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Advances of Microgravity Sciences

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ABSTRACT

Advances of microgravity sciences in China are introduced. The research works include ground-based study and space experiments. In the recent years, the main means still are theoretical analysis, numerical simulation, ground-based experiment, and short-time microgravity experiments of drop tower. Besides, many space experiment projects are arranged. SJ-10 recoverable satellite will carry out 19 scientific experiment projects. Nine of them are for microgravity Sciences. The other ways for space microgravity experiment are with the help of Chinese Shenzhou spacecraft, Chinese Tiangong space laboratory, and Chinese space station in the near future. The Chinese space station will become main platform of Chinese microgravity sciences experiment in space.

KEY WORDS

Microgravity sciences, Microgravity fluid physics, Microgravity combustion, Fundamental physics in space, Space experiment projects

The researches of microgravity science in China are mainly based on the work on the ground in recent years. Through theoretical analysis, numerical simulation, experiment on ground and short-time microgravity experiments of drop tower, the research try to reveal the Law of Motion in microgravity environment.

In recent years, Chinese Academy of Sciences has approved the plan of space science. And the development programs of microgravity science were also proposed. A series of key technical projects of microgravity science research has been supported by advanced research program (the first batch, the second batch) of the Strategic Priority Research Program on Space Science, Chinese Academy of Sciences.

1 Research of Microgravity Sciences on Ground

1.1 Microgravity Fluid Physics

1.1.1 Fluid Dynamics

Chinese researchers carried out further studies of the basic laws of fluid dynamics in microgravity, and further exploration of basic laws of the macro and micro fluid motion, diffusion, heat and mass transfer in space. According to China's national strategic program of the development of science, technology and defense, aiming at the forefront of microgravity fluid physics and fields with industrialization and commercialization prospects, we carried out microgravity fluid dynamics research. The studies on flow stability of thermal convection, instability mechanism, the turbulent transition pathways, as well as interface of fluid flow system coupling with the convection which include bubble/drop thermo-capillary migration and contact angle, diffusion mechanism, will deepen understandings of the basic laws of the microgravity fluid and interfacial phenomena, and will bring about new ideas and new concepts. Accumulation of ground based results and experiences could support the microgravity fluid space experiments and to promote interdisciplinary science, together with biotechnology, manufacturing of new materials, energy, environment, *etc*. The studies will enhance academic status and the influence of China's microgravity fluid physics research.

1.1.2 Two-phase Flow and Heat Transfer

In the past years, several series of studies in the field of multiphase thermal fluid dynamics have been conducted by the Chinese researchers. (1) Nucleate pool boiling on micro-pin-finned surface structure is proposed for efficiently cooling electronic components with high heat flux in microgravity, and was verified by experiments performed utilizing the Drop Tower of Institute of Mechanics in Beijing. It is found that, unlike much obvious deterioration of heat transfer of nucleate pool boiling on the smooth surface in microgravity, constant heater surface temperature of nucleate pool boiling for the micro-pin-finned surface was observed, even though a large coalesced bubble completely covered the surface under microgravity condition. The performance of high efficient heat transfer on micro-pin-finned surface is independent on the gravity, which stems from the sufficient supply of fresh liquid to the heater surface due to the capillary forces. (2) Two-phase flow inside passive direct methanol fuel cell and its electric performance in microgravity was studied experimentally utilizing the drop tower in Beijing, as well as on the ground with different inclination angle. Furthermore, the orientation influence on the two-phase flow patterns inside the cathode flow field of a down-scaling visible SPE electrolytic cell model and its electrical performance were also studied experimentally on the ground. The results are helpful for the related space applications. (3) Focused on the problem of liquid discharge in the high vacuum environment during space flight, the thermal dynamical behaviors of the liquid flashing jets and flashing evaporation phenomenon of single droplets in the high vacuum environment were studied experimentally, in order to enhance the understanding of flashing evaporation phenomenon, to reveal mechanism underlying the phenomenon, and to provide theoretical guidance for development of the related application technology in space engineering and their in-orbit control. Three patterns of liquid jets, namely continuous liquid jet, partly flashing liquid jet and completely flashing liquid jet, were observed at different backpressure. It was also shown that there was flow choking behavior as the flow rate became constant and insensitive to pressure reduction below some back-pressure threshold. The influences of the nucleate time, the backpressure, and the initial droplet size on the thermal dynamical process of the flashing evaporation/freezing of single droplets were obtained.

