



Academician Wen-Rui Hu — Eminent Pioneer and Prominent Leader of Microgravity Science in China

Kai Li^{1,2} · Jian-Fu Zhao^{1,2} · Qi Kang^{1,2} · Shuang-Feng Wang^{1,2}

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Abstract

In 2021, the scientific community celebrated the 85th anniversary of the Chinese scientist Academician Wen-Rui Hu. In addition to his innovative contributions to cosmic magnetohydrodynamics (MHD) during his early scientific career, he has initiated microgravity science research in China from the middle of 1980s, and made many pioneering contributions to microgravity fluid physics. He has also promoted researches in China in the fields of space material science, space biotechnology, space fundamental physics, and relevant applications. He is respected as the founder of microgravity science in China because of his eminent pioneering contributions and prominent leadership. This article tries to provide a brief historical perspective of the tireless explorations of Academician Wen-Rui Hu in the field of microgravity science and other relevant disciplines till today based on personal views of his former students and colleagues.

Keywords Academician Wen-Rui Hu · China Manned Space Program · Microgravity research in China · National Microgravity Laboratory · Drop Tower Beijing · Chinese recoverable satellite · China Space Station · Thermocapillary convection · Volume ratio · Gravity independence criteria of two-phase flow · Taiji program in space gravitational wave physics

Introduction

In 2021, the scientific community celebrated the 85th anniversary of the Chinese scientist Academician Wen-Rui Hu (Fig. 1). A special seminar was held in the National Microgravity Laboratory (NML), Institute of Mechanics, CAS (IM/CAS) on April 2, 2021 (Fig. 2) to pay a warm tribute to his birthday. An elaborate video was broadcast on the seminar to review the scientific life of Academician Wen-Rui Hu

and highlight his exceptional contribution to China's microgravity research and relevant applications. Academicians Wei-Hua Wang (Chair of Academic Committee of NML), Yue-Liang Wu (Chief Scientist of the Taiji Program in Space Gravitational Wave Physics), Prof. Gui-Ju Liu (Director of IM/CAS), and many scholars and specialists from relevant institutions congratulated him with a Chinese calligraphy of “Shou (longevity)”, a big birthday cake, congratulatory letters and flowers. On the seminar, Academician Yue-Liang Wu and other invited guests also delivered several academic lectures to the audiences on the latest progress in relevant fields.

Academician Wen-Rui Hu, born on April 2, 1936, started his academic career from cosmic magnetohydrodynamics (MHD) after he graduated from Peking University in 1958, and had become a famous scientist in this field with international influence and reputation by the early 1980s. In the mid-1980s, he initiated microgravity science research in China. Starting from thermocapillary convection and instability, he has gradually expanded his research interests to other disciplines of microgravity fluid physics, including gas–liquid two-phase flow, colloids and complex fluid, and combustion in microgravity. He has also promoted

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Guest Editors: Jian-Fu Zhao, Kai Li

✉ Jian-Fu Zhao
jfzhao@imech.ac.cn

¹ CAS Key Laboratory of Microgravity (National Microgravity Laboratory), Institute of Mechanics, Chinese Academy of Sciences (CAS), 15 Beisihuan Xilu, Beijing 100190, China

² School of Engineering Science, University of Chinese Academy of Sciences (UCAS), No.19(A) Yuquan Road, Beijing 100049, China

Fig. 1 Academician Wen-Rui Hu (Photo: NML-IM/CAS)



researches in China in the fields of space material science, space biotechnology, space fundamental physics, and relevant applications. He is the founding director of the National Microgravity Laboratory (NML), CAS). NML is now the sole microgravity science research center and user support center in China, as well as one of the famous microgravity

science research centers in the world. He is also one of the sponsors of the Chinese Society of Space Research (CSSR) and the founding president of the National Society on Microgravity Sciences and Applications (NSMSA), CSSR. Since 2008, he has also initiated and promoted China's space gravitational wave detection project. With the excellent efforts

Fig. 2 2020 NML Annual Meeting and Anniversary Celebration of the 85th Birthday of Academician Wen-Rui Hu held on April 2, 2021. In the right-down figure, Academician Yue-Liang Wu (right) and Prof. Qi Kang (Director of NML) showed the Chinese calligraphy of “Shou (longevity)” to the audiences (Photo: NML- IM/ CAS)



both on academic research and organizational work, he paves the way to the prosperity of microgravity science research in China nowadays. Therefore, Academician Wen-Rui Hu is respected as the founder of microgravity science in China, as well as a world-renowned microgravity scientist, because of his eminent pioneering contributions, prominent leadership of China's microgravity research, and great contributions to microgravity science. In view of his outstanding contributions to space science, especially microgravity science, Academician Wen-Rui Hu was elected as an academician of CAS in 1995, corresponding member of the International Academy of Astronautics (IAA) in 1996 and then academician of IAA in 2001.

In this paper, we attempt to provide a non-exhaustive summary of Academician Wen-Rui Hu's contributions to the various subjects. After briefly introducing his early studies on cosmic MHD, we focus on some representative researches initiated by Academician Wen-Rui Hu in the field of microgravity fluid physics and the latest progress. Moreover, his contributions to China's strategic planning on space science, especially on microgravity science, as well as his efforts in promoting domestic and international academic exchanges and cooperation, are also highlighted.

Achievements in Early MHD Researches

After graduated from the Department of Mathematics and Mechanics, Peking University in 1958, Academician Wen-Rui Hu started his academic career in the Power Laboratory, CAS. In 1960, he transferred to IM/CAS with the merger of these two institutes, and began to study MHD under the guidance of Academician Yong-Huai Guo (Yung-Huai Kuo), the deputy director of IM/CAS.

The first topic he studied is about MHD pipe flow. He obtains an analytical solution of MHD flow in a homopolar device with annular linear electrodes by using the series expansion method, in which the elementary solutions are summed and matched in two regions or the homopolar device (Hu 1977). Due to the death of Academician Yong-Huai Guo in an accident while on duty in 1968, the results were not published until 1977. A further development of this solution was published in 1987 (Hu 1987a, b), which was translated into Chinese and re-printed in 2009 with a historical note in memory of the 100th birthday of Academician Yong-Huai Guo (Hu 2009).

In view of his MHD research background, Academician Wen-Rui Hu was named in 1973 to participate in the study of celestial evolution, which is one of the Three Natural Science Issues, namely the origin of life, material structure and celestial evolution, advocated by Chairman Ze-Dong (Tse-Tung) Mao. He analyzed the mechanism of magnetospheric substorm and the MHD waves of the solar wind (Hu 1981),

and the accelerating mechanism of the solar wind and high speed stream from coronal holes (Hu 1982). He also analyzed the topological properties of magnetic field lines, and showed generally the three-dimensional features of the field (Hu et al. 1983) and the linear and non-linear characteristics of cosmic magnetic field (Hu 1983). In addition, he studied the co-rotational singularity of the density wave of spiral galaxies, and suggested a model of spiral galaxies based on the galactic shock wave. His researches involve the galaxy spiral structure, jet fine structure of radio galaxies, three-dimensional configuration of cosmic magnetic field, origin and acceleration of solar wind, solar flare, magnetospheric substorm, and so on. The fruitful innovative contributions won him the award of the National Advanced Sci-Tech Workers on the noted National Science Conference (Beijing, March 18–31, 1978), which is known as “the Spring of Science” in China after the end of “the Cultural Revolution” (Fig. 3).

His contributions on cosmos MHD also won him an international reputation. He was invited to give lectures in institutions in the United States and Canada, and became a member of the editorial board of *Astrophysics and Space Science* in 1981. In the same year, he was invited by the National Center for Atmospheric Research (NCAR), USA to serve as a senior visiting scientist at the High Altitude Observatory (HAO) for one year. For a native scientist trained domestically in China, it was extraordinary at that time.

