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COMMENTARY

Comprehensive utilization of energy for phase change heat transfer regulated by magnetic field in space

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For advancements in deep space exploration technology, the establishment of an efficient space energy system has become imperative for ensuring the normal operation of spacecraft and the life activities of astronauts. In this review, the study of magnetic field-regulated phase change materials (PCM) in microgravity is explored. The thermal-fluid-magnetic coupling effect and modulation mechanism of composite phase change system are systematically discussed about how to overcome the bottleneck of low thermal conductivity of PCM in microgravity. Future perspective ideas of constructing a space system that utilizes comprehensively multiple forms of energy are proposed. It highlights the significance of the thermal-fluid-magnetic coupling effect of phase change dynamics, with the objective of promoting magnetic field modulation technology to achieve substantial breakthroughs in space fundamental researches.

BACKGROUND

The continuous breakthrough of deep space exploration technology will help mankind expand the boundaries of cognition and reveal the mysteries of the origin and evolution of life. The establishment of a sound space energy system is an important guarantee for maintaining the normal operation of spacecraft and the life activities of astronauts. Energy storage technology runs through three important links of energy collection, storage and release, which is the key to ensuring excellent performance and reliable operation of energy systems. However, the density, efficiency, and economics of energy storage have become critical bottlenecks in realizing efficient and comprehensive utilization of energy in space.

The latent heat thermal energy storage (LHTES) technology based on phase change material (PCM) can provide high energy storage density and efficiency over a small temperature variation range. It is an effective means of mitigating the mismatch of energy demand in different gravity conditions in terms of time, space and location.[1] Nevertheless, the low thermal conductivity drawback of PCM remains one of the biggest obstacles to the development of space LHTES technology. The introduction of thermocapillary convection can provide additional heat transport for the phase change process, but it leads to non-uniform evolution of phase change interface and instability of flow field. In addition, applying an external magnetic field and adjusting the energy input can regulate phase change dynamics, but the complex thermal-fluid-magnetic coupling mechanism needs to be further explored.

This commentary reviews the recent progress of the thermocapillary convection mechanism and magnetic field regulation mechanism for enhancing the thermal response performance of PCMs in microgravity. In addition, the ways to overcome the technical barriers are sought from the selection of PCMs, the source and response of magnetic fields, the analysis of magnetic convection, and the comprehensive utilization of multi-form energies. Overall, a deeper understanding of coupled thermal-fluid-magnetic effects on the phase change process contributes to the solution of key scientific issues in space energy storage technology.

RECENT PROGRESS AND EXISTING CHALLENGES

In a microgravity environment, the natural convection driven by density differences cannot be utilized to accelerate the melting of PCM. To ensure the thermal response performance of space PCM devices in complex operating environments, thermocapillary convection is considered as a feasible solution to compensate the driving force. This mechanism stems from the fact that surface tension gradients in non-equilibrium multiphase systems resulting from temperature gradients and/or concentration gradients drive shear flow of fluids along interfaces. Kang et al.[2] studied the critical conditions and oscillatory transition properties of thermocapillary convection in space experiments aboard the satellite SJ-10. The fluid transition routes in space included the quasi-periodic route, the period-doubling bifurcation and intermittency. However, during the phase change process, the dynamic evolution of the melting interface will further induce mode shifts and convective instabilities in thermocapillary convection. In particular, the thermocapillary convection unit will transition from a steady multi-vortex to an oscillatory mode when the aspect ratio and temperature gradient exceed the critical values of the steady mode. They can be observed in the form of travelling waves or (approximate) standing waves. In addition, the heat flow boundary condition is an important factor affecting the presence or absence of oscillatory thermocapillary convection. Applying a sufficiently large transverse heat flow to the sides of the cavity can lead to oscillatory standing wave and hydrothermal traveling wave modes, respectively, during the melting process.[3] However, if a constant heat flow is applied to the top free surface, no oscillatory modes occur for a given range of parameters.

