Thermal Management System based on Phase Change Slurry Liquid-cooling for Space Lithium Battery

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Abstract

Too high temperature and too large average temperature difference in battery pack will lead to battery life shorten, reduce its energy efficiency and with other problems. In order to solve the problem of thermal management of spacecraft lithium battery pack, a thermal management method of spacecraft lithium battery pack based on the combination of phase change slurry (PCS) and cooling plate was proposed in this paper. A three-dimensional thermal management model of PCS liquid cooling and cooling plate was established, the cooling effect of PCS and other working fluid under different gravity conditions was studied by numerical simulation, and the influence of mass flow rate of PCS on the cooling effect was investigated. The results showed that the liquid cooling at low flow rate in the spacecraft battery was the best when the mass flow rate was lower than 3.5 E-4 kg/s, the cooling effect of PCS was the best when the mass flow rate was lower than 3.5 E-4 kg/s, both maximum temperature and temperature uniformity are the best choice. The scheme in this paper not only can control the whole temperature field of the battery, but also does not need too much energy because of the low flow rate, which is in line with the original intention of low energy consumption and high cooling effect of the battery thermal management, it will be a certain reference significance for the design of Spacecraft Battery Thermal Management system(BTMS).

Keywords

Microgravity; Phase Change Slurry; Battery Thermal Management System.

1. Introduction

Energy storage battery is a key component of spacecraft, and its performance directly affects the safe operation and stability of the system. Lithium ion batteries are widely used because of their environmental friendliness, long cycle life, high Power-to-weight ratio, high energy density and wide storage temperature range. Working temperature is the key factor that affects the performance of lithium battery pack: too high temperature will lead to a reduction in battery life, even uncontrolled explosion; This can lead to problems such as shorter battery life and energy efficiency. Therefore, it is necessary to develop an effective thermal management scheme to reduce the surface temperature and improve the uniformity of temperature distribution in order to improve the system efficiency. The existing spacecraft working battery mainly uses the vacuum packing method, the traditional spacecraft battery heat management method [1], for the exposed deep space battery, the simplest temperature control method is to attach the battery pack to a heat conducting bus in direct contact with the radiation surface.

In the current thermal management research of Power Battery, the main methods of thermal management are natural or forced air cooling, liquid cooling, heat pipe cooling, phase change material cooling and so on. Compared with the natural convection cooling, the forced convection heat transfer

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combined with liquid cooling was used to cool the space battery, which reduced the temperature difference and the maximum temperature of the spacecraft battery. A hybrid battery thermal management system combining forced convection of air with phase change material (PCM) was proposed by Peng Qin et al [2]. The maximum temperature difference and maximum temperature were reduced by 1.2 °C and 16 °C respectively at 3C rate. Xinhai Xu et al [3]. proposed a water cooling system consisting of two new t-shaped split covers and eight conventional cold plates, which can keep the maximum temperature of the modules below 32.5°C under abnormal operating conditions, the difference between the maximum and minimum temperatures was maintained at about 1.5°C; Morteza Alipanah et al [4]. studied the thermal management system of pure octadecane, Gallium and octadecane aluminum foams by means of numerical simulation, using the thermal management system of the lithium-ion battery, which is composed of pure octadecane, pure gallium and octadecane aluminum foams, the effect of TMS thickness on the cell stack was analyzed. Compared with octadecane, Gallium as phase change material had more uniform surface average temperature, discharge time is doubled, and metal matrix with porosity of 0.88 was added to octadecane, the discharge time was prolonged by 7.3 times, and a heat management method based on phase change slurry and microchannel cooling plate was put forward by Fanfei Bai et al[5]., the effects of physical parameters and flow characteristics of PCS on heat transfer and cooling performance were predicted.