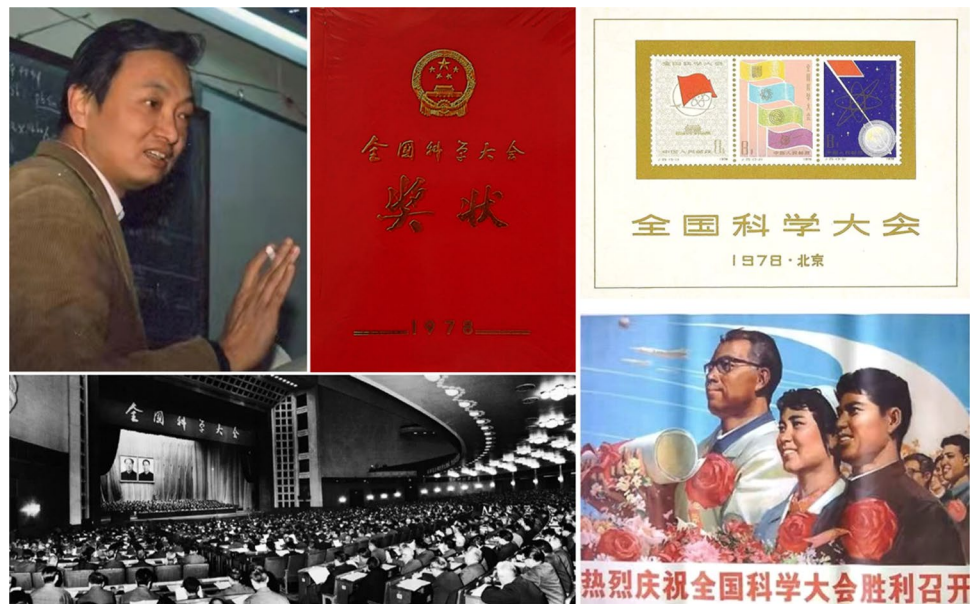
Academician Wen-Rui Hu summarizes his achievements on MHD in several monographs, among which *Cosmic Magnetohydrodynamics* (Hu 1987a, b, 2007), firstly published in 1987 and reprinted in 2007, may be the most influential one for its high academic level and practical value.

Pioneering Work and Contributions to Microgravity Fluid Physics

In 1987, Academician Wen-Rui Hu initiated and organized an investigation group to comprehensively investigate the development of international microgravity sciences, especially microgravity fluid physics. The group initially involved only three people, namely Ze-Mei Tang, Shuo-Chang Xu, and Academician Wen-Rui Hu himself, and subsequently grew to form the main backbone of NML.

If the previous MHD researches are mainly his personal accomplishments, the researches on microgravity sciences are more the achievements of close cooperation between Academician Wen-Rui Hu and his colleagues. Their study covers thermocapillary convection and the stability, thermocapillary migration of fluid droplet/bubble, two-phase gas–liquid flow and heat transfer with phase change, colloids and complex fluids, combustion science and fire safety of manned spacecraft in alternative gravity

Fig. 3 Academician Wen-Rui Hu won the award of the National Advanced Sci-Tech Workers on the National Science Conference in 1978, for which stamps and posters were issued specially to celebrate “the Spring of Science”



environments, as well as space material science related to the preparation of metallic glass and colloidal crystals in microgravity. Some important pioneering work and the subsequent developments are briefly reviewed as follows.

Academician Wen-Rui Hu and his colleagues systematically study the thermocapillary convection in half floating zones. The liquids being studied are divided into two categories: One corresponds to the case of liquids with very low Prandtl number (Pr), i.e. $Pr < 1$, such as semiconductors, metals and alloys related to space materials processing. They usually are non-transparent liquids and easy to be contaminated on their surface. The other corresponds to the case of liquids with $Pr > 1$, which are usually transparent and easy for optical diagnostic such as silicon oils.

In the case of $Pr < 1$, due to difficulties in experimentations including the non-transparency and easy free-surface pollution of the liquids, experiment studies are extremely limited till now. Academician Wen-Rui Hu and his colleagues (Han et al. 1996; Sun et al. 1997) experimentally investigated the thermocapillary convection in a small-sized mercury liquid bridge of 3 mm in diameter on the ground. To overcome the observation problem of opaque liquid bridge, non-contact optical diagnostic techniques based on the free surface oscillation were developed to monitor surface flow and surface deformation. They observed directly the onset process of oscillation on a liquid bridge with low Pr number for the first time, and also pointed out that the critical Marangoni number (Ma_{c2}) for the second bifurcation to oscillatory flow may prone to be over-estimated in the experiments due to the pollution film appearing on the free surface which easily alters the surface tension and the corresponding critical conditions.

Later, there are only very limited experiments on thermocapillary convection in low Pr number liquid bridges (Takagi et al. 2001; Yang and Kou 2001). A novel diagnostic method by using the ultrasonic detection technique with trace particles was also proposed by JAXA to overcome the difficulty for observing the flow inside non-transparent liquids (Matsumoto et al. 2005). Ultrasonic velocimetry was also used by Cramer et al. (2014) to measure fluid velocities in a model of a Czochralski crystal growth system, in which the ternary alloy GaInSn melt having a Prandtl number of 0.021 was used as the working liquid.

However, it should be pointed out here that although the two bifurcation theory (Levenstam and Amberg 1995) of low Pr number liquid bridge has been widely accepted, the feature of the first bifurcation from axisymmetric stationary flow to non-axisymmetric stationary flow has not been proven experimentally up to now. Most of the results relevant to instability of thermocapillary convection in low Pr number liquid bridges come from a large number of numerical simulations (Li et al. 2015; Le et al. 2021). The innovation of low Pr number liquid bridge experimental technology is still an extremely urgent challenge in this field.

On the other hand, with the benefit of its transparency to the optical measurements, liquid bridges in the case of $Pr > 1$ attracted extensive theoretical studies, numerical simulations, 1 g-experiments with small Bond number by using small size liquid bridges on the ground, and μ g-experiments both in in space and in ground-based short-term microgravity environments. The aim has also shifted from crystal growth in space to fundamental fluid dynamics in microgravity, including critical conditions and, after the onset of oscillation, successive bifurcation routes, even to chaos or

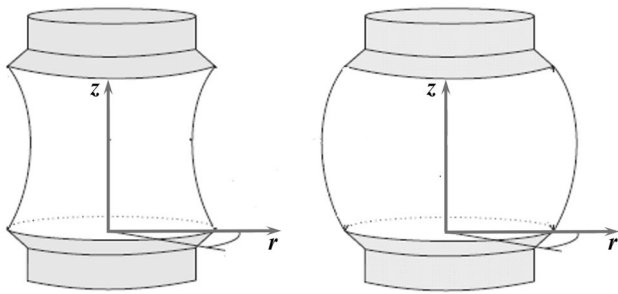


Fig. 4 Comparison between the slender liquid bridge $Vr < 1$ (left) and the fat one $Vr > 1$ (right)

turbulence. Thus, it becomes a hotspot in microgravity fluid science. In this field, Academician Wen-Rui Hu and his colleagues have made unique contributions.

Academician Wen-Rui Hu and his colleagues proposed a brand new geometrical critical parameter, the volume ratio Vr of the liquid bridge, which is more precisely to describe the onset of oscillation in comparison with the aspect ratio $Ar = H/R$, namely the ratio between the height H and the radius R of the liquid bridge. The volume ratio Vr is defined as follows (Hu et al. 1994),

$$Vr = V/V_0 = \frac{1}{r_0^2} \int_0^1 r^2(z) dz \quad (1)$$

where $r_0 = 1/A$ denotes the non-dimensional radius of the liquid bridge with an ideal cylindrical free surface, while $r = r(z)$ denotes the non-dimensional radius of the actual curved free surface at the non-dimensional location z . All

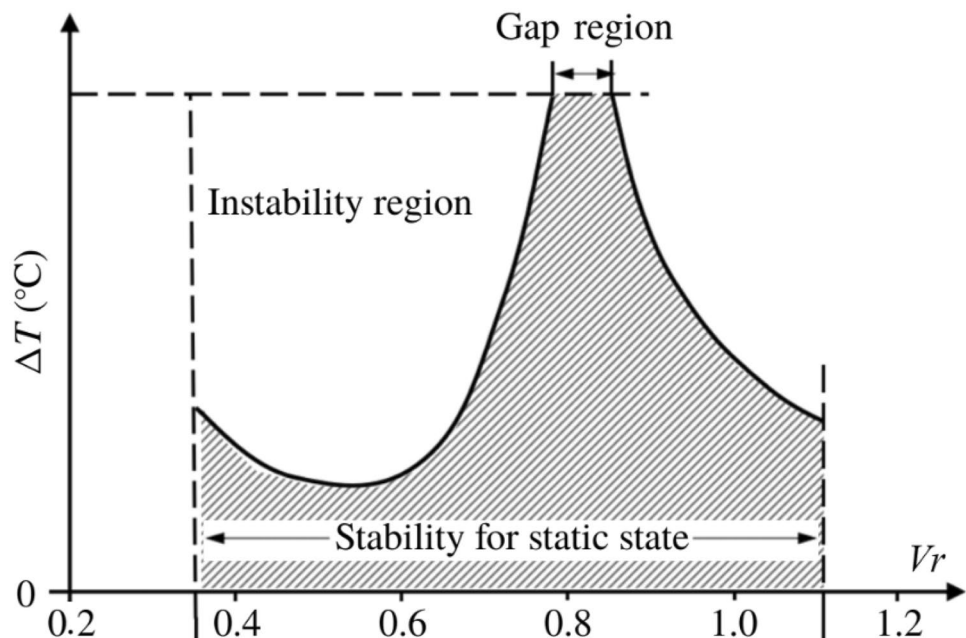
dimensions here are characterized by the height H of the liquid bridge. Figure 4 schematically shows the comparison between the slender liquid bridge with $Vr < 1$ and the fat one with $Vr > 1$.