1.1.3 Complex Fluid

In recent years, the researches of complex fluid in China were focused on studying the phase transitions and aggregations in colloidal suspension which is a typical system of complex fluids. The main contributions include the finding of the transition from bcc metastable state to fcc stable state in colloidal crystallization, and the improvement in coagulation rate measurement of colloidal dispersions, *etc*. By transforming the reflection spectra at different wavelength to that corresponding to wave vector, we proposed a method to rapidly determine the structures of colloidal crystals. With such a newly developed method, we monitored the structural changes in situ during the colloidal crystallization. The result presents direct experimental evidence of liquid-bcc-fcc phase transition in crystallization of charged colloidal particles, as a manifestation of the Ostwald's step rule. As for the measurement of coagulation rate of colloidal dispersions, it is essential to get precise value of this parameter for understanding the aggregation process. Turbidity measurement is one of the most commonly used methods to determine this parameter. However, due to the difficulties of theoretically evaluating the extinction cross section of 2-particle aggregates of large sized particles, the applicability of this measurement is rather limited. By using T-matrix method we solved this problem, which makes it possible to study the influence of gravity on aggregation for which large sized particles will be preferred. Besides these contributions, we have studied the influence of the surface charge on the homogeneity of colloidal crystals. And the influence of sedimentation on colloidal crystallization and aggregation were also studied by both experiments and computer simulations. All these terrestrial contributions will be helpful for future microgravity experiments, especially the innovations on relevant measurements which can certainly be used under microgravity condition.

1.2 Microgravity Combustion

Microgravity combustion has been an active area driven by scientific issues and the practical importance for spacecraft fire safety. In the past years, ground-based research for combustion science was funded by the Strategic Priority Research Program on Space Science/CAS, and the National Natural Science Foundation of China. The research topics were broad, including technological development for space experimentation as well as fundamental questions. For experimental techniques, optical diagnostic methods were designed and tested for simultaneous measurement of flame structure and temperature, and a suggested plan for turbulent combustion research was evaluated and refined. Central to the fundamental research were investigations on premixed flame, flame spread and coal combustion, and microgravity experiments were performed in the Drop Tower Beijing. A unique feature of the microgravity combustion research in China is that three space experiments are now in preparation, and they will fly onboard the China Recoverable Satellite SJ-10 in 2015. These investigations are concerned with smoke emission from combustion of wire insulation, ignition and burning of solid materials, and combustion and pollutant emission of coal, respectively. The space experiments are anticipated to provide valuable information both for practical application and for fundamental research, and relevant ground-based experiments and modeling efforts are under way.

1.3 Fundamental Physics in Space

Several projects of Fundamental Physics have been supported by advanced research program of the Strategic Priority Research Program on Space Science, Chinese Academy of Sciences, as follows.

The first batch of project includes "Concept study on the test of the new equivalence principle in space by use of a gyro-accelerometer".

The second batch of projects includes (i)"concept research on the test of equivalence principle by using a spatial cold atom interferometer", (ii) "concept study on the quantum phase transition experiments in space", (iii) "Concept research on the cold atomic physics experiments in space".

Besides, two projects were accredited in the third batch of advanced research program of the Strategic Priority Research Program on Space Science, CAS, which are: (i) "research on key techniques in the new equivalence principle experiment by using a gyro-accelerometer", and (ii) "preliminary study on scheme of the gravitomagnetism experiments in space".

2 Space Experiment on Microgravity Sciences

On the basis of the ground based research, the limited space experiment opportunities are utilized to obtain the scientific experiments results under microgravity conditions. Currently, the platforms of space experiments in China for microgravity science are spacecraft, space laboratory and satellite. China has started to build its own manned space station. In the station a series of microgravity science experiment platforms and projects are planned.