In order to improve the temperature uniformity and control the maximum temperature of spacecraft li-ion battery, an integrated cooling method of PCS liquid cooling cycle and cooling plate was proposed. A three-dimensional model of cooling directly on the side of a cylindrical battery was established, and the effectiveness of the integrated cooling method was verified by numerical simulation, the cooling effect of PCS and other cooling medium under different gravity was discussed, and the influence of mass flow rate on cooling effect was analyzed. The integrated cooling method can effectively reduce the maximum temperature of the battery and improve the uniformity of the whole temperature field, and improve the performance and reliability of the space battery system.

2. Experiments and Models

2.1 Physical Problem

When the battery is assembled into a battery pack, the temperature of the pack is significantly higher than that of a single battery, and the temperature of each battery is uneven due to the working condition of the battery. The cells were cooled by a liquid cooling device based on PCS in this paper. The schematic diagram of the cooling unit is as follows:

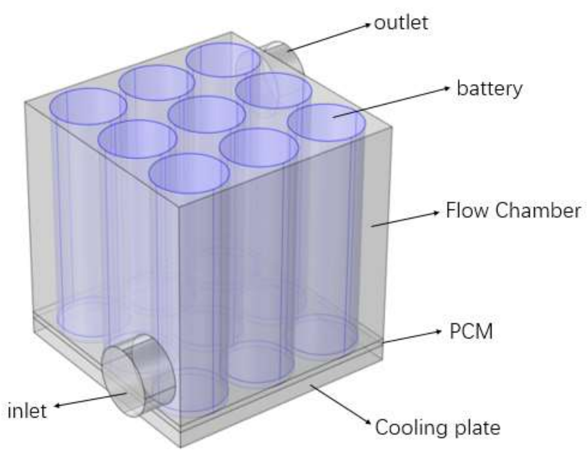

Fig.1 Structure of battery cooling device

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The battery pack were consisted of nine 21700 batteries, arranged in 3*3 arrangement as shown in Fig.1. The batteries were directly inserted into the battery position of the cooling device, and the cooling fluid flows in from the bottom inlet and out from the top outlet, convection heat transfer is carried out directly with the cell wall in the flow chamber to remove most of the heat generated by the cell, and a PCM layer of 2mm thickness was arranged at the bottom of the flow chamber, which can reduce the temperature difference of the cell stack due to its high latent heat, aluminum cooling plate is used at the bottom of the device for even heat dissipation.

The maximum Reynolds number of PCS is less than 2300, so the model uses a laminar flow model with the cell and ambient temperature set to 293.15K. In order to simplify the calculation model, the model was developed based on the following assumptions:

1) the microphase change capsules were uniformly distributed in PCS.

2) the density of mPCM in both liquid and solid phases was constant.

3) the particle volume change of mPCM during phase transition was ignored.

4) the PCS fluid was incompressible in its flow process.

According to the actual situation of the battery, under 4C discharge, the effective working time is about 0.25 hours. For guaranteed the accuracy of simulation, the number of mesh and the time step are independently tested. The mesh with 51214 grids, and the initial time step was 0.0001. Because the current, voltage and temperature of the battery were inseparably connected in the working process, different from the traditional numerical study of the battery thermal management that the coupling of the electrochemical field and the solid-fluid heat transfer multi-physical field was used in this paper, it was closer to the actual heat generation situation of battery.

2.2 Governing Equations

2.2.1 Battery Working Model

For simulated the heat generation of the battery, the lumped cell semi-empirical model [6] was used to calculate the parameters of the current, voltage and so on, and the ohmic overpotential based on physics was defined, activation and concentration (diffusion) loss.

The model defines the voltage and current of the battery which varies with time. The voltage and current load which varies with time have the following relations:

$$E_{\mathrm{bat}} = E_{\mathrm{OCV}}(SOC|_{X=1}, T) + \eta_{\mathrm{IR}} + \eta_{\mathrm{act}} \tag{1}$$

where $E_{OCV}(\overline{\mathrm{SOC}},\mathrm{T})$(V) is the battery open circuit voltage(OCV) as function of SOC(1), the battery state-of-charge. The SOC depends on the battery current as:

$$\frac{dSOC}{dt} = \frac{I_{batt}}{Q_{cell}} \tag{2}$$

where Q_{cell} (C) is the battery capacity, η_{IR} is the overpotential caused by the ohmic loss of the battery, can be defined by the following formula:

$$\eta_{IR} = R_{ohm} I_{batt} \tag{3}$$

where R_{ohm} is the Ohmic resistance.