For the application of periodic heat storage and release in microgravity, the thermophysical properties of PCMs need to be adapted to the demands of special space thermal environments. Therefore, thermocapillary convection can be utilized and combined with a thermally conductive framework in the form of porous media, nanoparticles, or fins. Porous media constructs high thermal conductivity channels inside the PCM, thus improving the heat storage and discharge performance. However, the phase change process usually suffers from competing effects between the thermal conduction of the skeleton and the thermocapillary convection. Compared to porous media, nanoparticles (NPs) will be uniformly distributed in the PCM base fluid on a microscopic scale to form a nano-enhanced phase change material (NEPCM) to enhance its thermal properties. However, the NPs increase the apparent viscosity of NEPCM and induce a complex non-Newtonian behavior in the thermocapillary convection zone. Overall, coupled thermally conductive frameworks are usually accompanied by competition for heat transfer and loss of heat storage, and their structure-activity relationship on the melting process is worth investigating.

Compared to the passive techniques mentioned above, the active techniques based on magnetic or electric fields can dynamically regulate the heat and mass transfer process of the PCM by adjusting the external energy input. Zhuang et al.[4] numerically analyzed the regulation mechanism of ferrohydrodynamics (FHD) for the phase change process driven by thermocapillary convection. They noted that when the magnetic field strength exceeded the critical value for stable magnetic convection, an oscillatory convection mode would depart in the low surface tension range. In fact, magnetic field regulation techniques based on the FHD effect have also been used for fluid management in microgravity environments. Under the external magnetic field, the paramagnetic NPs in the magnetic nanofluid will remain oriented along the magnetic induction lines. They will undergo dynamic tip aggregation in a chain-like distribution and transition to a zip state at higher magnetic strengths. These abundant self-assembled morphologies lead to significant changes in the thermophysical properties of ferromagnetic fluids. On the other hand, the magnetic damping effect induced by magnetohydrodynamics (MHD) has been proven to be effective in suppressing the non-constant flow induced by thermocapillary convection. It is used in crystal growth processes in microgravity to reduce growth stripes, control the growth interface, and separate impurities. Thus, for phase change processes driven by