2.1 Space Microgravity Experiment in Manned Space Mission

2.1.1 TG-2 Space Laboratory

An experiment of microgravity fluid physics was arranged in TG-2 Space Laboratory, which is high Prandtl number liquid bridge space experiment as follow.

The main research purposes are for studying flow stability of thermal convection in high *Pr* number liquid bridge, finding thermocapillary convection instability mechanism in microgravity, expanding the field of fluid mechanics, providing guidance for floating zone crystal growth, archiving research results at the international advanced level, mastering the key technologies of liquid bridge establishment, fluid interface keeping, broken liquid bridge reestablishment, improving China's capacity and technology for space experiment in microgravity fluid science.

The experimental contents of the project are taking advantage of space laboratory for conducting experiments of liquid bridge thermocapillary convection; researching the influence of height to diameter ratio $Ar = L/D$ and volume effects on the critical process; and exploring secondary transition and other issues.

By changing the height and diameter of liquid bridge, the relationship of critical Marangoni and aspect ratio (height to diameter ratio) could be obtained. The relationship between the critical oscillations and aspect ratio with different diameters is not clear. The space experiment results will give the data with different aspect ratio in large diameter liquid bridge.

By changing the volume of the liquid bridge, the influence of volume ratio (V/V_0, where V_0 is the cylindrical volume of the liquid bridge) on the critical oscillation could be achieved. Usually thin liquid bridge (with low volume ratio) and fat liquid bridge (with high volume ratio) have different oscillation onset disciplinarian and have different oscillation mode. The volume effect in high *Pr* liquid bridge could be studied by analyzing the flow field image and the temperature variation.

Now, the project is in flight model phase. China would perform high Prandtl liquid bridge space experiment in 2016.

2.1.2 TZ-1 Cargo Spaceship

Two projects of microgravity sciences are planned in TZ-1. One is a microgravity fluid physics experiment, which will focus on two-phase flow and evaporate heat transfer. Other one is a key technical experiment for fundamental physics in space, which will test the property of high precision accelerometer.

2.1.3 China Space Station

In 2010, the Chinese central government has already formally approved the program of building up Chinese Space Station (CSS), which is planned to be launched around 2020. In the fields of microgravity fluid physics and combustion, researches in 5 panels are planned, including: (i) microgravity fluid dynamics, (ii) two-phase flow and fluids management, (iii) complex fluid, (iv) microgravity combustion science, (v) fire prevention, mitigation, and recovery study. These cover 3 areas of studies in the field of fundamental physics in space, respectively are: (i) high-precision time-frequency system, (ii) cold atomic physics, (iii) relativity and equivalence principle test.

2.1.3.1 Microgravity Fluid Physics

Microgravity fluid physics focuses on the special laws of fluid dynamics in microgravity, and is key to verify related theories and physical models. Its mechanism and application are closely related to a variety of important production processes, such as space fluid management, propulsion, life support systems, and of special importance to the understanding of improvement of materials processing technology, biotechnology processes, *etc*.

Combustion is the foundation of energy, power and related fields. In a microgravity environment, buoyancy convection almost disappears, and some of the weak effects, such as diffusion, radiation and thermophoresis effect, dominate the combustion processes and change the flame features. The research outcomes of microgravity combustion and their application will play important roles in energy utilization on Earth, and in fire safety in microgravity.

(1) Microgravity Fluid Dynamics

In microgravity environment, surface-tension driven convection and diffusion is one of the main forms of fluid movement as well as the heat-mass transport. The basic flow and diffusion characteristics and instability are important research issues in microgravity fluid physics. The microgravity environment in CSS can be utilized to promote studies on the capillary and interfacial phenomena and laws.

(2) Complex Fluids

Research in this field will cover several directions, such as the aggregation in dispersions, colloidal phase transitions (including colloidal crystals and liquid crystals), plasma dust crystals, electric/magnetic rheological fluid, granular materials, foam, emulsion and aerosols.