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It has been proved that the accuracy of the SOP model can be improved by introducing the nonlinear term in the current-voltage dependence. In this work, including the activation overpotential η_{act} due to the charge transfer process in the cell, it is defined using the inverted Butler-Volmer equation (using the anode and cathode symmetry factor equal to 0.5):

$$\eta_{act} = \frac{2RT}{F} arc\sinh\frac{I_{batt}}{2I_0} \tag{4}$$

where R(8.314J(molK)-1) is the molar gas constant, F(Cmol-1) is the Faraday constant, T(K) the temperature, I_0(A) the exchange current. Equation(4) shows the nonlinear relationship between current and potential in electrochemical system.

2.2.2 Heat Transfer Model of Battery

The multi-physical field coupling model of lumped battery and solid-fluid heat transfer was used in this paper, the energy conservation equation for the heat dissipation process of the battery is as follows:

$$\rho_{bat} c_{p,bat} \frac{\partial T}{\partial t} = \lambda_{bat} \nabla^2 T + Q_{bat} \tag{5}$$

where the ρ_{bat}, $c_{p,bat}$, λ_{bat}, Q_{bat} represents the density, specific heat capacity, thermal conductivity, and heat produced during the operation of the battery respectively. T is the temperature of battery, and t is the working time of battery.

Batteries generate different amounts of heat because of their size, model and rate of charge and discharge. The heat generated by the battery during operation can be obtained by the following methods:

$$Q_{bat} = (\eta_{IR} + \eta_{act} + T\frac{\partial E_{OCV}(\mathrm{SOC}|_{X=1}, \mathrm{T})}{\partial T})\mathrm{I}_{cell} + Q_{mix} \tag{6}$$

$$Q_{mix} = \frac{3Q_{cell,0}}{\tau}\int_0^1 \frac{\partial E_{OCV,therm}}{\partial SOC}\frac{\partial SOC}{\partial X}\frac{\partial SOC}{\partial X}X^2 \partial X \tag{7}$$

$$E_{OCV,therm} = E_{OCV,ref}(\mathrm{SOC}) - \mathrm{T}_{ref}\frac{\partial E_{OCV}(\mathrm{SOC})}{\partial T} \tag{8}$$

Where η_{IR} is the ohmic loss of electrode and electrolyte; η_{act} is the activation polarization, voltage loss due to electrochemical reaction to overcome a certain potential barrier; E_{OCV} is the open-circuit voltage; SOC is the state of charge of the battery, I_{cell} is the current of the battery during operation; Q_{mix} is the mixed heat; $E_{OCV,therm}$ is open-circuit voltage under a certain thermal field; $E_{OCV,ref}$ is reference value of open-circuit voltage; T_{ref} is reference temperature.

PCS was responsible for the transport of heat throughout the thermal management unit, where the mass flow of PCS can be derived from the following formula:

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$$q_{PCS} = c_{p,PCS} \rho_{PCS} u_{PCS} A_{in} (T_{out} - T_{in}) \tag{9}$$

where $c_{p,PCS}$, ρ_{PCS} , u_{PCS} represents the Specific heat capacity, density and inlet velocity respectively, A_{in} refers to the area of the inlet interface.

The convection heat transfer conditions between the cell wall and the fluid can be described by the conservation of energy, the conservation of momentum, and the continuity equation:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T + \nabla \cdot (-\lambda \nabla T) = q \tag{10}$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} = -\frac{1}{\rho}\nabla P + \vec{f} + \frac{1}{\rho}\vec{F}_{viscous} \tag{11}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{12}$$

where $\vec{V}$, $\vec{f}$, $\vec{F}_{viscous}$ and P represents the velocity vector, volume force vector, viscous force vector and static pressure respectively.