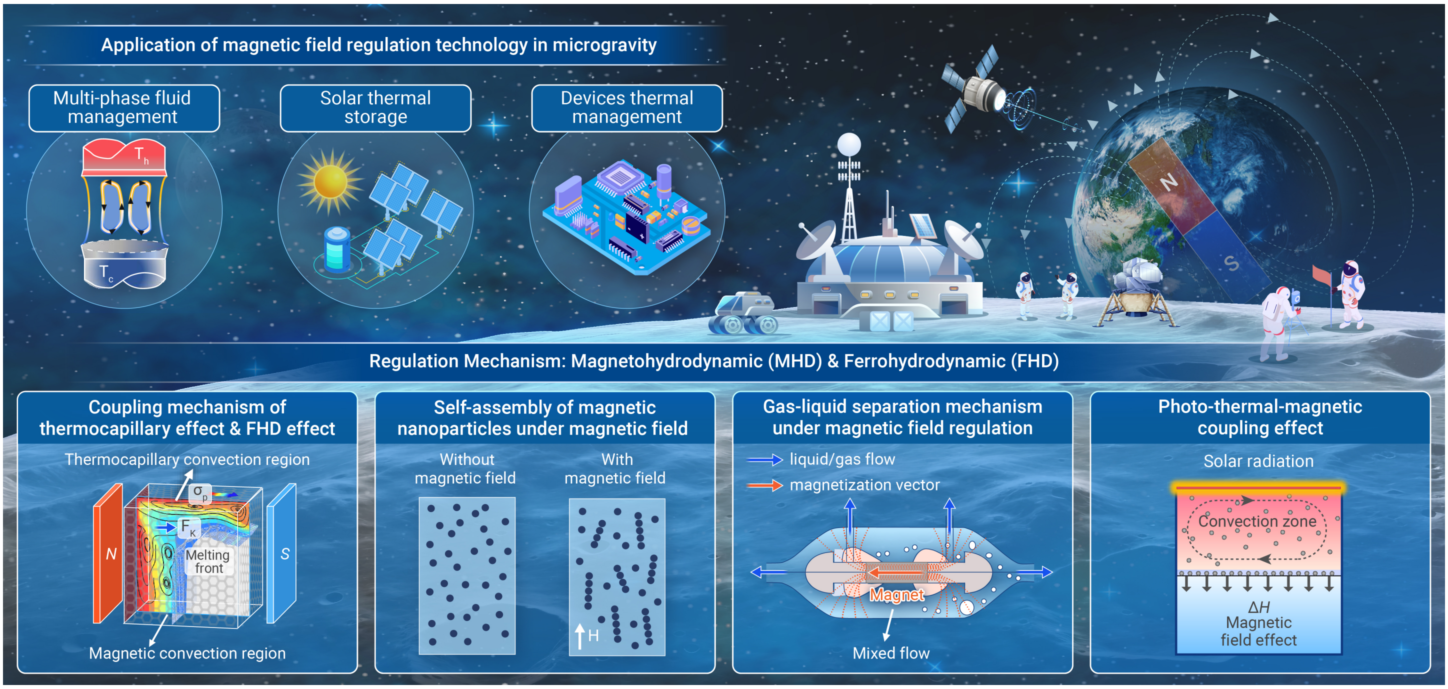

Figure 1. Magnetic field-regulated phase change materials (PCM) in microgravity.

thermocapillary convection, the Lorentz force can counteract the surface tension, thereby controlling the development of the convection unit and promoting homogenization of the melting interface. In addition, two mechanisms based on the MHD mechanism, namely diamagnetic and Lorentz forces, hold considerable promise in addressing the challenges posed by electrolytic cells under microgravity conditions.[5] In the future, the theory of magnetic field regulation under microgravity will provide important guidance for the management of multiphase flow systems in the space environment.

FUTURE DIRECTIONS

In order to break through the technical bottleneck of efficient energy storage and accurate heat flow control in microgravity, the utilization of magnetic field control technology has been a subject of space exploration. However, overcoming the following key challenges is essential to further achieving comprehensive energy use in space.

(1) The mechanisms of regulating phase change heat transfer under MHD and FHD mechanisms in microgravity will provide new ideas for the development of novel generation of space energy storage technology. Meanwhile, deep learning techniques of physical information can be utilized to further investigate these issues. This helps to predict and analyze the non-uniform evolution and magnetic convection mode shift laws of complex phase change interfaces under magnetic field regulation. For planetary exploration, transporting PCMs from Earth to space for large-scale construction is not feasible, limited by rocket capacity and transport costs. Maximizing the in-situ utilization of PCM resources is a crucial strategy to achieve the objective of high temperature and heat storage.

(2) Accurate analysis of the spatial distribution characteristics of celestial magnetic fields can provide a scientific basis for magnetic field regulation. Directional adjustment of specific regions by means of spacecraft electromagnetic systems (such as magnetic field sensors and magnetic coils and other magnetic field enhancement devices) will further reduce the complexity of the system. In addition, magnetic or superparamagnetic nanoparticles can be utilized to quickly respond to changes in the external magnetic field. On this basis, controlling the magnetic field distribution helps to delicately arrange the nanomaterials with different shape parameters. The field-induced aggregation property of the magnetofluid will construct low thermal resistance heat transfer channels inside it. This will achieve directional heat transfer and high-speed transport, thus enhancing the stability and efficiency of the LHTES system.

(3) Ferromagnetic fluids possess unique optical properties such as high light absorption, selective light filtering, adjustable light scattering and controllable light switching. These open up entirely new avenues for improving the efficiency of photo-thermal conversion in LHTES systems in space environments. It is necessary to explore the interaction law between gravity change and magnetic field and further analyze the dynamics of ferromagnetic fluid under the coupling of the optical-thermal-electrical-magnetic multi-physics field. This will provide new ideas for the construction of a multiform energy comprehensive utilization system for aerospace. However, the deposition and clogging of magnetic nanofluid need to be addressed to develop more efficient systems for integrated multiform energy utilization in microgravity.

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DECLARATION OF INTERESTS

The authors declare no competing interests.