A review of applications of handling particular materials under microgravity

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Abstract. Microgravity research has been carried out by researchers around the world for many years. By using space flight experiments (the International Space Station) and ground-based experiments (the Microgravity Sounding Rocket, a landing tower, and weightless aircraft), the investigations under microgravity conditions are thought to be beneficial to human life in terms of chemical, physical, and biological aspects, and more. It has become a very important tool for scientific research and industrial applications today. This paper reviews the work in this area with special reference to the applications in chemical engineering processes such as particle conveying and flow and material science under different gravity levels, including microgravity environments. It has been demonstrated that gravity has a strong effect on particle conveying and flow. Reduced gravity can make materials more cohesive, which further influences particle conveying. Actually, the effect of gravity can be ignored when the gravity level is less than 0.0001g. In the field of material science, the microgravity environment can accelerate the formation process of materials, like crystal growth, and then lead to a better structure.

Keywords: Microgravity Research, Space Flight Experiments, International Space Station, Mictogravity Sounding Rocket, Particle Conveying.

1. Introduction

With the development of human space exploration, it is significant to understand the behaviour of matter under different gravity environments [1, 2]. It is well known that gravity plays a very important role on Earth. In other words, the behaviour of matter is controlled by gravity on Earth. However, microgravity means a state of quite small gravity, that is, around 10^{-5}g. In such a microgravity environment, everything shows different behaviours than on Earth [3–5]. Therefore, it is necessary to develop a new and simple method or technique for transporting materials, especially under reduced gravity conditions.

Numerous studies have been carried out on the effects of microgravity on the states of matter, phase transitions, and forces of objects, which have been found to be very important in the development of fundamental physics, and matter flow in industrial processes [6–10]. Particle conveying under different gravity conditions is also studied in some papers [11–15]. Researchers pay much attention on the behaviors of fluid, i.e. the fluid physics [16–18]. Macrogravity materials science is one of the most important NASA's programs [19–21]. One of important issues is microgravity combustion science, numerous work has been done in the area [22–26]. The numerical studies in microgravity combustion can further revel the mechanism of combustion [27, 28]. More detailed information are reviewed by Ulises and Grunde [29]. Additionally, microgravity biotechnology, as one of the most well-known research fields, is gaining its increasing popularity [30–33]. This paper will focus on aspects such as granular material conveying and matter flow in chemical engineering processes.

The research under different gravity levels is very important, as mentioned above. However, it is difficult to realise the environment with different gravity levels on Earth. Generally, the physical experiments are conducted using microgravity sounding rockets (MSR) and the International Space Station (ISS). It is very expensive and cannot provide opportunities for all researchers to conduct flight experiments. On the other hand, numerical simulation is one alternative that can simulate the microgravity environment easily and conduct investigations under different gravity levels. For particulate systems, numerical study using the discrete element method (DEM) shows its advantages in this area [34]. DEM simulation can provide detailed dynamic information about particles, including the particle velocity and the forces between particles. Therefore, DEM simulation has been widely used in the past many years [35–38]. In this paper, the research in the fields of particle conveying and matter flow under different gravitational conditions using space flight experiments and numerical simulation is reviewed.

2. Particle conveying and flow under different gravity levels

Transportation of solid particulate materials in many industrial processes, like chemical, steel, mineral, medical, and so on, is one of the most important research issues. Pneumatic conveying, which uses gases in a pipeline, can transport particles whose sizes range from 10 m to 10cm [39]. Studies indicate that particle conveying is affected by pipe geometries, operational conditions, and particle properties and is also dependent on vertical pipelines [39–41]. However, much more efforts are carried out in horizontal pipelines [42–46]. Actually, gravitational acceleration has a strong effect on particle conveyance. As mentioned above, more and more attention has been paid to microgravity research. Among these studies, particle conveying under different gravity levels is a hot research issue. With the progress of human lunar missions and the plan for a permanent lunar outpost, how to utilise the resources of the moon to produce water, oxygen, and other survival necessities should be considered carefully [13]. These operations, like those on Earth, will require mining and transporting the granular materials to the reactor for chemical reactions. As for the post-processing process after the reactions, it also needs the technique for particle conveying under lunar gravitational conditions. If these necessities for life can be produced on the destination planet, there is no need to launch them from Earth. More importantly, it will allow our astronauts to stay on the destination planet for a longer period of time. In that case, it will make space missions more economically feasible in the future.

