0254-6124/2022/42(4)-0772-14   *Chin. J. Space Sci.*   空间科学学报

ZHAO Jianfu, DU Wangfang, KANG Qi, LAN Ding, LI Kai, LI Weibin, LIU Y C, LUO Xinghong, MIAO Jianyin, WANG Qinggong, WANG Shuangfeng, ZHANG Tao, ZHANG Xingwang, ZHANG Yonghai, ZHENG Huiqiong. Recent Progress of Microgravity Science Research in China. *Chinese Journal of Space Science*, 2022, **42**(4): 772–785. DOI:10.11728/cjss2022.04.yg23

Recent Progress of Microgravity Science Research in China

ZHAO Jianfu[1,2] DU Wangfang[1,2] KANG Qi[1,2] LAN Ding[1]
LI Kai[1,2] LI Weibin[1] LIU Y C[3] LUO Xinghong[4]
MIAO Jianyin[5] WANG Qinggong[6] WANG Shuangfeng[1,2] ZHANG Tao[7]
ZHANG Xingwang[8] ZHANG Yonghai[9] ZHENG Huiqiong[10]

1(*CAS Key Laboratory of Microgravity*, *Institute of Mechanics*, *Chinese Academy of Sciences*, *Beijing* 100190)

2(*School of Engineering Science*, *University of Chinese Academy of Sciences*, *Beijing* 100049)

3(*Center for Combustion Energy*, *Tsinghua University*, *Beijing* 100084)

4(*Institute of Metal Research*, *Chinese Academy of Sciences*, *Shenyang* 110016)

5(*Institute of Spacecraft System Engineering*, *China Academy of Space Technology*, *Beijing* 100094)

6(*Qian Xuesen Laboratory of Space Technology*, *China Academy of Space Technology*, *Beijing* 100094)

7(*Shanghai Institute of Technical Physics*, *Chinese Academy of Sciences*, *Shanghai* 200083)

8(*Institute of Semiconductors*, *Chinese Academy of Sciences*, *Beijing* 100083)

9(*School of Chemical Engineering and Technology*, *Xi'an Jiaotong University*, *Xi'an* 710049)

10(*Center for Excellence in Molecular Plant Sciences*, *Chinese Academy of Sciences*, *Shanghai* 200032)

Abstract Microgravity science is an important branch of space science. Its major objective is to study the laws of materials movement in microgravity, as well as to reveal the influence of gravity on the movement of materials in different gravity environments. Application researches relevant to these basic studies are also important contents of microgravity science. The advanced subjects, to some extent, reflect the ability of human beings to understand nature and the R&D level in this field in various countries. In this paper, the recent progress and the latest achievements of microgravity science and application researches in China aboard space platforms such as the Core Capsule Tianhe of the China Space Station (CSS) and satellites, as well as utilizing ground-based short-term microgravity facilities such as the Drop Tower Beijing and TUFF, are summarized, which cover the following sub-disciplines: microgravity fluid physics, microgravity combustion science, space materials science, space fundamental physics, space bio-technology, and relevant space technology applications.

Key words Microgravity science, China Space Station (CSS), Ground-based short-term microgravity platforms, Microgravity fluid physics, Microgravity combustion science, Space materials science, Space fundamental physics, Space bio-technology

Classified index V524

Received June 29, 2022

E-mail: jfzhao@imech.ac.cn

1 Introduction

Microgravity is one of the extreme conditions of space environment, as well as its most valuable resource. In this environment, there are potential possibilities to discover new phenomena and new laws in physical and chemical processes as well as material fabrication and biological processes, and to test and verify some fundamental laws of physics with higher precision. Studies on microgravity science and technology not only have scientific significance for people to understand nature, but also have great application values both in activities of space exploration and in development of new ground-based technologies.

Microgravity science and application research in China can be traced back to the 1960s, but it really rose in the late 1980s[1,2]. The rapid progress of China's aerospace industry, especially that relevant to manned spaceflight and deep space exploration, not only puts forward an urgent demand for microgravity science, but also provides a great opportunity for microgravity science experiments. Furthermore, the construction and operation of the China Space Station (CSS) will provide a great opportunity for the development of microgravity science, which arouses more enthusiasm of scientific research on microgravity science in China. In the present paper, the most recent progress of microgravity science in China is summarized. The vision of China's microgravity science, looking into the coming era of the CSS, is to promote the rapid and sustainable development of microgravity science and application researches in China, for better serving the country and benefiting mankind.

2 Interfacial Phenomena-Capillary Flow, Marangoni Convection and the Instability

Interfacial phenomena, in which flow is driven by the difference of interfacial tension along the interface, are of great importance in microgravity science and technology. There are two categories of interfacial phenomena. The first category, in which the difference of interfacial tension is caused by the gradient of applied fields such as temperature, solution concentration, electric, or other fields, is usually called as Marangoni phenomenon. In the second category, the difference of interfacial tension is caused by the difference of the curvature itself along the interface, and is usually called as capillary phenomenon. Chinese scholars paid some special attentions on these themes, including in-orbit long-term microgravity experiments, ground-based short-term microgravity experiments, numerical simulations, and theoretical analyses.

In the first category, a large amount of efforts have been made on Marangoni convection and the instability, focusing mainly on enriching human's understanding of nonlinear dynamics of fluid flows in extreme conditions.

Focusing on the thermocapillary convection of liquid bridge with large Prandtl number, Kang *et al.*[3] performed a series of experiments aboard China's Tiangong-2 (TG-2) space lab. They established large-scale liquid bridges with different geometric shapes (maximum height 22 mm) and studied their bifurcation mechanism of oscillatory thermal capillary convection. More than 740 groups of experiments have been completed during 32 months.

The space experiment gives the critical Marangoni number and the critical spectrum of liquid bridge thermocapillary convective oscillation tanking geometric parameter effect into account (covering volume ratio and height diameter ratio). An abrupt jump of the oscillation mode is found as the geometry changes. Two regions corresponding to two basic modes are defined in the parameter space of geometry. Multiple transitions are found in the marginal region between these regions and a neutral stability with the novel configuration of the two branches is concluded from the experimental data. The diagram of the transitions between the traveling waves and standing wave under different geometric parameters is drawn (Fig.1). Moreover, abundant and complex coupling bifurcation routes under microgravity are discussed[4,5].

Apart from space experimental studies, a large number of ground experiments, theoretical analyses and numerical simulations have also been carried out on the instabilities of thermocapillary flow both in liquid bridge and in annular liquid pool with low Prandtl number fluids, including the effects of aspect ratio, volume ratio, rotation, heating strategy, magnetic field, and so on[6]. Thermocapillary convection of nano-fluids was also in-