Fluid Physics Exp. Rack (FPER) will be deployed in the Core Module of CSS. The FPER is a fluid physics research facility and will conduct the experiment in basic laws of microgravity fluid physics. FPER is able to support a variety of microgravity fluid experiments, including: microgravity fluid dynamics, microgravity complex fluids research, crystal growth from solution, fluid transport processes research for space biotechnology.

(3) Two-phase Flow, Phase Change Heat Transfer and its Application

The gas/liquid two-phase medium phase distribution will be simplified in microgravity environment, and phase change (evaporation and condensation) interface effects become prominent. The laws of two-phase flow and phase change heat transfer in the space environment are to be studied.

Research will be carried out on the main laws of gas/liquid two-phase fluid system with phase-change heat and mass transfer in microgravity conditions, and the effect of gravity to fluid phase change heat and mass transfer. It is expected to better understand the ground based two-phase system flow mechanism and essential characteristics of the phase transition, and to promote the understanding of the heat and mass exchange complex interfacial kinetics.

Two-phase Flow Experiment Rack (TFER) will be deployed in the Experiment Module of CSS. TFER accommodates the key scientific issues and engineering technology research of two-phase system in microgravity. TFER is used to conduct experiments on two-phase flow and fluids management, phase change heat transfer and the related application research.

2.1.3.2 Microgravity Combustion

(1) Combustion Science

Utilizing the microgravity environment, research will support the development of basic combustion theories related to ignition, flame extinction, flame propagation, flammability limits, flame structure of laminar flame, turbulent flame, flame instability and other issues.

Meanwhile, special attention will be paid to the application of industrial combustion processes, and the effects of weak forces on the ignition and combustion process, which are usually concealed by the convection in normal gravity conditions.

(2) Fire Prevention, Detection, and Suppression

By utilizing the microgravity environment, researches will support the development of the following critical technologies: (i) materials standards related to ignition, flame spread and smouldering, (ii) fire detection related to fire signatures, transport of combustion products, and (iii) fire suppression related to the interactions among suppression agents, flames, and fuel surfaces.

Combustion Exp. Rack (CER) is still being planned. CER will be used to perform combustion experiments in microgravity, to address the fundamental problems in combustion science as well as fire prevention, mitigation, and recovery aboard spacecraft.

2.1.3.3 Fundamental Physics in Space

The modern physics is based on the theory of relativity, quantum mechanics, electrodynamics, the standard model of particle physics, *etc*., which laid the foundation stone of almost the whole edifice of modern science and technology. However, some inherent flaws in basic physical theory as well as some experimental evidence that may led to the failure of theory will promote new physical theories, such as gravitational gauge field theory, super-gravity, grand unified theory, the latter standard model of particle and so on, as well as near the critical point of the physical form and the development of quantum theory.

The main purpose of the fundamental physics research in CSS is to examine the existing physical theories, discover new physical phenomena and new laws of physics.

(1) Cold Atomic Physics

The space based cold atomic physics experiment platform will be build, and the platform will be used to study the possibility of p-Kelvin. Based on the platform, research on quantum phase transition, the new quantum states of matter, quantum vortex superfluid, matter-wave interference, long-range interactions, BEC complex dynamics in microgravity will be carried out.

Research will be further extended to the simulation of physical processes in extreme conditions and celestial environment, such as supernovae, black hole physics, strongly correlated quantum states such as BEC novelty.

Cold Atom Exp. Rack (CAER) will be deployed to attain the degenerate quantum gases in orbit, where temperature is three orders of magnitude lower than the ground. The CAER will promote the research on magnetic and disordered quantum effects, novel quantum states of matter, Bose-Fermi gas mixture and other cutting-edge issues of fundamental physics.

(2) High-precision Time-frequency System

Space based high-precision time-frequency system running on the CSS will study the time-frequency comparison and allocation technology, linking and measuring space based atomic clock. Using the space based time-frequency system along with the ground based atom clocks, microgravity fundamental physics experiments will be conducted, such as precise measurement of gravitational redshift and the fine structure constant change; high-precision time-frequency signal generation and comparison studies will be carried out, including dealing with the relativistic problem and testing the theory of relativity in high precision.