Academician Wen-Rui Hu and his colleagues have carried out a lot of theoretical, numerical and experimental work to systematically and comprehensively study the crucial influence of the volume ratio on the instability of thermocapillary convection. The corresponding margin instability profile depending on the volume ratio of liquid bridge are given typically in Fig. 5. It separated into two branches of the slender liquid bridge and the fat one, and the critical conditions are relatively high in the gap region. Special axisymmetric oscillation mode with the azimuthal wave number $m = 0$ is revealed in the gap region (Xun et al. 2010).

The results imply that the effect of the free surface curvature determined by the stress balance in the normal direction plays a crucial role in the spatio-temporal evolution of the thermocapillary convection driven by the stress balance in the tangential direction. The critical conditions, such as the critical temperature difference, oscillation frequency and flow structure, are highly dependent on the volume ratio of the liquid bridge coupled with other critical parameters, which have been verified by a bundle of numerical simulations (Tang and Hu 1994; Hu and Tang 2003; Xun et al. 2010), ground experiments on small sized liquid bridges in normal gravity (Hu et al. 1994; Cao et al. 1991a, b; Aa et al. 2011), and space experiments in microgravity aboard China space lab Tiangong-2 (Kang et al. 2019c, 2020).

In the 34 months from 2016 to 2019, there are 740 groups of experimental runs on thermocapillary convection of liquid bridges completed and a large amount of space experimental

Fig. 5 Schematic of the dependence of critical conditions on the volume ratio Vr of liquid bridges



data accumulated aboard TG-2 (Kang et al. 2019c, 2020). The comprehensive effect of the aspect ratio and the volume ratio of liquid bridges on critical conditions and oscillation characteristics of thermocapillary convection instability were studied in detail (Fig. 6). It indicated that the Ar – Vr space can be divided into two regions, zone 1 and zone 2, and the values of critical Marangoni number and oscillation period are different between these two zones. In zone 1, the oscillation has characteristics of large critical Marangoni number and short oscillation period; in zone 2, the oscillation has characteristics of small critical Marangoni number and long oscillation period. The demarcation line between zone 1 and zone 2 is approximately a straight line, $Ar - 3.2Vr + 1.4 = 0$ through fitting. It was also found that the heating rate affects the selection of critical mode, which results in a jump change of critical temperature difference.

In addition to the liquid bridge configuration, the highly dependency of the critical parameter, the volume ratio, is also applicable to the configurations of rectangle liquid pool (Li et al. 2012) and annular liquid pool (Kang et al. 2019a, b, d).

Academician Wen-Rui Hu and his colleagues identified the subharmonic bifurcation in a liquid bridge of 10 cSt silicon oil (3 mm in diameter) both by numerical simulation (Tang and Hu 1995) and corresponding experimentation on the ground (Aa et al. 2010). The Feigenbaum constant of 4.6 ± 0.1 was determined, nearly identical to its universal value of 4.664 (Feigenbaum 1979). In a successive numerical simulation, Li et al. (2016) studied the bifurcation routes to chaos of thermocapillary convection in two-dimensional limited liquid layers filled with 10 cSt silicone oil. They observed the variations in the spatial structure and temporal evolution of thermocapillary convection and a complex sequence of transitions as the laterally applied temperature difference is raised. The results showed that the limited extension of the liquid layer significantly influences the tempo-spatial

evolution of thermocapillary convection. Moreover, the bifurcation route is sensitive to the changes in the aspect ratio of the limited liquid layer. The process of destabilization and transition routes of thermocapillary convection in an annular (cylindrical) liquid pool was studied experimentally by Kang et al. (2019a, b, d) aboard China recoverable satellite SJ-10. The system is established by heating the inner copper wall and cooling the outer copper wall of the annular liquid pool. It was found that thermocapillary convection generally stays in the steady periodic oscillation state, while transitions appear in the condition when the temperature difference between two sides of the liquid layer is large. Three types of transition routes have been observed, including the quasi-periodic route, the period-doubling bifurcation and intermittency. All these three transition routes could be acquired likewise in ground-based experiments, however, thermocapillary convection in the microgravity is harder to transit to the phase of bifurcation, and the flow even returns to the periodic oscillation state after the period-doubling bifurcation appears. It is totally different from the transition process in buoyant-thermocapillary convection on the ground, which is the transition from the periodic state to the transition, and then to chaos in a short time. A comprehensive review on the up-to-date experimental and numerical results on the transition of surface tension gradient-driven convection, especially the nonlinear analysis on the flow bifurcations to chaos, was presented very recently by Academician Wen-Rui Hu and his colleagues (Guo et al. 2021).

The second subfield of microgravity fluid physics that Academician Wen-Rui Hu and his colleagues systematically studied is thermocapillary or Marangoni migration of liquid droplets and/or gas bubbles suspended in an ambient fluid with a non-uniform temperature field, mainly focusing on nonlinear dynamics in the case of medium and high Marangoni number.

Based on the years of ground-based research of the drop or bubble migration by means of matched-density and the

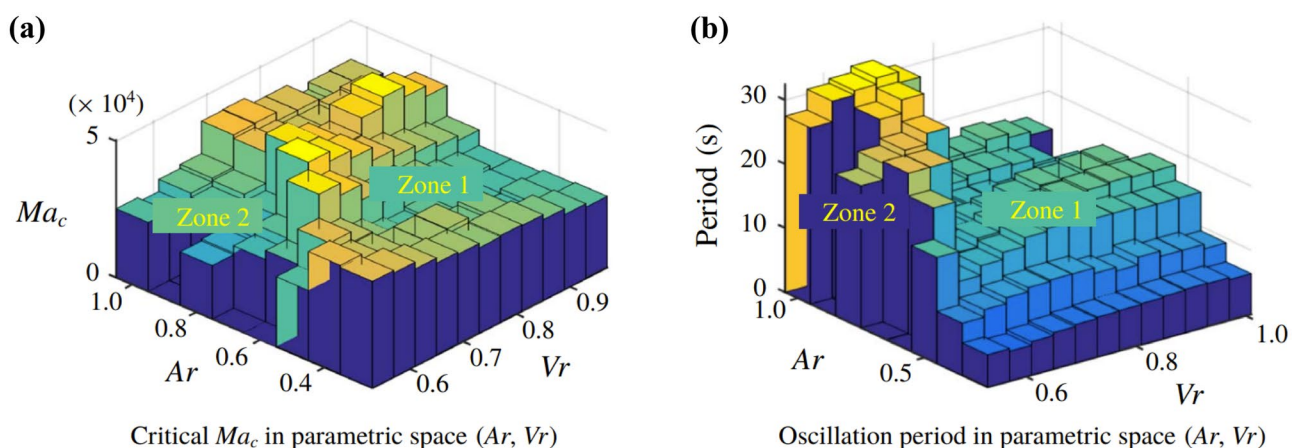


Fig. 6 Distributions of oscillation starting condition and period in Vr – Ar parametric space (Kang et al. 2019c)

facility of drop shaft (Xie et al. 1996, 1998), the space experiment of drop thermocapillary migration at large Ma was performed aboard the fourth unmanned spacecraft Shenzhou (SZ-4) of China in 2002 (Xie et al. 2005). FC-75 and 5cSt silicone oil were adopted as the mediums for drop and matrix liquid phases, respectively. Accurate volume of FC-75 liquid was injected into the matrix liquid to form a preset drop size with a special dual-pipe injection technique. The migration behaviors of drops moving in matrix liquid with a set of drop diameters under different temperature gradients were observed and the migration properties and nonlinear dynamic features were attained. Space experimental data shows a descending proclivity that the scaled drop migration velocity V/V_{YGB} , here V_{YGB} denotes the velocity predicted by the linear YGB model (Young et al. 1959) for the case of $Ma < 1$, dwindle with the increment of Marangoni number, and the dimensionless velocity V/V_{YGB} gradually approaches its asymptotic value 0.4 approximately when the Marangoni number reaches up to a large value of 5500.