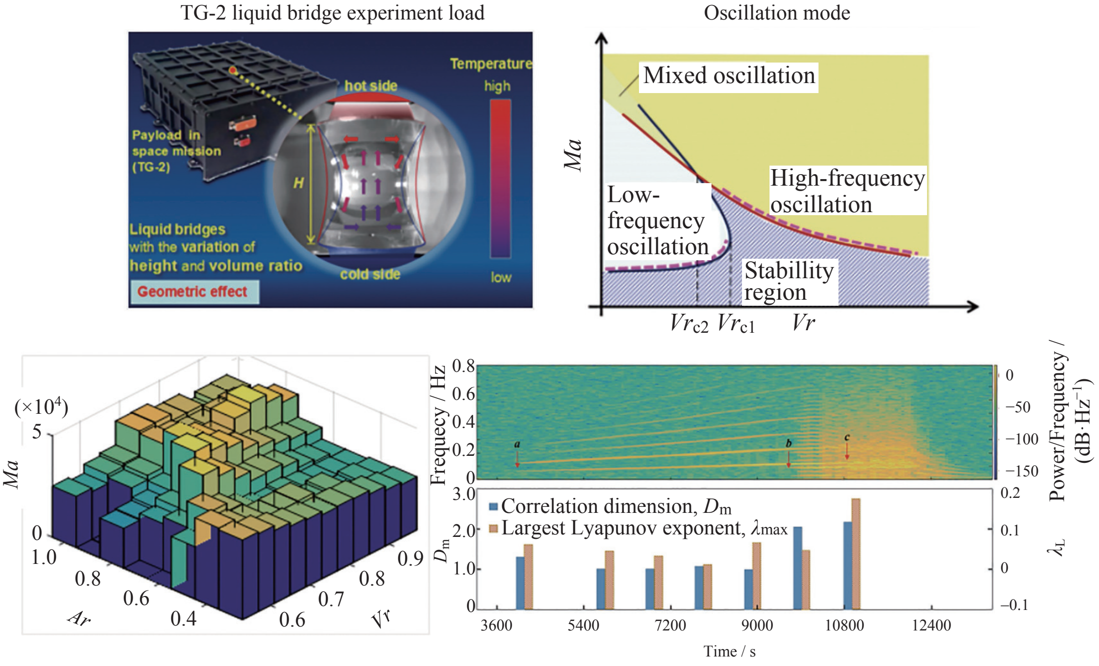


Fig. 1 Experiments on thermocapillary convection of liquid bridge aboard the China Space Lab TG-2

vestigated numerically[7,8]. A POD reduced-order model and numerical bifurcation analysis are applied to explore the bifurcation behavior of thermocapillary convection in two-dimensional cavity[9]. Wang *et al.*[10−12] studied the phenomenon of electrocapillary of an oil-water system concerning the interface control under both DC and AC electric fields, which uses the principle of electrowetting to enhance fluid wicking in a weightless environment.

In the second category, the dynamics of liquid flow in capillaries, metallic wire meshes, and vane tanks are studied intensively in China, focusing on the potential applications for advanced propellant management in space.

The dynamics of capillary flow in tubes with different cross-sections are studied by using theoretical analysis and drop tower experiments[13−16]. The wicking performance of cryogenic propellants within metallic screens including vapor evaporation effect is also studied by Ma *et al.*[17]. The results showed that the wicking velocity and maximal wicking height both have a negative correlation with the gravity and superheated degree.

To investigate the liquid transport in a vane type tank, several series of experiments in the Drop Tower Beijing, as well as numerical simulations, were performed[18−24]. It was found that the direction of microgravity had great effects on the expulsion efficiency of a vane-type tank. The influence of liquid flow in vane tank under different filling volumes, number of vanes, clearances and guiding vanes' thickness on the climbing height of the fluid were discussed in detail. Li *et al.*[25] considered the problem of temperature stratification for a hydrogen propellant tank, and introduced the cryogenic jet mixing effect to suppress temperature stratification. The results showed that a higher incident mass flow rate effectively destroyed the temperature stratification inside the tank and promoted an inside fluid flow for a given liquid filling ratio, while a smaller filling ratio resulted in a faster growth in both average temperature and average pressure and a larger amount of mass transfer inside the tank.

In the near future, the Fluid Physics Rack (FPR) aboard the Experimental Capsule II Mengtian of the CSS, which is a specific experimental device for microgravity fluid science including capillary flow, Marangoni convection and the instability, soft matter or complex fluids, *etc.*, is planned to be launched. More opportunities will be provided to carry out space experiments and then provide more insights on interfacial phenomena.

3 Two-phase Flow and Heat Transfer with Phase Change

Two-phase systems have great potential advantages for space applications. The huge density difference between liquid and gas phases in two-phase systems leads to significant gravity effects, which makes the flow structure and relevant characteristics of dynamics and heat transfer in microgravity environment in space very different from those in normal gravity environment on the ground. Furthermore, spacecraft often experience different levels of gravity or acceleration during the whole mission cycle. Thus, the influence of gravity on two-phase flow and heat transfer with or without phase change plays an important role in this topic.

Du *et al.*[26] reviewed comprehensively the gravity-independent criteria in the literature. They found that the dominant force criteria proposed by Zhao *et al.*[27] can better predict the boundaries of gravity independence regions of a two-phase system. It defines two dimensionless parameters and introduces the corresponding critical values as follows:

$$\begin{aligned} Bo &= \frac{(\rho_{\mathrm{L}}-\rho_{\mathrm{G}})\, g d^2}{\sigma} \leqslant Bo_{\mathrm{cr}}, \\ Fr_{\mathrm{SG}} &= \frac{U_{\mathrm{SG}}}{\sqrt{(\rho_{\mathrm{L}}-\rho_{\mathrm{G}})\, g d/\rho_{\mathrm{G}}}} \geqslant Fr_{\mathrm{SG,cr}}, \end{aligned} \qquad (1)$$

where the critical values were suggested as $Bo_{\mathrm{cr}} = 1.5–6$, and $Fr_{\mathrm{SG,cr}} = 0.54–2.2$, respectively. Fig.2 shows three regions, namely the Gravity Dominant Region (GDR), Surface tension Dominant Region (SDR), and gas-phase Inertial force Dominant Region (IDR). Two-phase flow in the latter two regions is gravity independent. The boundary corresponding to a constant of the gas phase superficial Weber number $We_{\mathrm{SG}} = \rho_{\mathrm{G}} U_{\mathrm{SG}}^2 d/\sigma = Fr_{\mathrm{SG}}^2/Bo$ was also suggested between these two regions. The critical value of the gas phase superficial Weber number can be obtained by solving the intersection of Eq.(1) for the first two boundaries. The dominant force criteria were used successfully in the design of the cryogenic loop heat pipe[28] for space test on cryogenic two-phase thermal transport aboard China's new technology test satellite SJ-20, which was launched at the end of 2019. It was also recommended by Brendel *et al.*[29] for potential space applications.

Du and Zhao[30] reviewed the up-to-data progress on gravity scaling law of nucleate pool boiling heat transfer. They pointed out that there are some deficiencies and/or unsolved problems in the RKM (Raj-Kim-McQuillen) gravity scaling law[31], which implicitly assumed that the characteristic temperature of the boiling incipiency and that of the CHF (critical heat flux) are constants in different gravity conditions. These assumptions, however, have no theoretical or empirical basis in fact. Moreover, recent numerical studies utilizing the lattice Boltzmann method[32], as well as some experimental evidences including recent results obtained from the project SOBER-SJ10[33], showed that the temperature of CHF increases with the gravity level. Furthermore, the hypotheses on the asymptotic behaviors near the boiling incipiency and the critical heat flux confused the meaning of different gravity scaling parameters, which are defined clearly by Du and Zhao[30]. An important reason for the deficiencies of the RKM gravity scaling law is the lack of empirical data, especially experimental results in long-term, steady state pool boiling in different levels of reduced gravity. Thus, a variable gravity pool boiling experiment project utilizing CSS (the Chinese Manned Space Station) under construction, as well as systematic numerical simulations, are suggested in order to promote the research in this field.

Liu *et al.*[34] studied the effects of electric field on pool boiling heat transfer over microstructured surfaces in normal and microgravity. The results showed that the CHF enhancement of the smooth surface by the electric field ranges from 15% to 23% and increases with liquid subcooling. The effects of electric field on CHF of micro-pin-finned surfaces depend on the liquid subcooling and size of micro-pin-fins. The enhancement of CHF due to the electric field is closely related to the field-trap

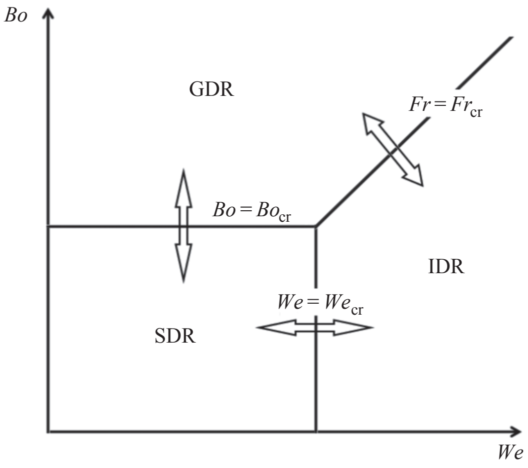


Fig. 2 Dominant force regions in the *Bo*-*We* parameter space

effect, which can be strengthened by liquid subcooling.

