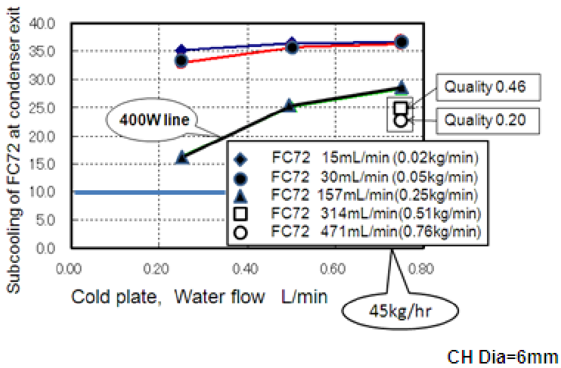



**Fig.6** Liquid subcooling of FC72 at exit of condenser tube

## 5. Results of qualification test for EM

Qualification test for the engineering model of TPF test loop was already performed. Results and evaluations for the performance of condenser will be presented in detail at the conference.

## 6. Conclusion

Thermal design and evaluation test on condenser for TPF; ISS Boiling Flow Experiment were carried out. Results are summarized as follows;

(1) Arithmetic thermal model for condenser on flat type cold plate was created. By this analytical model, the specification of condenser which satisfies the requirements of ISS experiments, that is, 10K in outlet sub-cool temperature could be determined.

(2) Ground based experiment for BBM condenser shows that heat of 400W was transported to the cold plate from the condenser tube at 45kg/h of cooling water flow. The liquid subcooling of FC72 was higher than 10K at the exit of condenser tube.

(3) Results of BBM and EM tests proved that the present condenser satisfied the requirements in the TPF experimental system.

## Acknowledgement

The authors express appreciation for the support of TPF project by JAMSS, JSF, and for the contribution by Prof. Kiyosumi Fujii in Nara Institute of Science and Technology moved from JAXA.

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