Another space experiment on bubble migration had also been performed aboard the 22nd recoverable satellite of China, which was launched in 2005 (Kang et al. 2008; Cui et al. 2008). KF96L 5cSt silicone oil was used as the continuous phase medium in the space experiment. The Reynolds number and Marangoni number ranged from 2.3 to 217.9 and from 98.04 to 9288, respectively. Several groups of experiment results were obtained on bubble's interaction. The analysis of experiment results indicated that the velocity of smaller bubble decreased when a large bubble was migrated over it, and this effect increased when the size ratio of two bubbles was increased.

In addition to experimental studies, Academician Wen-Rui Hu and his colleagues also conducted a series of theoretical analyses (Sun and Hu 2002, 2003; Wu and Hu 2012, 2013) and numerical simulations (Geng et al. 2002; Wang et al. 2004; Gao et al. 2007, 2008; Zhao et al. 2010, 2011; Yin et al. 2008, 2011, 2012) on Marangoni migration of droplets/bubbles. The detailed discussions and physical explanations of migration phenomena were presented for the different values of the Marangoni numbers and Reynolds numbers of continuous phases and drops, the ratios of drop densities and specific heats to those of continuous phases, as well as the initial and boundary conditions. The influence of the deformation of droplets/bubbles, as well as the complicated migrating processes, corresponding to fairly large Marangoni number was studied in detail. Furthermore, the interaction of two droplets/bubbles in the thermocapillary migration were analyzed and verified by space and ground experiments. These findings are very helpful for understanding the strong nonlinear dynamic behavior of thermocapillary migration phenomena in the case of medium and high Marangoni number.

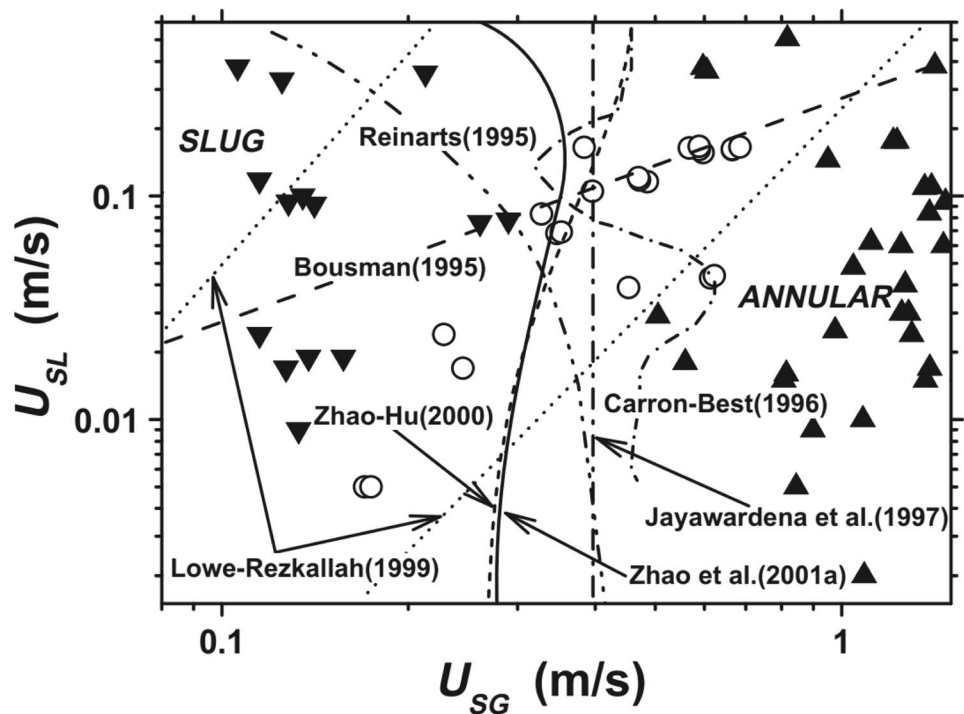
Two-phase gas–liquid flow and heat transfer in microgravity is the third subfield of microgravity fluid physics that Academician Wen-Rui Hu and his colleagues systematically studied, including theoretical analyses and experimental investigations.

Zhao and Hu (2000) presented a semi-theoretical Weber number-type model for slug-to-annular flow transition of two-phase gas–liquid flow in microgravity, based on the dominant force balance hypothesis between gas phase inertial force and surface tension force acting on the interface. Comparing comprehensively with the experimental data and other common-used models, it was verified (Zhao 2010a) that Zhao-Hu model can be used to accurately predict the transition boundary between slug and annular flow in microgravity with fairly large range of parameters, including working fluid and tube size (Fig. 7). Furthermore, it can also accurately predict the results obtained from low Bond number simulated microgravity experiments by using neutral suspension liquid–liquid system and small-scale capillary liquid–gas system on the ground. A slight revision was reported by Zhao et al. (2001a) to account the influence of cross-section shape of the tube, and then extended its application from circular tube to square one.

A series of experiments of flow patterns and pressure drop of two-phase air–water flow through a square channel were conducted both in normal and reduced gravity aboard the Russian IL-76 reduced gravity aircraft in July 1999. The test channel had a square cross-section of 12 mm × 12 mm and a length of 960 mm (Zhao et al. 2001a, b). The influences of the gravity level and the cross-sectional shape on flow pattern transition and pressure drop were studied. It was found that gravity could affect the characteristics of bubble and slug flows and the transition condition between them, but could not affect obviously the transition condition between slug and annular flows. Based on the characteristic of bubble flow in microgravity, Zhao et al. (2002) proposed that the friction factor and two-phase Reynolds number should be defined by the liquid material properties and mixture velocity of two-phase flow, and thus obtained a good correlation for the data of pressure drop in microgravity bubble flows. In the whole range of studied parameters, there were obvious differences between the experimental data of two-phase pressure drop and the predictions of the commonly used correlations in the literature. Among them, Friedel model agreed with the experimental data quite well, and then could be used to estimate pressure drop in two-phase systems for space application (Zhao et al. 2001b).

Collaborating with the researchers from the Keldysh Research Center of Russia, the first experimental study on two-phase flow patterns in a long-term, steady microgravity environment was carried out aboard the Russian Space Station Mir in August 1999 (Zhao et al. 2001c, d). Some data in partial gravity conditions were also collected by

Fig. 7 Comparisons of Zhao-Hu model with experimental data and other common-used models for slug-to-annular flow transition in microgravity (Zhao 2010a)



rotating the experimental facility with constant speeds (Zhao et al. 2004). The test tube had a length of 356 mm and a diameter of 10 mm. Carbogal and air were used as the liquid and the gas phase, respectively. The experimental data of flow patterns observed in partial and microgravity conditions were compared with predictions of transition models of flow patterns in microgravity commonly used in the literature, including Zhao-Hu model (Zhao and Hu 2000) which was further verified.

Based on the observed characteristics of two-phase flow structures in different gravity conditions, Zhao et al. (2000) presented gravity-independent criteria as follows,

$$Bo = \frac{(\rho_L - \rho_G)gd^2}{\sigma} \leq Bo_{cr}, Fr_{SG} = \frac{U_{SG}}{\sqrt{(\rho_L - \rho_G)gd/\rho_G}} \geq Fr_{SG,cr} \quad (2)$$

where the critical values were suggested as $Bo_{cr} = 1.5 \sim 6$, and $Fr_{SG,cr} = 0.54 \sim 2.2$, respectively. These criteria were later called as the dominant force criteria (Du et al. 2018, 2019). Another boundary corresponding to a constant of the gas phase superficial Weber number $We_{SG} = \rho_G U_{SG}^2 d / \sigma = Fr_{SG}^2 / Bo$ was also suggested between the surface tension dominant region and gas phase inertial force dominant region. The critical value of the gas phase superficial Weber number can be obtained by solving the intersection of Eq. (2) for the first two boundaries. Thus, three regions, namely the gravity dominant region (GDR), the surface tension dominant region (SDR) and gas phase inertial force dominant region (IDR), can be

categorized in the $Bo-We$ parameter space as shown in Fig. 8 (Zhao 2010b), which is similar to Baba et al. (2011) except for the different definition of Froude number.