In order to obtain the influence law and microscale mechanism of droplet wetting state in microgravity, the model of nano-droplet on micro-structured surface with different wettability and gravity was built and simulated by molecular dynamics[35,36]. As shown in Fig.3, the simulation results showed that keeping droplets in the environment of no gravity or microgravity as far as possible is more beneficial to the rolling and shedding of droplets, and gravity is more important to change the overall trend of droplet contact angle. Moreover, a reliable method was put forward to judge the droplets wetting state under different gravity. The effect of gravity on the motion of droplets on the surface is studied by lattice Boltzmann method[37]. And the results show that the existence of gravity reduces the bouncing frequency and energy conversion rate of droplets on the surface. The ground experiments of steam condensation based on various microstructured surfaces have been carried out, which provides guidance for the selection of space condensation heat transfer surface. Meanwhile, a microgravity condensation experimental platform that can be used in the platform of The Chinese Space Station has been built and is currently undergoing ground basic experiment debugging.

A kind of shape-stable water/PVA sponge composite PCM for space microgravity application, including the development of the Two-Phase System Rack (TPSR) aboard the Experimental Capsule II Mengtian of the CSS, was proposed to overcome the expansion issue of water-based PCM[38]. The effective cold storage density of the prepared PCMs is about 254.8 kJ·kg^{-1}. The phase change temperature range was −1℃ to 1℃, the undercooling temperature was no more than 0.8℃, and the effective cold storage was about 254.8 kJ·kg^{-1}. The melting characteristics of the proposed PCM and the movement of the solid-liquid interface were explored through two-dimensional numerical simulation. The cold storage and release capacity were verified by heat absorption and release experiments.

4 Soft Matter or Complex Fluids

Soft matter or complex fluids is another important topic in Chinese activities of microgravity fluid physics.

Experimental investigations of granular mechanical properties under microgravity were carried out in SJ-10 satellite and in the drop tower Beijing, as well as *via* on-ground experiment and simulation[39–42]. In SJ-10, experimental observation provides us data for the granular clustering phase diagram. The segregation mechanism was further studied by CT analyses. A constitutive model for shear flow transitions in moderate dense granular systems was proposed which provided a theoretical basis to understand the high friction angle of granular materials observed in microgravity. The model is verified by simulation for predicting the bearing capacity of the foundation in low-gravity condition.

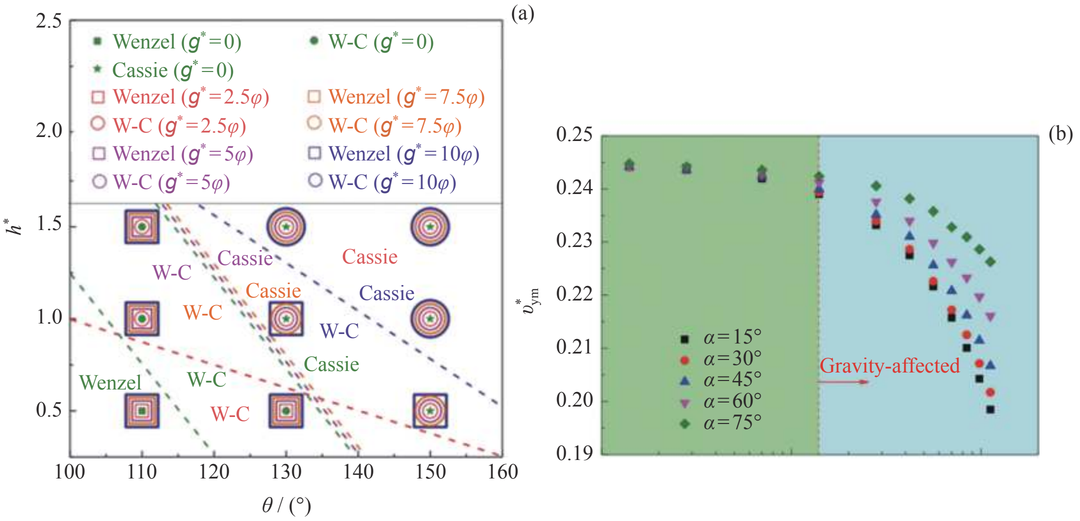


Fig. 3 Change of droplet wetting state under different gravity (a) and the effect of the Bond number on maximum vertical jumping velocity (b)

Li *et al.*[43] adopted the colloidal suspension as a model system of functional solutions to investigate two key processes of printing under a microgravity environment: manipulation of the droplet and formation of the drying patterns. It was showed that the dynamics of the droplet, which would determine the size of the features, could be controlled by tuning the wettability of the needles and the solid surface. Compared to the ground, the "coffee ring" effect was weakened for the drying patterns because of the strong interfacial effect under weightless conditions. They further developed an ultrafast, robust, and scalable approach of Imbibition-Induced Assembly (IIA). The solvent imbibition of the nanoporous media will induce the strong capillary flow that can make the rapid transport of the colloidal particles towards the triple contact line, and the nanoporous surface will further direct the self-assembly of particles into colloidal crystals. Additionally, the IIA is spatially and temporally combined with the meniscus-guided printing method to fabricate multiscale and patterned colloidal photonic crystals. The printing speed (about 10 mm·s^{-1}) is improved by 1–3 orders of magnitude than the traditional evaporation methods (Fig.4). An effective and ultrafast approach was demonstrated by the authors for assembling microscale particles into colloidal photonic crystals with controllable sizes and shapes on the macroscale.

5 Microgravity Combustion

Microgravity combustion phenomena, including ignition and combustion characteristics of overloaded wire insulations, flame spread over flat and cylindrical Polymethyl Methacrylate (PMMA) in low-speed forced flows, burning behaviors and models for single coal particles, dripping droplet combustion of Polyethylene (PE), and flame extinction of spherical PMMA, were recently reported based on experimental results from the recoverable satellite SJ-10 and the Drop Tower Beijing (Fig.5). Primary institutes include Tsinghua University, Huazhong University of Science and Technology, Institutes of Engineering Thermophysics and Institutes of Mechanics of Chinese Academy of Sciences, Hong Kong Polytechnic University, *etc*. In particular, a 1-D transient model considering intra-particle thermal combustion[44] and devolatilization models[45] was shown to improve predictability of ignition of isolated coal particles. Burning rate models with gasification efficiency developed with validations from microgravity dripping droplet experiments showed fundamental insights regarding comet flame due to fuel ejection for the burning of thermoplastic materials[46]. For microgravity flame of spherical fuels, critical mass flux and the mass-transfer number were adopted to reveal underlying mechanisms of extinction limit[47, 48], providing the foundation for developing "fire-safe" shape materials for spacecraft usage. The SJ-10 experiments of smoke emission of the overloaded wire insulations were investigated in long-term microgravity for the first time[49]. Two smoke emission modes, namely the end smoke jet and the bubbling smoke jet, were identified with PE insulations[50]. The