The shell and core of the mPCM used in this study were polystyrene and N-octadecane respectively. The physical properties of the PCS are shown in the following table [1]:

Table 1. PCS material properties table

Item	n-octadecane	Polystyrene	Water
ρ (kg·m^3)	814	1050	998.2
c_p (J·kg^{-1}·K^{-1})	1900	1300	4182
λ (W·m^{-1}·K^{-1})	0.21	0.08	0.6
v (kg·m^{-1}·s^{-1})	0.003541	-	1.01*10^{-3}
L (J·kg^{-1})	24400	-	-

3. Results and Discussion

3.1 The Cooling Performance Comparison of Pcs with Other Fluids

Table 2. Thermophysical properties of cooling media

Item	PCS(20microcapsule/80water)	water	air
ρ(kgm^{-3})	961	1000	1.293
C_p(Jkg^{-1}K^{-1})	3713.916	4182	1004
λ(Wm^{-1}K^{-1})	1.109	0.6	0.024
μ(Pas)	2.3727e-3	1.01e-3	17.9e-6

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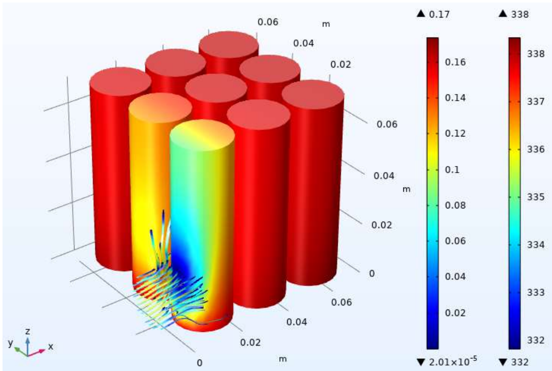
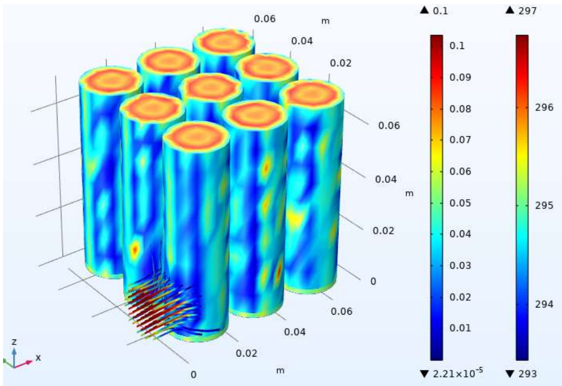
In order to compare the cooling performance of PCS with that of other fluids, PCS (20% MPCM + 80% water), pure water and air were used as cooling mediums respectively, the physical properties of the different fluids are shown in the following table.

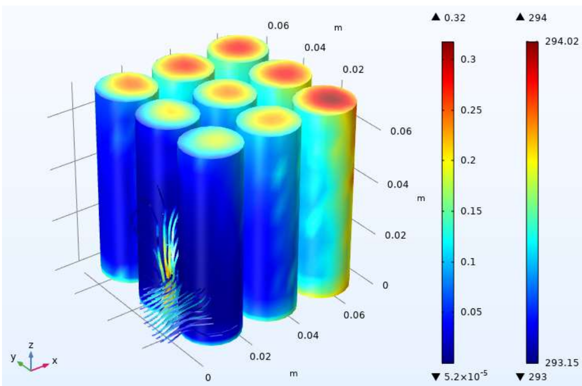
Under the influence of gravity, the liquid was subjected to a vertical force, and the flow in the z axis was controlled by gravity, creating a gravitational acceleration that slows down the flow of the fluid, when air, pure water and pcs are used as cooling medium to cool the battery, the requirement of the thermal management system for the temperature field control is between 30-45, it is clear that the cooling effect of air as a cooling medium can hardly suppress the heating problem of the battery, in contrast, water and pcs as cooling medium can easily control the temperature within the allowable temperature range, although the cooling medium of PCS still has 80% water, its cooling effect was nearly 10 times that of pure water cooling medium. Due to the addition of 20% mPCM, the heat absorption capacity and heat transfer effect of the synthesized cooling medium were increased, the cooling performance had been significantly improved.