The dominant force criteria were used successfully in the design of the cryogenic loop heat pipe (He et al. 2020) for space test on cryogenic two-phase thermal transport aboard the China's new technology test satellite SJ-20, which was

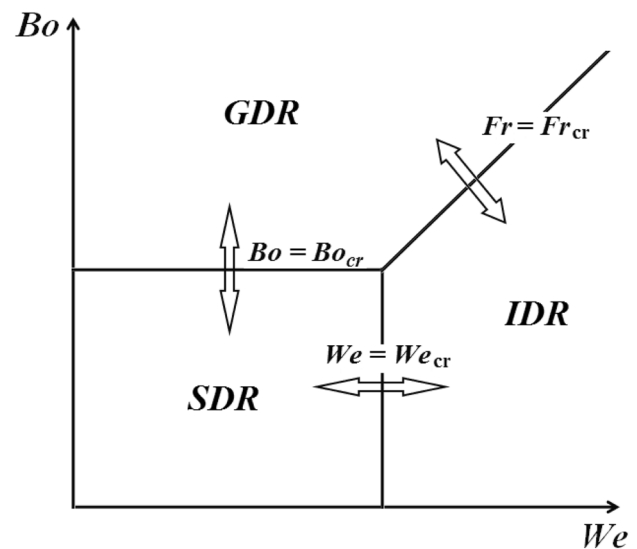


Fig. 8 Dominant force regions in the $Bo-We$ parameter space, in which the inertial force is relevant to the gas phase (Zhao 2010b)

launched in the end of 2019. It was also recommended by Brendel et al. (2021) for potential space applications.

Organizer and Leader of China's Microgravity Research

Academician Wen-Rui Hu is not only a famous scientist, but also an active academic organizer and social activist. In 1979, he participated in the joint initiative of the establishment of the Chinese Society of Space Research (CSSR) proposed by scholars and specialists in the field of space science and application, which led to the formal establishment of CSSR in 1980. In 1991, he further initiated the establishment of the National Society of Microgravity Science and Application (NSMSA), which was finally established as one of the branches of the CSSR in 1993. Academician Wen-Rui Hu was elected to serve as the first president of NSMSA/CSSR. Under the leadership and guidance of Academician Wen-Rui Hu, NSMSA/CSSR has become an excellent platform for condensing the team of Chinese microgravity research in microgravity sciences and applications and strengthening domestic and international academic exchanges and cooperation (Zhao et al. 2021). Up to now, NSMSA/CSSR has successfully held a total of 12 national conferences on microgravity sciences, and hosted or co-hosted several series of Bilateral Workshops on Microgravity Sciences between China and Germany, Japan, Russia, France, and other countries or regions, as well as Pan-Pacific Basin Workshops and International Seminar on microgravity sciences for many times (Fig. 9). In particular, after successfully holding six consecutive bilateral workshops alternately in China and Japan, the China-Japan Bilateral Workshop on Microgravity Sciences was expanded as the China-Japan-Korea

Symposium on Microgravity Sciences in 2010, and finally developed in 2014 into the Asian Microgravity Symposium (AMS) held biennially, which has now become an influential academic platform in the field of microgravity science both in Asia and in the world. The 10th AMS (AMS-2014, Seoul, South Korea), 11th AMS (AMS-2016, Hokkaido, Japan), and 12th AMS (AMS-2018, Zhuhai, China) have been held successfully. The 13th AMS (AMS-2020) originally planned to be held in Jeju Island, South Korea in November 2020. Due to the impact of COVID-19, it has been postponed twice. Presently preparations are under way, and it is expected to be held at an appropriate time this year.

Academician Wen-Rui Hu is distinguished by his intense international activities. He served as a member of the Space Processing and Microgravity Application Committee, International Federation of Astronautics (IAF), vice-chairman of the Scientific Committee G (microgravity), Committee on Space Research (COSPAR), as well as chairman, member or standing member of many other domestic and international academic organizations/programs. He actively participated in the cooperation and communication between China and foreign academic communities, promoting mutual understanding and friendship (Fig. 10).

He has also been invited to give plenary or invited lectures both on domestic and international conferences. For example, among many others, a sectional lecture, entitled *Onset of Oscillatory Thermocapillary Convection*, was given by him on the 22nd International Congress of Theoretical and Applied Mechanics (ICTAM) in 2008 (Hu and Tang 2013), which is the third sectional lecture in the history of ICTAM given by Chinese scientists from the mainland or the fourth given by Chinese scholars including overseas Chinese. Academician Wen-Rui Hu also jointly organized on 22nd ICTAM with Prof. H. Rath

Fig. 9 Academician Wen-Rui Hu presided over domestic/bilateral/international conferences relevant to microgravity science in 1990s (Photos: NSMSA/CSSR)



Fig. 10 Academician Wen-Rui Hu participated in the cooperation and communication between China and foreign academic communities (Photo: NML-IM/CAS)



one of the 16 pre-nominated sessions on fluid mechanics, namely FM16 *Microgravity Fluid Mechanics*. His intense activities, together with those of other Chinese participants, fully demonstrated the rapid improvement of China's academic level on mechanics and contributed to the success of China's bid to host the 23rd ICTAM in Beijing, China in 2012.

At the same time as his initial research on microgravity, Academician Wen-Rui Hu was recommended by CAS in 1987 and served as a member of the first committee of experts in the field of aerospace of the National High-Tech R&D Program (863 Program) of China. He was responsible for the demonstration of the Space Application System of China Manned Space Program (CMSP) and took the responsibility of the development of the strategy and planning for space science, especially microgravity science and application, and put forward the roadmap for the development of microgravity science in China.

The development of microgravity science needs experiments in microgravity environments, both space experiments and ground-based short-time microgravity experiments. Academician Wen-Rui Hu has served from 1992 to 1994 as the chief scientist and deputy director of the General Establishment of Space Science and Application (GESSA), CAS, the headquarters of the Space Application System of CMSP. The responsibility that he took is mainly focusing on the mission planning, implementation, achievement outreach of microgravity fluid physics and combustion science (Fig. 11). He has long been the chief scientist in the subsystem of microgravity fluid physics and combustion of the Space Application System, CMSP, and made great contributions, from the experiment of droplet thermocapillary migration aboard SZ-4 in the first stage of CMSP to the construction of the Fluid Physics Rack (FPR), Two-Phase System Rack (TPSR) and a great amount of scientific research projects in the third stage of CMSP. His insights and contributions

Fig. 11 Academician Wen-Rui Hu presided over the preparatory meeting for Space Application System of CMSP in the early 1990s (Photo: NML-IM/CAS)



will continue to benefit the development of microgravity research in China.

In addition to CMSP, Academician Wen-Rui Hu also actively seeks other space experiment opportunities to better develop China's microgravity science. Among many successful cases, the most notable projects are those aboard three Chinese recoverable satellites, namely RS-22, SJ-8, and SJ-10, which are China's 22nd to 24th recoverable satellites recovered successfully.