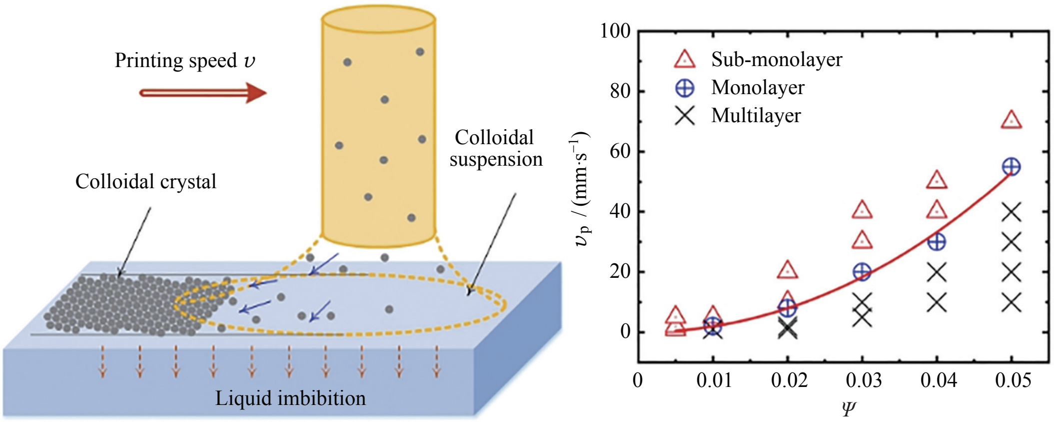


Fig. 4 Schematic diagram of convective flux induced by solvent imbibition during meniscus-guided printing (left). A phase diagram where sub-monolayer, monolayer, and multilayer phases are plotted as a function of the particle volume fraction φ and the printing speed v_p (right)

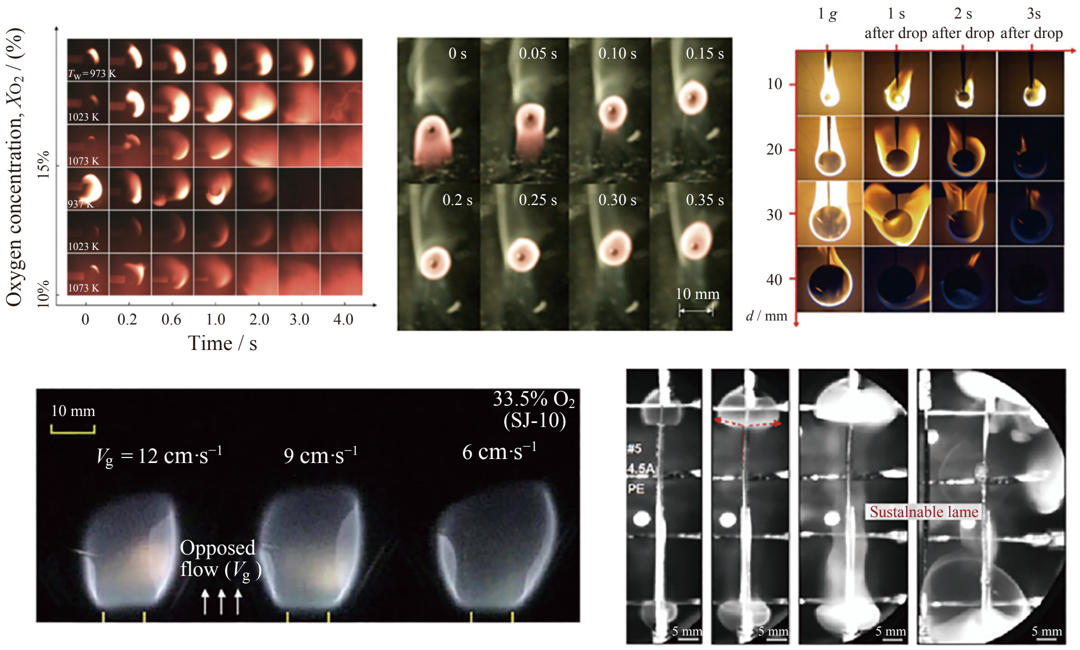


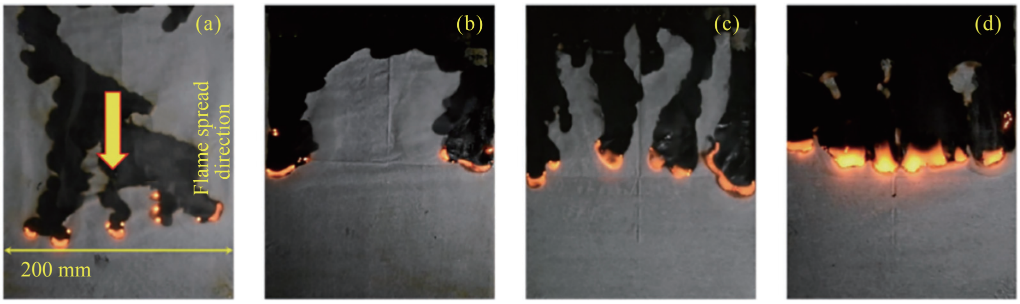
Fig. 5 Recent microgravity combustion investigations on coal particles, dripping PE droplets, spherical and cylindrical PMMA, and PE isolated wires

SJ-10 experiments of opposed flame spread over cylindrical PMMA revealed that the acceleration of flame spread in microgravity due to increased oxygen levels and corresponding fire risk can be overestimated by ground-based test methods[51].

In contrast with the Narrow Channel Apparatus (NCA) that has been employed to suppress buoyancy flow to emulate microgravity flame spread over solid materials, a Horizontal Channel Apparatus (HCA) was proposed[52, 53] based on scaling analysis to extend the buoyancy effect and study opposed flame spread in partial gravity conditions (Fig.6). Thin solid materials investigated include napkin and dictionary paper, with comparison with data of cellulose tissues (parabolic flight experiments) in literature. Collectively with the experimental results (also from the ISS) and modeling efforts, a review for effects of buoyant flow, fingering spread, smoldering spread, and various transition behaviors for near-limit opposed fire spread was provided to suggest valuable issues for future research[54].

Microgravity group combustion behaviors for coal particles and droplets were numerically investigated. Particle and droplet burning models with 1-D configuration and Neumann boundary conditions were used to examine effects of particle distance on diffusion, vaporization, and chemistry-controlled phenomena[55, 56]. An ignition group number (Gig) was proposed to differentiate various ignition mode regimes of two-stage external group combustion[57]. Further experimental validation of the proposed model is expected to be conducted using Tsinghua University Freefall Facility (TUFF)[58].

The Combustion Science Rack (CSR), which is planned to be aboard the Experimental Module II Mengtian of the CSS, will facilitate investigations in gaseous flame dynamics, combustion of solid and energetic materials, and liquid combustion in various configurations in long-duration microgravity environment through utilization of different Combustion Experimental Inserts (CEIs). Corresponding strategic goals of the space-based combustion program include: to extend combustion limits and associated theories for multiphase reacting flows and flame instabilities, to improve predictability of space fire incident and lay foundation for material selection for space utilization, and to promote original research approach and technology transfer for low pollution combustion and future space exploration. The first batch of domestic and international collaborative projects for combustion sciences onboard the CSS will make full usage of the gaseous CEI for exploring near-limit flame stagnation, liftoff and blowoff mechanisms, weakly tur-



Pattern 1
$L=5$ mm, $V_g=1.5$ cm·s^{-1}
$R_a=1099$, $R_e=1.35$

Pattern 2
$L=6$ mm, $V_g=1.5$ cm·s^{-1}
$R_a=1898$, $R_e=1.62$

Pattern 3
$L=6$ mm, $V_g=2$ cm·s^{-1}
$R_a=1898$, $R_e=2.17$

Pattern 4
$L=6$ mm, $V_g=2.8$ cm·s^{-1}
$R_a=1898$, $R_e=3.03$

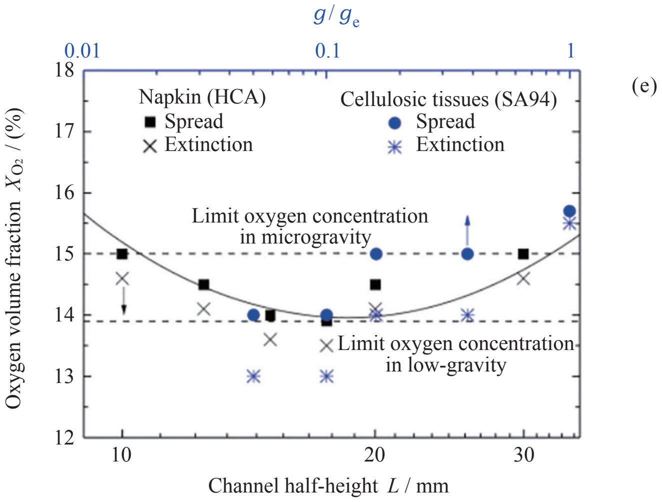


Fig. 6 Recent development of partial gravity flame spread and extinction of thin materials using the HCA

bulent flame dynamics, sooting flame structure and sooting limits, flame synthesis of functional particle materials, as well as flame instabilities under vortices and acoustic waves.