(a) Air Cooling



(b) water cooling



(c) PCS cooling

Fig. 2 temperature nephogram of different medium cooling effect under constant gravity field

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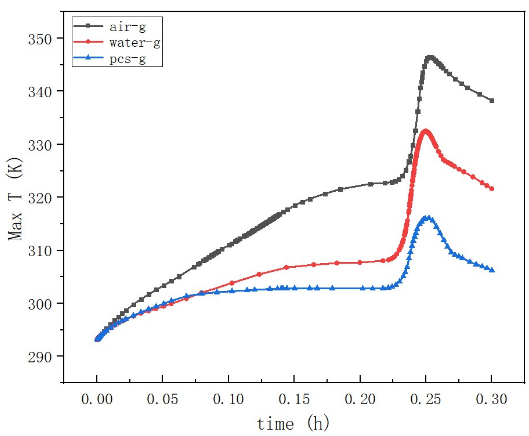
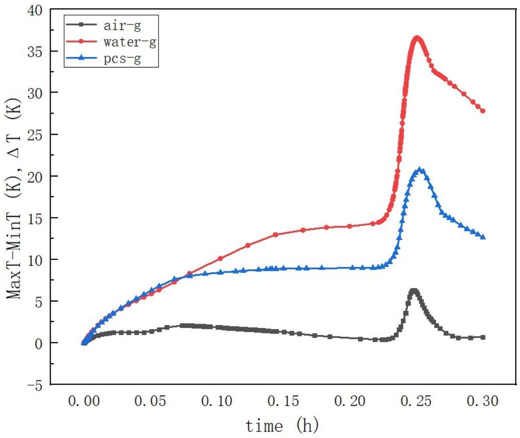


(a)

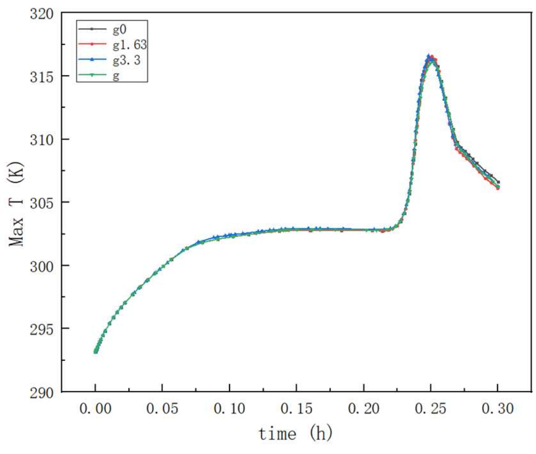


(b)

Fig. 3 Maximum temperature change plot(a) and temperature difference change(b) under normal gravity for different cooling medium

Fig.3 shows the maximum temperature change(a) and the maximum temperature difference change(b) of different cooling media under normal gravity field. The maximum temperature difference curve shown the pure water had maximum temperature difference change. The mass flow rate of cooling media was 3.5E-4 kg/s, although the maximum temperature difference of air cooling was the smallest, the whole temperature field of air cooling was in a high temperature state, which obviously can't satisfy the design requirements of battery heat management. In normal gravity, cooling using PCS, either maximum temperature or maximum temperature difference, was more effective than cooling with pure water.

It was found that the cooling effect of temperature field in microgravity field was lower than that in normal gravity field. The most obvious difference between the microgravity conditions and the normal gravity conditions is the gravity field, because the flow of fluid is accompanied by natural convection, the effect of natural convection in normal gravity field is larger than that in micro gravity field, so the temperature of cooling system in normal gravity field is lower than that in micro gravity field. Three microgravity conditions, G/6, g/3, G = 0, were studied in this paper. The simulated cooling effect of three different cooling mediums is shown as follows. The mass flow rate is 3.5 e-4 kg/s.