In the first two projects, microgravity experiments aren't the main mission but supplementary ones aboard these satellites. Academician Wen-Rui Hu acted in fact the General Engineer and Chief Scientist of the projects, while NML, as the leading department of the sub-system of scientific payloads, took the responsibility of scientific mission planning and implementation. There are 3 experiments, including pool boiling on a thin Pt wire (Zhao et al. 2008), bubble thermocapillary migration and interaction (Kang et al. 2008), and mammalian cell growth in a novel counter sheet-flow sandwich cell culture device (Sun et al. 2008), aboard RS-22 which was launched in 2005. SJ-8 was launched in 2006. The recoverable capsule was used for the breeding experiments as the main mission, while the un-recoverable capsule was used for microgravity research, including bubble dynamics and heat transfer during quasi-steady pool boiling on plane plate (Zhao et al. 2009), surface configuration and volume ratio effect of thermocapillary convection in a liquid pool, diffusion and mass transfer process of biomaterials, dynamical behavior of granular matter (Hou et al. 2008), smoldering of non-metallic materials (Wang et al. 2008), pre-ignition characteristics of wire insulation

(Kong et al. 2008), development of higher plants in closed ecosystem (Zheng et al. 2008), and mouse preimplantation embryos (Ma et al. 2008). A microgravity experiment support subsystem (MESS) was developed to provide power supply and distribution, telemetry and remote control, data acquisition, data compression, data cache and wireless downlink for on-board experimental devices, and the operation management of on-board experimental devices, ground receiving and preprocessing of experimental data for scientists on the ground. There was also a flight technique test of spaceborne accelerometer, which was also used to measure simultaneously the residual gravity environment aboard SJ-8. The major results obtained from the two missions were published in a special issue of *Microgravity Science and Technology* in August 2008, of which Academician Wen-Rui Hu served as the Guest Editor (Hu 2008).

The recoverable satellite "Shi-Jian Ten" (SJ-10) mission, originally organized by China National Space Administration (CNSA) in the middle of 2000s, is the second mission of the Strategic Priority Research Program (First Stage) on Space Science, CAS. Academician Wen-Rui Hu is the Chief Scientist (Fig. 12), who has made a lot of indispensable key contributions to the mission planning, selection of candidate scientific projects, engineering implementation, and achievement outreach. The National Space Science Center (NSSC), CAS is the general engineering management organization, while NML, on behalf of IM/CAS, is in charge of the scientific application system, which is one of six systems of the mission. There are totally 28 space experiments integrated into 19 payloads (Hu et al. 2014), including 18 experiments in the field of microgravity physical science (microgravity

Fig. 12 Academician Wen-Rui Hu is the Chief Scientist of the mission SJ-10 (Photo: NSSC)



fluid physics 6, microgravity combustion science 4, space material science 8) and 10 experiments in the field of space life science (radiation biology 3, gravitational biology 3, space bio-technology 4).

SJ-10 was launched on April 6, 2016. The recoverable capsule was landed safely on the ground after 12 days of the launch, and the experiments of fluid physics and combustion aboard the un-recoverable capsule continued for another week afterward. To support the analysis of space experimental data, a series of joint grants were founded by the National Natural Science Foundation of China (NSFC) and the CAS in 2017. Some of the main results related to the mission SJ-10 were summarized in two monographs (Hu and Kang 2019; Duan and Long 2019), published jointly by Science Press, Beijing and Springer Nature Singapore Pte Ltd. in 2019.

In 2008, Academician Wen-Rui Hu actively initiated the demonstration for space gravitational wave detection in China. He, as one of executive chairmen, organized three Xiangshan Science Conferences on space gravitational wave detection in 2008, 2011 and 2018, respectively (Fig. 13). China's current two plans on space gravitational wave detection, namely Taiji and Tianqin, have evolved from these efforts. Furthermore, Academician Wen-Rui Hu once served as the first Chief Scientist of the program Taiji, and is still very active as Taiji's General Consultant after his retirement (Hu and Wu 2017).

At present, the first stage of the two plans has been successfully completed. Two pilot satellite missions, namely Taiji-1 and Tianqin-1 for the corresponding plans, were respectively launched in Jiuquan Satellite Launch Centre (JSLC) in August, 2019 and in Taiyuan Satellite Launch Center (TSLC) in December, 2019 in order to verify the plans' feasibility. Several key technologies have been successfully tested and verified (Luo et al. 2020; Wu et al. 2021), providing a good start and sound foundation for the subsequent development of corresponding plans. It



Fig. 14 The Drop Tower Beijing (Photo: NML-IM/CAS)

is expected that China's space gravitational wave detection program will be implemented in the early 2030s.

Academician Wen-Rui Hu also led the completion of the feasibility demonstration of the construction of the National Key Laboratory of Microgravity Science and Application in 1993, which was approved to start construction in 1995 and

Fig. 13 Academician Wen-Rui Hu presided over meetings of the Taiji program in space gravitational wave detection (Photo: NML-IM/CAS)



was officially named the National Microgravity Laboratory (NML), CAS. He was appointed the first Director of NML. During the construction period from 1995 to 2003, there are 35 sets of advanced large-scale equipment imported from abroad, 14 sets of advanced experimental devices/systems developed domestically. The Drop Tower Beijing (Fig. 14), which is 110 m in height and can provide a duration of 3.6 s for microgravity experiments, has also been built for conducting ground-based short-term microgravity experiments (Zhang et al. 2005). There are two assembly configurations of the drop capsule in the Drop Tower Beijing, namely single-capsule mode and double-capsule mode. The single capsule mode can provide convenient operation but the microgravity quality of $10^{-2} \sim 10^{-3} g_0$ (here, g_0 denotes the normal gravity on Earth) is lower. On the other hand, the second mode, consisting of inner capsule (experiment package) and outer capsule (drag shield), can provide high quality microgravity environment of about $10^{-5} g_0$ to meet requirement of precise microgravity experiments (Min et al. 2021).

Based on the principle of “studying while building”, Academician Wen-Rui Hu and his colleagues had also completed in the construction period of NML a number of space experiments, including the multi-layer thermocapillary convection experiment aboard the satellite SJ-5 (1999), two-phase gas–liquid flow experiment aboard the Russian space

station MIR (1999) and droplet thermocapillary migration experiment aboard SZ-4 (2002–2003), as well as a large number of ground-based short-time microgravity experiments, theoretical analyses and numerical simulations. After he stepped down as Director of NML in 2004, he served as the Chair of NML Academic Committee until 2015 and then the Honorary Chair of NML Academic Committee. Up to now, he is still very active in various affairs related to the development of NML. Under the leadership and guidance of Academician Wen-Rui Hu, NML, as the only research center of microgravity science and user support center in China, has become one of the world-renowned microgravity science research centers.

Academician Wen-Rui Hu authored and co-authored hundreds of scientific works, including more than a dozen monographs. In addition to those on MHD mentioned above, several monographs, shown in Fig. 15, in the field of microgravity science are the ones most referred to scientists around the world.

The achievements of Academician Wen-Rui Hu were acknowledged both by the international scientific community and by the Chinese government, awarding him the most prestigious awards. In particular, he won the Special Award of the National Science and Technology Progress Award in 2003 for his outstanding contribution to CMSP, especially to the Scientific Application System of CMSP. On October 1,



Fig. 15 These books are referenced by scientists worldwide

Fig. 16 Academician Hu on the 70th Anniversary of the Founding of the People's Republic of China (top: photo by Academician Wei-Hua Wang). Certificates of the Special Award of the National Science and Technology Progress Award in 2003 (bottom-left) and Commemorative Medal of “Celebrating the 70th Anniversary of the Founding of the People's Republic of China” in 2019 (bottom-right)



2019, he was invited to the 70th Anniversary of the Founding of the People's Republic of China held in Tiananmen Square, Beijing, China, and was awarded a commemorative medal of “Celebrating the 70th Anniversary of the Founding of the People's Republic of China” (Fig. 16).

Conclusions

A 85-year period is only a short moment in the long river of history, but at this moment, Academician Wen-Rui Hu made outstanding contributions to the promotion of human knowledge of physics in space. Particularly, as the eminent pioneer and prominent leader of microgravity research in China, his foresight, pragmatism and preciseness have made him and his colleagues create many outstanding achievements in the field of microgravity science and application.

The Core Module Tianhe of the Chinese Space Station (CSS) was successfully launched into orbit last year. At present, six astronauts from two teams have visited the Core Module Tianhe. The two experiment modules, namely Experiment Module I Wentian and Experiment Module II Mengtian, will be launched into orbit this year to complete the construction

of the CSS Tiangong. It can 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. All of these owe much to Academician Wen-Rui Hu. For all this and all that Academician Wen-Rui Hu has done and is doing, ... “Health and longevity, Academician Wen-Rui Hu!”.