6 Space Material Science

Big progress in space material field has been made in the past two years in terms of platform construction. One of the two material experiment racks on the CSS, Containerless Material Experiment Rack (CMER), had been completed and was launched with the core module Tianhe of China Space Station (CSS) on 29 April 2021. Meanwhile, after selection and ground tests a batch of experimental samples were also sent into space with the rack. An electrostatic levitation facility installed in the rack would be applied to study the containerless solidification mechanism and thermophysical properties of the material samples in microgravity environment. Till now, the on-orbit functional verification of the rack and electrostatic levitation facility have been successfully completed. Spherical samples of Zr were melted and some thermophysical properties were measured under microgravity condition, as shown in Fig.7. Next, containerless experiments on various material samples, such as superalloys, metallic glasses, and oxide ceramics, *etc*., will be conducted gradually.

The main performances of the containerless experimental device included as follows: (i) a coupling laser heating system composed of semiconductor laser with output power of 300 W and carbon dioxide laser can heat the samples heated up to 3000℃; (ii) a molecular pump vacuum system and argon pressurization unit are installed in the rack to supply pressure environments from 10^{-4} Pa to 3 atm; (iii) a serials of optical devices are mounted on a polyhedron chamber with 38 faces for the positioning of samples with an accuracy of ±0.1 mm, measuring of thermophysical property such as density,

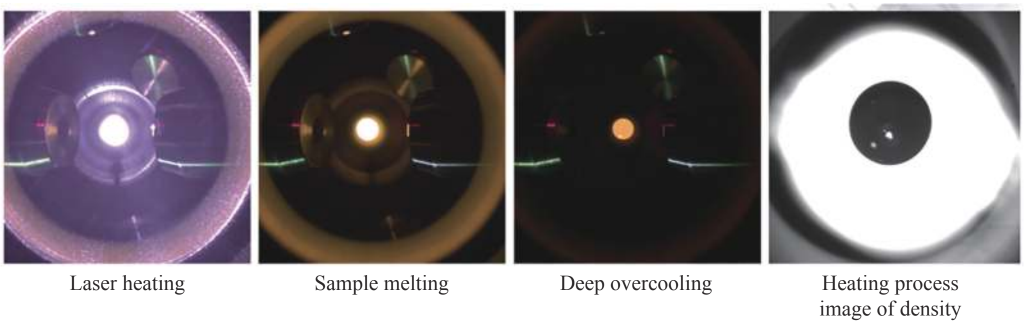


Fig. 7 Containerless experiment of a Zr sample on CSS

viscosity, surface tension, specific heat and spectral emissivity, and providing a triggering nucleation function to realize different supercooling degrees.

The other CSS material experiment rack, High Temperature Material Rack (HTMR), has been almost completed and the test of it is underway. It is scheduled to be launched with the Mengtian module in October 2022, followed by a series of material science experiments. The rack allows for study of a variety of materials, including high-temperature metals & alloys, semiconductors, crystals, ceramics, glasses, *etc*., onboard the CSS.

Some ground-based microgravity material researches were still ongoing. Using the 50-meter-high drop tube at IMR, CAS, Luo *et al*.[59] investigated the effect of microgravity on the solute segregation and dendrite growth of Al-2.8 wt.% Cu alloy, grain and bubble morphology evolution of Al-9.5 wt.% Zn alloy, and primary phase formation and peritectic reactions of Sn-20 wt.% Ni, Ni-25 wt.% Zr, and Cu-15 wt.% Ge alloys. Some phenomena, such as, microgravity weakened central enrichment of Cu solute and led to smaller dendrite spacing and more mild microsegregation in Al-2.8 wt.% Cu alloy, did not cause grain and bubble movement and produced larger grain size in Al-9.5 wt.% Zn alloy, and was favorable to the formation and growth of the primary phase but not peritectic reaction in Sn-20 wt.% Ni alloy, were observed. Other alloys such as the ternary alloy Cr-Ni-Fe, Ni-Fe-Ti, Al-Ag-Ge, and Ga-In-Sb, are also studied respectively in the Northwestern Polytechnical University and the Tianjin Polytechnic University, focusing on the heat transfer dynamics, eutectic growth mechanism, structural evolution, micromechanical properties, and so on.

Wang *et al*.[60] investigated the Marangoni effect by using a new method to directly measure the acetic acid (solute) concentration with a Planner Laser-Induced Fluorescence (PLIF) system. Based on the concentration contours of solute, they could probe into the bulk flow and occurrence of the Marangoni effect. It was found that the density effect of solute, coupled with Marangoni effect, further affected the distribution of solute and then influenced the location and evolution of Marangoni effect. In the same group, the effect of gravity (including 0, 0.16, 0.38, 1 and 1.8 g) on the polymorphs was studied with the anti-solvent crystallization of L-histidine from an ethanol water mixture by adding ethanol, operated in both continuous and batch modes[61]. The experiments were conducted in a self-designed microchannel crystallizer on a zero-G flight. The stable form of L-histidine was obtained under microgravity, while only the metastable form can be observed in the ground experiments with the same inlet conditions. The possible reason is the extremely ordered flow field of the system in microgravity environment. A large amount of small particles aggregated at 1.8 g due to the enhanced micro-mixing, which favors nucleation. Bigger particles crystalized at Moon gravity (0.16 g) without the excessive consumption of the supersaturation by explosive nucleation and with moderate convection of the system. It is concluded that both nucleation and crystal growth were influenced by the micro-mixing status in the system due to the altered gravity extent.

7 Space Fundamental Physics

The projects Taiji and Tianqin, which are all scheduled to be launched in the early 2030s, are two missions for gravitational wave detection in space[62]. The pilot satellite missions for these two projects, namely Taiji-1 and

Tianqin-1, were launched successfully in the middle and end of 2019, respectively. Fig.8 shows the distribution of the payloads in Taiji-1. The successful flights of Taiji-1 and Tianqin-1 have verified the feasibility of the corresponding projects. Meanwhile, with the support of the Strategic Priority Research Program of the Chinese Academy of Sciences, the key technology research of Taiji-2 was completed, laying a foundation for the implementation of Taiji-2 project.

Cold atomic physics is another topic in China's space fundamental physics researches. The successful operation of the space cold atomic clock aboard the China Space Lab Tiangong-2 is the first time in the world[63]. It was found that the performance remained stable after three-year in-orbit test, paving the way for the space application of cold atom technology. Recently, the same team developed a simple, reliable and universal method for generating one-dimensional cold gases of ^{87}Rb atoms by diffuse laser cooling[64]. A horizontal slender vacuum glass tube with a length of 105 cm and diameter of 2 cm was used in the experiment. The diffuse laser light inside the tube, which was generated by multireflection of injected lasers, cooled the background vapor atoms. With 250 mW of cooling light and 50 mW of repumping light, an evenly distributed 1-m-long profile of cold atom cloud is obtained. A factor 4 improvement in the atomic optical density was observed for a typical cooling duration of 170 ms and a sub-Doppler atomic temperature of 25 μK. The central number of detected cold atoms remained constant for a free-fall duration of 30 ms.