Hofmeister et al. performed a series of reduced-gravity measurements to analyse the flow behaviour on granular matter urfaces [47]. Their results show that the size, velocities, and repose angles of the surface flow clearly depend on gravity. In other words, the duration and width of the avalanche and the maximum slope angle are all functions of the gravity level. Increasing gravity results in faster avalanches and shallower slopes for small, sphere-shaped materials. They use the Bremen drop tower and a small centrifuge to realise that the reduced gravity levels range from 0.01g to 0.3g. Their experiments are done in a tilting avalanche box. However, more research is in the pipeline. Liu and Marrerro investigated the transportation of pipelines in space colonies under reduced gravity conditions, which demonstrated gravity plays an important role in liquid and solid behaviours [48].

For the process of particle conveying under different gravity levels, there are different situations based on whether gas is involved. Louge and Xu studied the flow of granular materials with and without gas interaction in a long-lasting microgravity environment [49]. In real physical experiments, the wall has dissipation and slip, and they cannot show profiles of flow variables that are consistent with simple shear. However, unbounded simple shear flows can exist in numerical simulations when periodic conditions are applied to the flow. It should be noted that the change in particle flow behaviour is caused by reduced gravity. Furthermore, reduced gravity makes material appear more cohesive, which has effects on conveying efficiency and power requirements for small-scale screw conveyors [50]. Lan et al. also studied the gas-solid flows under different gravitational fields but in the horizontal channel (rectangular cross-section) under normal (Earth), lunar, and microgravity conditions [6, 10]. Their results showed that particle conveying characteristics are similar in the three gravity conditions mentioned above when wall roughness and/or particle-to-fluid mass ratios are high. However, particle conveying velocity increases as gravity level reduces in cases of low roughness and low mass loading. More importantly, their results indicate that gravity levels have nearly no effect on the additional pressure drop. Under the same gravity environment, Pan et al. also investigate the gas-particle flows in horizontal channels by using numerical simulations, combining the gas-particle two-phase turbulent model with the kinetic theory of granular flows [7]. Results show that gravity levels have an effect on particle concentration distribution, particle velocity, and fluctuation velocity. In addition, particle temperature is also affected by gravity level. When the microgravity condition applies, the particle temperature and collision frequency are much lower than those in the earth's and moon's gravity environments.

If gas is not considered, just like in the lunar environment without air, what will happen to particle conveying under reduced gravity conditions? Li et al. numerically studied the spherical particles conveying, but in a specially designed vessel composed of parallel plates with sawtooth wavy surfaces that is the same as that used in Ohyama's space flight experiments [14]. It should be noted that particle conveying in a vertical direction is considered. Additionally, in Li et al.'s work, vibration is applied to realise the particle movement from the bottom to the top. Utilising vibration to achieve particle motion can be found in lots of research [51–53]. Li et al.'s work shows that gravity level has a strong effect on particle convection rate. With the decrease in gravity level, particle conveying rates increase obviously. However, the effect can be ignored when the gravity level is less than 0.0001g. This is because the force of gravity can be ignored when compared with the force between particles. Under reduced gravity conditions, the effects of vibration amplitude and frequency on particle flow are also different from those of normal gravity (1g). The result indicates that when the vibration frequency increases, there is no dense flow in the process of conveying. However, when vibration amplitude increases to greater than 0.3mm, dense flow and even slug flow appear in the vessel. In fact, this situation can be alleviated by increasing vibration frequency or decreasing gravity. In other words, gravity has an effect on particle aggregation in the process of conveying. Love et al. also investigate particle aggregation in microgravity on the International Space Station (ISS) [16]. In their experiments, millimeter- and submillimeter-sized particles are used. The results show that the smaller the particles, the more strongly and quickly the clusters form. More importantly, round, smooth particles can hardly aggregate together. Dong et al. studied the particle dispersion in a horizontal vibrating vessel, which is also specially designed with the top corner being round-shaped [51]. The results show that gravity largely affects the distribution patterns and particle velocity. When gravity increases, the local packing density and kinetic energy of particles decrease. When the gravity level is greater than a certain value, particles cannot be agitated by vibrations.

To sum up, particle conveying under reduced gravity conditions is an important issue in space research. These investigations can provide human beings with techniques for better scientific exploration on destination planets in the future.