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References

- Aa, Y., Li, K., Cao, Z.H., et al.: Aspect-ratio dependent oscillatory thermocapillary convection in the floating half zone. *Sci. China Phys. Mech. Astron.* **54**, 338–341 (2011)

- Aa, Y., Li, K., Tang, Z.M., et al.: Period-doubling Bifurcations of the Thermocapillary Convection in a floating half zone. *Sci. China Phys. Mech. Astron.* **53**, 1681–1686 (2010)
- Baba S., Sakai T., Sawada K., et al.: Proposal of experimental setup on boiling two-phase flow on-orbit experiments onboard Japanese experiment module ‘KIBO’. *J. Phys. Conf. Ser.* **327**, 012055 (2011)
- Brendel, L.P.M., Braun, J.E., Groll, E.A.: Comparison of gravity independence criteria for two-phase flow. *J. Thermophys. Heat Transfer* **35**(4), 830–842 (2021)
- Cao, Z.H., Xie, J.C., Tang, Z.M., et al.: The influence of buoyancy on the onset of oscillatory convection in a half floating zone. *Adv. Space Res.* **11**(7), 166–170 (1991a)
- Cao, Z.H., You, H.T., Tang, Z.M., et al.: Experimental investigation of thermocapillary convection in a half floating zone. *Adv. Space Res.* **11**(7), 232–236 (1991b)
- Cramer, A., Pal, J., Gerbeth, G.: Ultrasonic flow measurements in a model of a Czochralski puller. *Flow Measur. Instr.* **37**, 99–106 (2014)
- Cui, H.L., Hu, L., Duan, L., et al.: Space experimental investigation on thermocapillary migration of bubbles. *Sci. China Ser. G* **51**, 894–904 (2008)
- Du W.F., Yue S.W., Zhao J.F., et al.: Criteria of Gravity Independence in Multiphase Thermal Fluid Systems. *J. Heibei Univ. Water Resources Electr. Eng.* **2019**(2), 1–7 (2019)
- Du W.F., Zhao J.F., Li K.: Criteria for Dominated Force Regime Map in Multiphase Thermal Fluid System. *J. Heibei Univ. Water Resources Electr. Eng.* **2018**(1), 1–5 (2018)
- Duan, E.K., Long, M.: *Life Science in Space: Experiments on Board the SJ-10 Recoverable Satellite*. Beijing & Springer Nature Singapore Pte Ltd., Science Press (2019)
- Feigenbaum, M.J.: The onset spectrum of turbulence. *Phys. Lett.* **74A**, 375–378 (1979)
- Gao P., Yin Z.H., Hu W.R.: Numerical investigation of thermocapillary migration of the drop for large Marangoni numbers. *Sci. China Ser. E – Tech. Sci.* **50**(5), 694–696 (2007)
- Gao, P., Yin, Z.H., Hu, W.R.: Thermocapillary motion of droplets at large Marangoni numbers. *Adv. Space Res.* **41**, 2101–2106 (2008)
- Geng, R.H., Hu, W.R., Jin, Y.L., et al.: Unsteady model of drop Marangoni migration in microgravity. *Acta Mech. Sinica* **18**(3), 227–234 (2002)
- Guo, Z., Li, K., Kang, Q., et al.: Study on bifurcation to chaos of surface tension gradient driven flow. *Adv. Mech.* **51**(1), 1–28 (2021)
- Han, J.H., Sun, Z.W., Dai, L.R., et al.: Experiment on the thermocapillary convection of a mercury liquid bridge in a floating half zone. *J. Crystal Growth* **169**(1), 129–135 (1996)
- 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. *Microgravity Sci. Technol.* **32**(3), 179–188 (2020)
- Hou, M., Liu, R., Zhai, G., et al.: Velocity distribution of vibration-driven granular gas in Knudsen regime in microgravity. *Microgravity Sci. Technol.* **20**, 73–80 (2008)
- Hu, W.R.: Magnetohydrodynamic flow in a straight tube with rectangular cross section. *Acta Mech. Sinica* **13**(4), 283–293 (1977)
- Hu, W.R.: The mechanism of magnetospheric substorm and the MHD waves of the solar-wind. *Planet. Space Sci.* **29**(6), 695–702 (1981)
- Hu, W.R.: High-speed streams from coronal holes and the accelerating mechanism of the solar-wind. *Geophys. Astrophys. Fluid Dyn.* **19**(3–4), 311–330 (1982)
- Hu, W.R.: The non-axisymmetrical configuration of a large-scale solar and stellar magnetic field. *Astrophys. Space Sci.* **90**(2), 391–403 (1983)
- Hu, W.R.: MHD flow in a homopolar device with annular wire electrodes. In: Chien, W.-Z. (ed.) *The Advances of Applied Mathematics and Mechanics in China*, pp. 65–87. China Academic Publishers, Beijing (1987a)
- Hu W.R.: *Cosmic Magnetohydrodynamics*. Science Press, Beijing (1987b, 2007)
- Hu, W.R.: Preface of special issue: microgravity experiments on board the Chinese recoverable satellite. *Microgravity Sci. Technol.* **20**, 59 (2008)
- Hu, W.R.: MHD flow in a homopolar device with annular wire electrodes. *Adv. Mech.* **39**(4), 440–449 (2009)
- Hu, W.R., Hu, Y.Q., Low, B.C.: Non-axisymmetric magnetostatic equilibrium. I. A Perturbation Theory. *Sol. Phys.* **83**(2), 195–205 (1983)
- Hu, W.R., Kang, Q.: *Physical Science under Microgravity: Experiments on Board the SJ-10 Recoverable Satellite*. Beijing & Springer Nature Singapore Pte Ltd., Science Press (2019)
- Hu, W.R., Shu, J.Z., Zhou, R., et al.: Influence of liquid bridge volume on the onset of oscillation in floating zone convection. I. Experiments. *J. Cryst. Growth* **142**(3–4), 379–384 (1994)
- Hu, W.R., Tang, Z.M.: *Floating Zone Convection*. Science Press, Beijing (2003)
- Hu W.R., Tang Z.M.: Onset of oscillatory thermocapillary convection. In: Denier, J.P., Finn, M.D. (eds.) *Mechanics Down Under – Proc. 22nd ICTAM*, Adelaide, Australia, 24–29 August 2008, pp. 85–99. Springer, Dordrecht (2013)
- Hu, W.R., Wu, Y.L.: The Taiji program in space for gravitational wave physics and the nature of gravity. *Natl. Sci. Rev.* **4**, 685–686 (2017)
- Hu, W.R., Zhao, J.F., Long, M., et al.: Space program SJ-10 of microgravity research. *Microgravity Sci. Technol.* **26**, 159–169 (2014)
- Kang, Q., Cui, H.L., Hu, L., et al.: On-board experimental study of bubble thermocapillary migration in a recoverable satellite. *Microgravity Sci. Technol.* **20**, 67–71 (2008)
- Kang, Q., Jiang, H., Duan, L., et al.: The critical condition and oscillation-transition characteristics of thermocapillary convection in the space experiment on SJ-10 satellite. *Int. J. Heat Mass Transfer* **135**, 479–490 (2019a)
- Kang, Q., Wang, J., Duan, L., et al.: The volume ratio effect on flow patterns and transition processes of thermocapillary convection. *J. Fluid Mech.* **868**, 560–583 (2019b)
- Kang, Q., Wu, D., Duan, L., et al.: The effects of geometry and heating rate on thermocapillary convection in the liquid bridge. *J. Fluid Mech.* **881**, 951–982 (2019c)
- Kang Q., Wu D., Duan L., et al.: Surface configurations and wave patterns of thermocapillary convection onboard the SJ10 satellite. *Phys. Fluids* **31**, 044105 (2019d)
- 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. *Phys. Fluids* **32**, 034107 (2020)
- Kong, W., Wang, B., Zhang, W., et al.: Study on prefire phenomena of wire insulation at microgravity. *Microgravity Sci. Technol.* **20**, 107–113 (2008)
- Le C., Liu L., Li Z.: Oscillatory thermocapillary convection in deformed half zone liquid bridges of low Prandtl number fluids. *Int. Comm. Heat Mass Transfer* **127**, 105499 (2021)
- Levenstam, M., Amberg, G.: Hydrodynamical instabilities of thermocapillary flow in half-zone. *J. Fluid Mech.* **297**, 357–372 (1995)
- Li, K., Matsumoto, S., Imaishi, N., et al.: Marangoni flow in floating half zone of molten tin. *Int. J. Heat Mass Transfer* **83**, 575–585 (2015)
- Li, K., Tang, Z.M., Hu, W.R.: Coupled thermocapillary convection on Marangoni convection in liquid layers with curved free surface. *Int. J. Heat Mass Transfer* **55**, 2726–2729 (2012)
- Li, K., Xun, B., Hu, W.R.: Some bifurcation routes of thermocapillary convection in two-dimensional liquid layers of finite extent. *Phys. Fluids* **5**, 54106 (2016)
- Luo J., Bai Y.Z., Cai L., et al.: The first round result from the Tianqin-1 satellite. *Class. Quantum Grav.* **37**, 185013 (2020)
- Ma, B., Cao, Y., Zheng, W., et al.: Real-time micrography of mouse preimplantation embryos in an orbit module on SJ-8 satellite. *Microgravity Sci. Technol.* **20**, 127–136 (2008)