8 Space Life Science and Bio-Technology

Spaceflight conditions, including microgravity or low gravity, radiation, temperature, air and soil composition constraints, *etc*., greatly affect life survival and adaption. Moreover, the volume and energy supply in the isolation chambers in space used to live are very limited. Thus, a systematic analysis of regulatory mechanism of higher plants and other organisms in response to space environments and construction of higher resource-use efficiency life support system are needed.

The Chinese space life research activities on board the Chinese recoverable satellite SJ-10 in 2016 spanned three life science fields, including micro-gravitational biological effects, space radiation biological effects and space cell culture biotechnology. In the same year, a seed-to-seed experiment on board the Chinese space lab TG-2 was carried out. One of the most prolific series of investigations is the Higher Plant Flowering Experiment (HPFE) in space on board SJ-10 and TG-2. In these two years, samples of HPFE recovered from the SJ-10 and

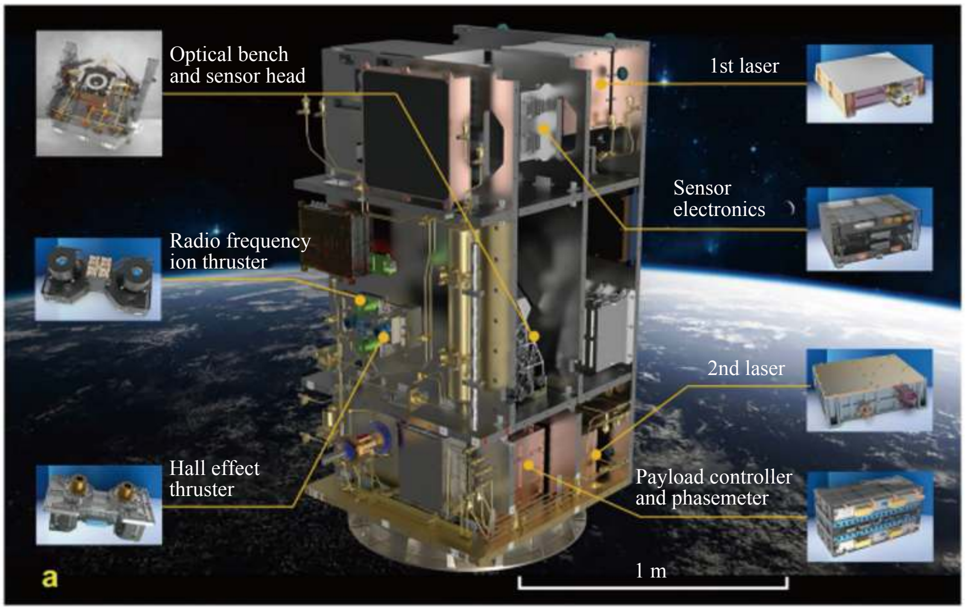


Fig. 8 Anatomy of Taiji-1 and its payloads

TG-2 were used to test molecular basis to integrate microgravity signals into the photoperiodic flowering pathway[65]. Potential evidence for transgenerational epigenetic memory in Arabidopsis and metabolomics of rice seeds after spaceflight were also investigated[66–69]. The data indicated that the roles of the circadian oscillator could act as integrators of spaceflight response and photoperiodic signals in plants grown in space and changes in epigenetic modifications caused by spaceflight affected the growth of two future seed generations. In addition, effects of microgravity on early mouse embryonic development and embryonic stem cell differentiation on board SJ-10 were analyzed[70, 71].

Data from SJ-10 and TG-2 operation have been used in the design of additional space experiments, which will be performed on board the CSS. The first 17 projects on life science and biotechnology in space have been considered for the CSS missions in the near future.

9 New Ground-based Facilities Developed in China

As effective complements to the CSS, several ground-based facilities have also been developed recently in China.

In addition to the Drop Tower Beijing operated by the National Microgravity Laboratory/CAS, a new drop tower, namely Tsinghua University Freefall Facility (TUFF), has been built and open for national users to conduct short-term microgravity experiments mainly in the field of combustion. TUFF allows for 2.2 s freefall with $10^{-3}\ g$ followed by a 10 m deceleration using magnetic breaks[58]. Another new microgravity experiment facility with electromagnetic launch is also under construction in the Technology and Engineering Center for Space Utilization of CAS[72] in order to meet the rapid increasing requirements of extensive preliminary ground experiments for projects aboard CSS, as well as those of scientific experiments utilizing ground-based short-term microgravity facilities. It is mainly composed of double layered tower, linear induction motors, experimental capsule, energy storing device, high-power converters, electrical control system and electromagnetic release device. The microgravity level of $10^{-5}\ g$ can be achieved for 4 s and optional gravity level from $10^{-5}\ g$ to $1\ g$ can be created.

The quick progress of commercial spaceflight in China also provides some short-term microgravity experiment opportunities. For example, DEAR (Discovery, Exploration, Advance, Recovery) family spacecraft, developed by AZSPACE, which was founded in 2019 as a Chinese spacecraft manufacturer, a provider of orbital experiment and recovery services, are developed for implementing scientific experiments, and then bring experimental items back to the Earth by recovery part. Inner or out of spacecraft, the experiments can be customized in the space natural environment, mixing the features of microgravity, weak geomagnetic, strong radiation, high vacuum, and ultra-low temperature. In orbital spaceflights, DEAR spacecraft is launched into space and flies in Low Earth orbit at 350 km altitude. Microgravity in orbital laboratory can be 10^{-5} to $10^{-6}\ g$. The recovery part will fly in space for nearly four weeks and then return to the Earth. The orbital part will stay in space for over one year and then burn down through the atmosphere. Different options on time periods will match different experiments as needed. Suborbital flights and experiment services can also be provided. In suborbital flights, DEAR spacecraft is launched to the space at 150 km altitude and land on the Earth. Microgravity (10^{-3} to $10^{-4}\ g$) environment will last 3–5 min.

10 Conclusions

Microgravity science has great importance in fundamental studies, affects directly mans' understanding of physical laws of nature, and has great application values in the development of space exploration and new ground-based technologies. The most recent progress of microgravity science in China is summarized briefly in the present paper, including microgravity fluid physics, microgravity combustion science, space material science, space bio-technology, and space fundamental physics. Several ground-based facilities for short-term microgravity experimental research are also developed in China, which will be effective complements to the CSS.

The Core Module Tianhe of the CSS was successfully launched into orbit last year. There have been six astronauts from two teams visiting successfully the Core

Module Tianhe. On 10 May 2022, the cargo spacecraft TZ-4 was launched successfully, which opened the on orbit construction stage of the CSS. The two experiment modules, namely the Experiment Module I Wentian and the Experiment Module II Mengtian, will be launched into orbit this year to complete the construction of the CSS. The new era of the CSS is coming. The CSS will provide essential conditions for carrying out multi-disciplinary space scientific experiments, especially long-term microgravity space experiments on microgravity science and application. It is bound to contribute to the further prosperity of China's microgravity research and to benefit microgravity research all over the world.

Acknowledgement The authors appreciate supports from all members of the National Society of Microgravity Science and Application (NSMSA), Chinese Society of Space Research (CSSR).