High-Precision Time-Frequency Rack (HPTFR) is an in orbit high-precision time-frequency generation and operation system employing different atomic clock combos. HPTFR not only do research on itself but also will support researches and applications in a wide area, especially in the relativity and equivalence principle test.

(3) Relativity and Equivalence Principle Test

CSS will carry out the relativity and gravitational physics experimental studies, including: tests of the equivalence principle, short range experimental tests of the Newton's law of gravity, as well as related key technologies.

To test the equivalence principle, high-precision gyro-accelerometers, high-precision atom interferometers, and related atomic manipulation techniques will be developed.

To test the non-Newtonian gravitational and look for new interactions, low disturbance inertial sensors, the weak force measurement technology, charge management technology will be developed.

2.2 Space Microgravity Experiment in Recoverable Satellites

Recoverable Satellite SJ-10, which is proposed by Hu Wenrui, academician of Chinese Academy of Sciences, is designed for space experiment research of microgravity science and space life science. The main task of the mission is to carry out various space scientific experiments on orbital module and recovery capsule using the satellite resources optimally. SJ-10 is one of scientific experimental satellite supported by the Strategic Priority Research Program on Space Science, the Chinese Academy of Sciences. The mission was started at the end of 2012. It has entered the prototype phase. The satellite would be launched by the end of 2015 or later.

19 scientific experiment projects will be carried out on board the SJ-10. These projects are involved in 6 scientific fields: microgravity fluid physics, microgravity combustion, space materials science, space radiation biology, gravity biology, and space biotechnology. The projects of microgravity fluid physics and microgravity combustion are as follow.

(1) Space Experiment of Evaporation and Fluid Interfacial Effects

The space experiment will be emphasized to study the thermocapillary effect at the liquid-gas phase change interface in the evaporation in space environment.

(2) Phase Separation and Dynamic Clustering in Granular Gas

In this project clustering conditions in single and connected double cells are studied and tested in microgravity for the first time.

(3) Thermal Dynamical Behavior of Vapor Bubble during Pool Boiling

The project SOBER-SJ10 (Single bubble pool Boiling Experiment aboard SJ-10) is proposed to study local convection and heat transfer around an isolated growing vapour bubble during nucleate pool boiling on a flat plate heater in microgravity.

(4) Space Experimental on Surface Wave of Thermocapillary Convection

This project will present an inner heated cylindrical liquid pool as convection system to study the instabilities of thermocapillary flow patterns and transition pathways. It will be the first time taking volume effect into account in deep understanding of thermocapillary convection and oscillation mechanism.

(5) Study on the Colloidal Assembling

The main space researching contents included: (i) self-assembly of the colloidal spheres (with or without Ag shell); (ii) liquid crystal phase transition.

(6) Soret Coefficient Measurement

The project was proposed by ESA to study the thermodiffusion and measure the Soret coefficient under microgravity condition.

(7) Study on Ignition, Soot Emission and Smoke Distribution of Wire Insulations by Overload

This project is going to investigate the pre-ignition characteristics of wire insulation by overload in microgravity, to investigate soot emission during the ignition stage and the smoke distribution of the wire insulation combustion.

(8) Investigation of the Coal Combustion and Pollutant Formation Characteristics under Microgravity

The scientific objectives of the project are to discover the fundamental phenomena and control mechanisms in the entire combustion process of single particles and pulverized clouds of a few kinds of typical China coals in an ideal buoyancy-free environment where surrounding mass and heat transfer is isotropic.

(9) Ignition and Burning of Solid Materials in Microgravity

The present investigation examines the ignition and burning characteristics of thermally thick solids with varying low velocity flow and varying ambient oxygen concentration. Other variables to be tested are the effects of fuel type and geometry.

The projects of microgravity fluid physics, microgravity combustion will be arranged in the orbital module of the satellite except the project of Soret coefficient measurement.