- Matsumoto S., Hayashida H., Natsui H., et al.: Experimental study of thermocapillary flow in the half-zone liquid bridge of low Prandtl number fluid, JAXA R&D Report JAXA-RR-04-027E, pp. 112–128 (2005)
- Min J., Wang Z.L., Li Y.P., et al.: Drop tower tests of Taiji-1 inertial sensor substitute. *npj Microgravity* **7**, 25 (2021)
- Sun, R., Hu, W.R.: The thermocapillary migration of two bubbles in microgravity environment. *J. Colloid Interface Sci.* **255**, 375–381 (2002)
- Sun, R., Hu, W.R.: Planar thermocapillary migration of two bubbles in microgravity environment. *Phys. Fluids A* **15**, 3015–3027 (2003)
- Sun, S.J., Gao, Y.X., Shu, N.J., et al.: A novel counter sheet-flow sandwich cell culture system to unravel cellular responses in space. *Microgravity Sci. Technol.* **20**, 115–120 (2008)
- Sun, Z.W., Han, J.H., Dai, L.R., et al.: Experimental study of thermocapillary convection on a liquid bridge consisting of fluid with low Prandtl number in a floating half-zone. *Sci China E.* **29**(1), 97–104 (1997)
- Takagi, K., Otake, M., Natsui, H., et al.: Experimental study on transition to oscillatory thermocapillary flow in a low Prandtl number liquid bridge. *J. Cryst. Growth* **233**, 399–407 (2001)
- Tang Z.M., Hu W.R.: Influence of liquid bridge volume on the onset of oscillation in floating zone convection ii. numerical simulation. *J. Cryst. Growth* **142**, 385–391 (1994)
- Tang, Z.M., Hu, W.R.: Fractal feature of oscillatory convection in half-floating zone. *Int. J. Heat Mass Transfer* **38**, 3295–3300 (1995)
- Wang, S.F., Zhang, X.: Microgravity smoldering combustion of flexible polyurethane foam with central ignition. *Microgravity Sci. Technol.* **20**, 99–105 (2008)
- Wang, Y.X., Lu, X.Y., Zhuang, L.X., et al.: Numerical simulation of drop Marangoni migration under microgravity. *Acta Astronaut.* **54**, 325–335 (2004)
- 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. *Comm. Phys.* **4**, 34 (2021)
- Wu, Z.B., Hu, W.R.: Thermocapillary migration of a planar droplet at moderate and large Marangoni numbers. *Acta Mech.* **223**(3), 609–626 (2012)
- Wu Z.B., Hu W.R.: Effects of Marangoni numbers on thermocapillary drop migration: Constant for quasi-steady state? *J. Math. Phys.* **54**, 023102 (2013)
- Xie, J.C., Lin, H., Han, J.H., et al.: Drop migration of middle Reynolds number in a vertical temperature gradient. *Microgravity Sci. Technol.* **9**, 95–99 (1996)
- Xie, J.C., Lin, H., Han, J.H., et al.: Experimental investigation on Marangoni drop migration using drop shaft facility. *Int. J. Heat Mass Transfer* **41**, 2077–2081 (1998)
- Xie, J.C., Lin, H., Zhang, P., et al.: Experimental investigation on thermocapillary drop migration at large Marangoni number in reduced microgravity. *J. Colloid Interface Sci.* **285**, 737–743 (2005)
- Xun, B., Li, K., Hu, W.R.: Effect of volume ratio on thermocapillary flow in liquid bridges of high-Prandtl-number fluids. *Phys. Rev. E* **82**, 0363241–0363247 (2010)
- Yang, Y.K., Kou, S.: Temperature oscillation in a tin liquid bridge and critical marangoni number dependency on Prandtl number. *J. Cryst. Growth* **222**, 153–143 (2001)
- Yin, Z., Chang, L., Hu, W., et al.: Thermocapillary migration and interaction of two nondeformable drops. *Appl. Math. Mech.* **32**(7), 811–824 (2011)
- Yin Z., Chang L., Hu W.R., et al.: Numerical simulations on thermocapillary migrations of nondeformable droplets with large Marangoni numbers. *Phys. Fluids* **24**, 092101 (2012)
- Yin Z., Gao P., Hu W., et al.: Thermocapillary migration of nondeformable drops. *Phys. Fluids* **20**, 082101 (2008)
- Young, N.O., Goldstein, J.S., Block, M.J.: The motion of bubbles in a vertical temperature gradient. *J. Fluid Mech.* **6**, 350–356 (1959)
- Zhang, X., Yuan, L., Wu, W., et al.: Some key technics of drop tower experiment device of National Microgravity Laboratory (China) (NML). *Sci. China Ser. E* **48**(3), 305–316 (2005)
- Zhao, J.F.: Two-phase flow and pool boiling in microgravity. *Int. J. Multiphase Flow* **36**(2), 135–143 (2010a)
- Zhao J.F.: Two-phase gas-liquid flow and heat transfer with phase change. In: Hu, W.R., et al. (eds.) *Introduction to Microgravity Sciences*, chapter 4. Science Press, Beijing (2010b)
- Zhao, J.F., Hu, W.R.: Slug to annular flow transition of microgravity two-phase flow. *Int. J. Multiphase Flow* **26**(8), 1295–1304 (2000)
- Zhao, J.F., Li, J., Yan, N., et al.: Bubble behavior and heat transfer in quasi-steady pool boiling in microgravity. *Microgravity Sci. Technol.* **21**(S1), 175–183 (2009)
- Zhao, J.F., Li, Z.D., Li, H.X., et al.: Thermocapillary migration of deformable bubbles at moderate to large Marangoni number in microgravity. *Microgravity Sci. Technol.* **22**(3), 295–303 (2010)
- Zhao, J.F., Liu, G., Wan, S.X., et al.: Bubble dynamics in nucleate pool boiling on thin wires in microgravity. *Microgravity Sci. Technol.* **20**, 81–89 (2008)
- Zhao, J.F., Wang, S., Liu, Q., et al.: Retrospect and perspective on microgravity science in China. *Chin. J. Space Sci.* **41**(1), 34–45 (2021)
- Zhao J.F., Xie J.C., Lin H., et al.: Experimental study of two-phase flow in microgravity. In: 51st Int. Astronautical Congr., Rio de Janeiro, Brazil, October 2–6 (2000)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Experimental study on two-phase gas-liquid flow patterns at normal and reduced gravity conditions. *Sci. China Ser. E* **44**(5), 553–560 (2001a)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Experimental study on pressure drop in two-phase gas-liquid flow at reduced gravity condition. *J. Basic Sci. Eng.* **9**(4), 373–380 (2001b)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Experimental studies on two-phase flow patterns aboard the Mir space station. *Int. J. Multiphase Flow* **27**(11), 1931–1944 (2001c)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Microgravity experiments of two-phase flow patterns aboard Mir space station. *Acta Mech. Sinica* **17**(2), 151–159 (2001d)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Pressure drop of bubbly two-phase flow through a square channel at reduced gravity. *Adv. Space Res.* **29**(4), 681–686 (2002)
- Zhao, J.F., Xie, J.C., Lin, H., et al.: Gas-liquid two-phase flow patterns in partial gravity conditions. *J. Eng. Thermophys.* **25**(1), 85–87 (2004)
- Zhao, J.F., Zhang, L., Li, Z.D., et al.: Topological structure evolution of flow and temperature fields in deformable drop Marangoni migration in microgravity. *Int. J. Heat Mass Transfer* **54**, 4655–4663 (2011)
- Zheng, H.Q., Wang, H., Wei, N., et al.: Live imaging technique for studies of growth and development of Chinese cabbage under microgravity in a recoverable satellite (SJ-8). *Microgravity Sci. Technol.* **20**, 137–143 (2008)

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