References

[1] ZHAO Jianfu, WANG Shuangfeng, LIU Qiang, *et al.* Retrospect and perspective on microgravity science in China[J]. *Chinese Journal of Space Science*, 2021, **41**(1): 34-45

[2] LI K, ZHAO J F, KANG Q, *et al.* Academician Wen-Rui Hu – proeminent pioneer and prominent leader of microgravity science in China[J]. *Microgravity Science and Technology*, 2022, **34**(2): 19

[3] KANG Q, WU D, DUAN L, *et al.* Space experimental study on wave modes under instability of thermocapillary convection in liquid bridges on Tiangong-2[J]. *Physics of Fluids*, 2020, **32**(3): 034107

[4] KANG Q, WU D, DUAN L, *et al.* The effects of geometry and heating rate on thermocapillary convection in the liquid bridge[J]. *Journal of Fluid Mechanics*, 2019, **881**: 951-982

[5] KANG Q, WANG J, DUAN L, *et al.* The volume ratio effect on flow patterns and transition processes of thermocapillary convection[J]. *Journal of Fluid Mechanics*, 2019, **868**: 560-583

[6] GUO Ziyi, LI Kai, KANG Qi, *et al.* Study on bifurcation to chaos of surface tension gradient driven flow[J]. *Advances in Mechanics*, 2021, **51**(1): 1-28

[7] CHEN C, FENG S Y, PENG H, *et al.* Thermocapillary convection flow and heat transfer characteristics of graphene nanoplatelet based nanofluid under microgravity[J]. *Microgravity Science and Technology*, 2021, **33**(3): 40

[8] ZHOU X M, CHI F X, JIANG Y N, *et al.* Moderate Prandtl number nanofluid thermocapillary convection instability in rectangular cavity[J]. *Microgravity Science and Technology*, 2022, **34**(2): 24

[9] GUO Ziyi, ZHAO Jianfu, LI Kai, *et al.* Bifurcation analysis of thermocapillary convection based on POD-Galerkin reduced-order method[J]. *Chinese Journal of Theoretical and Applied Mechanics*, 2022, **54**(5): 1186-1198

[10] WANG Q G, XU M, WANG C, *et al.* Actuation of a non-conductive droplet in an aqueous fluid by reversed electrowetting effect[J]. *Langmuir*, 2020, **36**(28): 8152-8164

[11] WENG N, WANG Q G, GU J P, *et al.* The dynamics of droplet detachment in reversed electrowetting (REW)[J]. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2021, **616**: 126303

[12] WANG Q G, LI L, GU J P, *et al.* Manipulation of a nonconductive droplet in an aqueous fluid with AC electric fields: droplet dewetting, oscillation, and detachment[J]. *Langmuir*, 2021, **37**(41): 12098-12111

[13] CHEN S T, YE Z J, DUAN L, *et al.* Capillary driven flow in oval tubes under microgravity[J]. *Physics of Fluids*, 2021, **33**(3): 032111

[14] LEI J C, XU Z M, XIN F X, *et al.* Dynamics of capillary flow in an undulated tube[J]. *Physics of Fluids*, 2021, **33**(5): 052109

[15] ZHU C W, ZHOU X P, ZHANG G. Capillary plugs in horizontal rectangular tubes with non-uniform contact angles[J]. *Journal of Fluid Mechanics*, 2020, **901**: R1

[16] WENG N, WANG Q G, LI J D, *et al.* Liquid penetration in metal wire mesh between parallel plates under normal gravity and microgravity conditions[J]. *Applied Thermal Engineering*, 2020, **167**: 114722

[17] MA Y, LI Y Z, XIE F S, *et al.* Investigation on wicking performance of cryogenic propellants within woven screens under different thermal and gravity conditions[J]. *Journal of Low Temperature Physics*, 2020, **199**(5): 1344-1362

[18] LIU J T, LI Y, LI W, *et al.* Experimental investigation of liquid transport in a vane type tank of satellite with microgravity[J]. *Aerospace Science and Technology*, 2020, **105**: 106007

[19] ZHUANG B T, LI Y, LIU J T, *et al.* Numerical simulation of fluid transport along parallel vanes for vane type propellant tanks[J]. *Microgravity Science and Technology*, 2020, **32**(2): 129-138

[20] LI Y Q, DONG J Y, RUI W. Numerical simulation for capillary driven flow in capsule-type vane tank with clearances under microgravity[J]. *Microgravity Science and Technology*, 2020, **32**(3): 321-329

[21] LI J C, LIN H, LI K, *et al.* Liquid sloshing in partially filled capsule storage tank undergoing gravity reduction to low/microgravity Condition[J]. *Microgravity Science and Technology*, 2020, **32**(4): 587-596

[22] ZHANG D Z, MENG L, LI Y Q. Numerical simulation analysis of liquid transportation in capsule-type vane tank under microgravity[J]. *Microgravity Science and Technology*, 2020, **32**(5): 817-824

[23] LI J C, LIN H, LI K, *et al.* Dynamic behavior in a storage tank in reduced gravity using dynamic contact angle method[J]. *Microgravity Science and Technology*, 2020, **32**(6): 1039-1048

[24] CHEN S T, DUAN L, KANG Q. Study on propellant management device in plate surface tension tanks[J]. *Acta Mechanica Sinica*, 2021, **37**(10): 1498-1508

[25] LI J C, GUO B, ZHAO J F, *et al.* On the space thermal destratification in a partially filled hydrogen propellant tank by jet injection[J]. *Microgravity Science and Technology*, 2022, **34**(1): 6

[26] DU Wangfang, YUE Shuwen, ZHAO Jianfu, *et al.* Criteria of gravity independence in multiphase thermal fluid system[J]. *Journal of Hebei University of Water Resources and Electric Engineering*, 2019(1): 1-8

[27] ZHAO J F, XIE J C, LIN H, *et al*. Experimental study of two-phase flow in microgravity[C]//51 st Int. Astronautical Cong. Rio de Janeiro, Brazil, October 2-6, 2000

[28] HE F L, DU W F, ZHAO J F, *et al.* Numerical simulation on the effects of component layout orientation on the performance of a neon-charged cryogenic loop heat pipe[J]. *Microgravity Science and Technology*, 2020, **32**(2): 179-188

[29] BRENDEL L P M, BRAUN J E, GROLL E A. Comparison of gravity independence criteria for two-phase flow[J]. *Journal of Thermophysics and Heat Transfer*, 2021, **35**(4): 830-842

[30] DU Wangfang, ZHAO Jianfu. Gravity scaling law of heat transfer in nucleate pool boiling[J]. *Chinese Science Bulletin*, 2020, **65**(17): 1629-1637

[31] RAJ R, KIM J, MCQUILLEN J. Pool boiling heat transfer on the international space station: experimental results and model verification[J]. *Journal of Heat Transfer*, 2012, **134**(10): 101504

[32] FENG Y, LI H X, ZHAO J F, *et al.* Lattice Boltzmann study on influence of gravitational acceleration on pool nucleate boiling heat transfer[J]. *Microgravity Science and Technology*, 2021, **33**(2): 21

[33] LIU Ping, DU Wangfang, WU Ke, *et al.* Study on performance of pool boiling heat transfer in SOBER-SJ10 based on genetic algorithm[J]. *Journal of Engineering Thermophysics*, 2021, **42**(7): 1784-1790

[34] LIU B, GARIVALIS A I, CAO Z Z, *et al.* Effects of electric field on pool boiling heat transfer over microstructured surfaces under different liquid subcoolings[J]. *International Journal of Heat and Mass Transfer*, 2022, **183**: 122154

[35] XU B, ZHANG C C, CHEN Z Q, *et al.* Investigation of Nano-droplet wetting states on array micro-structured surfaces with different gravity[J]. *Computers & Fluids*, 2021, **222**: 104936

[36] WANG X, XU B, WANG Y, *et al.* Directional migration of single droplet on multi-wetting gradient surface by 3 D lattice Boltzmann method[J]. *Computers & Fluids*, 2020, **198**: 104392

[37] WANG X, XU B, CHEN Z Q, *et al.* Effects of gravitational force and surface orientation on the jumping velocity and energy conversion efficiency of coalesced droplets[J]. *Microgravity Science and Technology*, 2020, **32**(6): 1185-1197