3. Material science under microgravity

Material science focuses on the microorganizational structure, properties, forming processes, and usage efficiency of materials, as well as the relationships among them. It is a science that combines physics, chemistry, metallurgy, and so on. In addition, it is also an applied science closely related to engineering technology. It is not difficult to understand that the microorganizational structure is about the arrangement of the atoms in the materials. More importantly, such material properties in physical, chemical, thermal, electronic, and magnetic aspects are decided by the atom arrangement. On the other

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hand, microatom arrangement can be controlled by the forming process of materials. However, how to develop a method to realise the microorganizational structure that we need is one of the hottest research issues. These methods can be rapid cooling technology, solidified, and/or evaporated techniques.

Microgravity material science mainly focuses on the solidification of metals and alloys, crystal growth from solutions, and glass formation, which is one of NASA's most important microgravity programs. It is well known that hard-sphere colloids can form a fully ordered packing within only two weeks under microgravity conditions, which cannot be realised on Earth even after one year [4-5]. Obviously, gravity levels have a significant and unexpected effect on the formation and structure of the final crystals. Zhu et al.'s work is carried out in the Space Shuttle, and the results show that the hexagonal, close-packed planes are formed in a microgravity environment [4].

As mentioned above, when gravity is applied, it will affect the formation process of material. For example, in the solidifying process of a melted alloy, gravity can cause fluid flows in the alloy, which will result in the formation of irregular dendrites. That will finally weaken the alloy and/or metal structure. Even worse, the solidifying process is quite complex, and it is difficult to measure, predict, and control under normal gravity conditions (on Earth's gravity environment). However, some of the phenomena, like convection, can be weakened due to reduced gravity. In that case, the whole process of solidifying will be simplified for the investigation. A tremendous amount of work has been done in microgravity material science. That will undoubtedly bring significant progress in the new material area, which will lead to the appearance of materials with stronger, lighter, and more beautiful properties. The results will be beneficial to our manufacturing industry on Earth in the future.

4. Discussions

In this paper, some of the work about microgravity research, like particle conveying and flow, and material science is simply summarized. For microgravity material science, much work needs to be done in the future, for example: interface and phase separation phenomena; liquid physics; rheological behaviour; melting and solidification phenomena; motion laws of (charged) solid particles and dust; super-cooling and glass state behaviour; and so on.

Other microgravity research in the fields of fundamental physics, life science, biotechnology, biomedicine, and combustion is not reviewed. However, these researches also address important issues that can have a significant impact on the quality of life for human beings, energy, and environmental development. Undoubtedly, microgravity research will further develop in the area, as mentioned above. Below are the microgravity research trends or areas of emphasis for the future.

1. Combustion, including liquid mist combustion, solid fuel combustion characteristics, dust combustion, the formation mechanism of carbon black, and turbulent combustion.

2. Complex fluids and particulate materials, including phase transition and aggregation processes of colloidal crystals and liquid crystals, motion behaviour and stress propagation laws of particulate matter under different gravity levels, particle-gas dynamics, particle flow patterns, dense particle system statics, stratification, diffusion, and transport of multiphase liquids, and movement of liquids in living cells.

3. Biotechnology and biomedicine, including three-dimensional structure growth in mammalian cells, the separation and purification process of bioengineering products like protein crystals, and research on hematopoiesis and neural stem cells;

With the rapid development of microgravity research, there is a strong motivation to move from fundamental research towards applied projects, which will definitely be beneficial to our human beings and environment.

5. Conclusion

In this paper, some of the research regarding microgravity science is reviewed, but it mainly focuses on particle conveying and flow and material science. The microgravity environment provides new fields and approaches for scientific research and manufacturing industries on earth. In other words, microgravity research and its applications have become a new field in high-tech development, receiving high attention from many governments and researchers. Compared to the reduced gravity environment created by microgravity sounding rockets, however, the International Space Station (ISS) can provide our researchers with a long-duration spaceflight environment for conducting physical experiments under different gravity levels. Granular material conveying, fluid mechanics, materials science, and biotechnology are the major parts of microgravity science. The main purpose of microgravity research is to study the differences in the behaviour of matter between normal gravity and reduced gravity. In space or under reduced gravity conditions, the effect of gravity is greatly weakened, and sedimentation, buoyancy convection, and the static pressure gradient are all eliminated to some degree. The studies indicate the effect of gravity on the processes of particle conveying and flow and other industrial processes in chemical, material, mineral, steel, and so on. In addition to space flight experiments, some studies are carried out using numerical simulations, which is an effective alternative and much more economical for these research projects under different gravity levels. Therefore, combining space flight experiments and numerical simulation, microgravity research will play a more important role in promoting the development of fluid physics, materials science, and biotechnology.

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