[38] MO S Y, CHEN Y S, HUANG L P, *et al.* Preparation and the cold storage performance of water/PVA sponge PCMs for aerospace applications[J]. *Microgravity Science and Technology*, 2022, **34**(3): 35

[39] LI Z F, ZENG Z K, XING Y, *et al.* Microscopic structure and dynamics study of granular segregation mechanism by cyclic shear[J]. *Science Advances*, 2021, **7**(8): eabe8737

[40] WU Q L, HOU M Y, YANG L, *et al.* Parametric study of the clustering transition in vibration driven granular gas system[J]. *Chinese Physics B*, 2020, **29**(5): 054502

[41] XIAO S Z, CHENG X H, HOU M Y, *et al.* Analysis of experimental results on the bearing capacity of sand in low-gravity conditions[J]. *Microgravity Science and Technology*, 2022, **34**(2): 16

[42] CHENG X H, XIAO S Z, CAO A S, *et al.* A unified constitutive model for pressure sensitive shear flow transitions in moderate dense granular materials[J]. *Scientific Reports*, 2021, **11**(1): 19669

[43] LI W B, LAN D, WANG Y R. Exploration of direct-ink-write 3 D printing in space: droplet dynamics and patterns formation in microgravity[J]. *Microgravity Science and Technology*, 2020, **32**(5): 935-940

[44] YANG W T, ZHANG Y, HU L L, *et al.* An experimental study on ignition of single coal particles at low oxygen concentrations[J]. *Frontiers in Energy*, 2021, **15**(1): 38-45

[45] YANG W T, LIU B, ZHANG H, *et al.* Prediction improvements of ignition characteristics of isolated coal particles with a one-dimensional transient model[J]. *Proceedings of the Combustion Institute*, 2021, **38**(3): 4083-4089

[46] YANG W T, ZHANG Y, LIU B, *et al.* Ignition predictions of isolated coal particles by different ignition criteria and devolatilization models[J]. *Fuel*, 2022, **314**: 122772

[47] SUN P Y, WU C J, ZHU F, *et al.* Microgravity combustion of polyethylene droplet in drop tower[J]. *Combustion and Flame*, 2020, **222**: 18-26

[48] WU C J, SUN P Y, WANG W Z, *et al.* Flame extinction of spherical PMMA in microgravity: Effect of fuel diameter and conduction[J]. *Microgravity Science and Technology*, 2020, **32**(6): 1065-1075

[49] KONG W J, WANG K, XIA W, *et al*. Ignition and combustion characteristics of overloaded wire insulations under weakly buoyancy or microgravity environments[M]//HU W R, KANG Q. Physical Science Under Microgravity: Experiments on Board the SJ-10 Recoverable Satellite. Singapore: Springer, 2019. DOI: 10.1007/978-981-13-1340-0_9

[50] XUE S, KONG W J. Smoke emission and temperature characteristics of the long-term overloaded wire in space[J]. *Journal of Fire Sciences*, 2019, **37**(2): 99-116

[51] WU C J, Huang X Y, WANG S F, *et al.* Opposed flame spread over cylindrical PMMA under oxygen-enriched microgravity environment[J]. *Fire Technology*, 2020, **56**(1): 71-89

[52] WU C J, XIAO Y, WANG S F, *et al.* Horizontal flame spread over thin solids in reduced buoyancy environments[J]. *Combustion and Flame*, 2022, **240**: 112008

[53] ZHU F, HUANG X Y, WANG S F. Flame spread over polyethylene film: effects of gravity and fuel inclination[J]. *Microgravity Science and Technology*, 2022, **34**(3): 26

[54] HUANG X Y, GAO J. A review of near-limit opposed fire spread[J]. *Fire Safety Journal*, 2021, **120**: 103141

[55] FENG L L, WU Y X, XU K L, *et al.* Effect of particle distance on combustion behaviors through 1-D model with Neumann boundary condition[J]. *Fuel*, 2020, **276**: 117974

[56] ZHOU H Y, ZHANG W Y, LIU Y C. A cell model analysis for droplets inside non-dilute n-heptane droplet clouds near autoignition limit[J]. *International Journal of Heat and Mass Transfer*, 2021, **175**: 121189

[57] ZHOU H Y, LIU Y C. External group combustion of droplet clouds under two-stage autoignition conditions[J]. *Combustion and Flame*, 2021, **234**: 111689

[58] LUO L, ZHOU H Y, SUN Y H, *et al.* Tsinghua university freefall facility (TUFF): a 2.2 second drop tunnel for microgravity research[J]. *Microgravity Science and Technology*, 2021, **33**(2): 26

[59] KONG Y F, LUO X H, LI Y, *et al.* Gravity-induced solidification segregation and its effect on dendrite growth in Al-2.8 wt.% Cu alloy[J]. *Microgravity Science and Technology*, 2021, **33**(6): 72

[60] WANG Z Z, CHEN J, FENG X, *et al.* Visual dynamical measurement of the solute-induced Marangoni effect of a growing drop with a PLIF method[J]. *Chemical Engineering Science*, 2021, **233**: 116401

[61] ZHANG Y, CHENG J C, GLICK Y, *et al.* Antisolvent crystallization of *L*-histidine in micro-channel reactor under microgravity[J]. *Microgravity Science and Technology*, 2020, **32**(1): 27-33

[62] WU Y L, LUO Z R, WANG J Y, *et al.* China's first step towards probing the expanding universe and the nature of gravity using a space borne gravitational wave antenna[J]. *Communications Physics*, 2021, **4**(1): 34

[63] LIU L, LÜ D S, CHEN W B, *et al.* In-orbit operation of an atomic clock based on laser-cooled ^{87}Rb atoms[J]. *Nature Communications*, 2018, **9**(1): 2760

[64] WAN J Y, WANG X, ZHANG X, *et al.* Quasi-one-dimensional diffuse laser cooling of atoms[J]. *Physical Review A*, 2022, **105**(3): 033110

[65] LEI X H, CAO Y J, MA B H, *et al.* Development of mouse preimplantation embryos in space[J]. *National Science Review*, 2020, **7**(9): 1437-1446

[66] LI F, YE Y, LEI X H, *et al.* Effects of microgravity on early embryonic development and embryonic stem cell differentiation: phenotypic characterization and potential mechanisms[J]. *Frontiers in Cell and Developmental Biology*, 2021, **9**: 797167

[67] WANG L H, XIE J Y, MOU C H, *et al.* Transcriptomic analysis of the interaction between *FLOWERING LOCUS T* induction and photoperiodic signaling in response to spaceflight[J]. *Frontiers in Cell and Developmental Biology*, 2021, **9**: 813246

[68] WU Y Y, XIE J Y, WANG L H, *et al.* Circumnutation and growth of inflorescence stems of *Arabidopsis thaliana* in response to microgravity under different photoperiod conditions[J]. *Life*, 2020, **10**(3): 26

[69] XIE J Y, WANG L H, ZHENG H Q. Molecular Basis to integrate microgravity signals into the photoperiodic flowering pathway in *Arabidopsis thaliana* under spaceflight condition[J]. *International Journal of Molecular Sciences*, 2022, **23**(1): 63

[70] XU P P, CHEN H Y, HU J B, *et al.* Potential evidence for transgenerational epigenetic memory in *Arabidopsis thaliana* following spaceflight[J]. *Communications Biology*, 2021, **4**(1): 835

[71] ZENG D Y, CUI J, YIN Y S, *et al.* Metabolomics analysis in different development stages on SP0 generation of rice seeds after spaceflight[J]. *Frontiers in Plant Science*, 2021, **12**: 700267

[72] ZHANG J Q, DONG W B, WANG Z, *et al.* Development of a new microgravity experiment facility with electromagnetic launch[J]. *Microgravity Science and Technology*, 2021, **33**(6): 68