(a)

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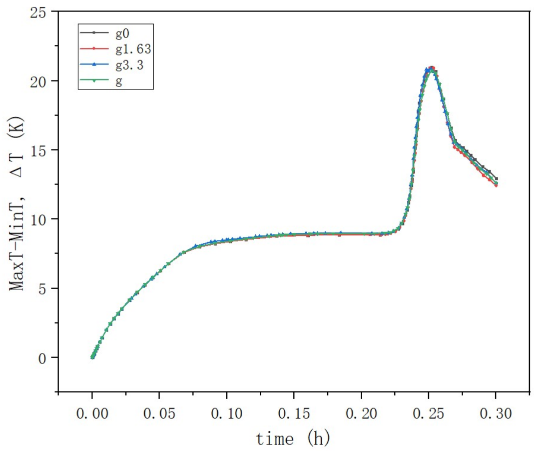
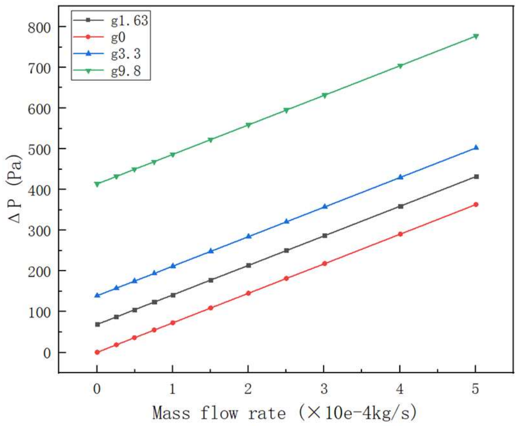


(b)



(c)

Fig. 4 (a) maximum temperature under four gravity conditions; (b) the maximum temperature difference under four gravity conditions; and (c) the pressure drop with the mass flow rate under different gravity conditions.

The graph above shown the maximum temperature and the maximum temperature difference for cooling the battery pack using PCS under four different gravity conditions. It can be seen that the temperature changes under the four gravity conditions were not very different during the whole operation of the battery, thus, the universality of PCS under different gravity conditions was explained. The pressure drop was linear with the mass flow rate under different gravity fields in (c) , and it can be seen that the pressure drop increases with the increase of gravity field gravitational acceleration, the pressure drop in both zero and microgravity was much smaller than that in normal gravity, which means that the thermal management effect of cells based on PCS was less energy consuming in space microgravity than in normal gravity, the advantages of PCS in spacecraft battery thermal management applications were also illustrated.

3.2 Effects of Different Inlet Interface Shape and Position

At the same mass flow rate, different inlet shapes and positions have different effects on the flow, because of the change of gravity field, different interface positions have different effects on the flow, in order to study the effect of interface shape and position on cooling effect in microgravity field, four kinds of interface were designed in this paper:

1) Rectangular interface, the entrance is at the top (rt).

2) Rectangular interface, the entrance is at the bottom (rb).

3) Circular interface, the entrance in the middle (cm).

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4) Circular interface, the entrance in bottom right (cb).

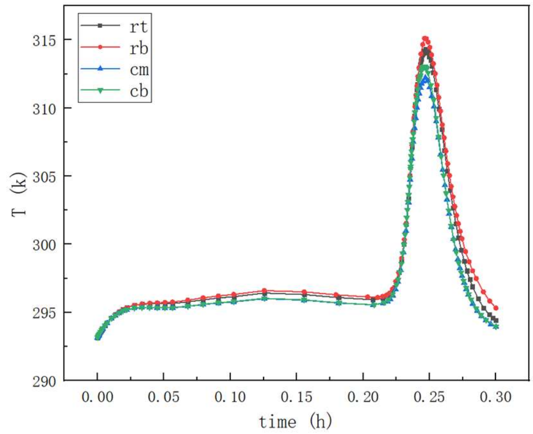
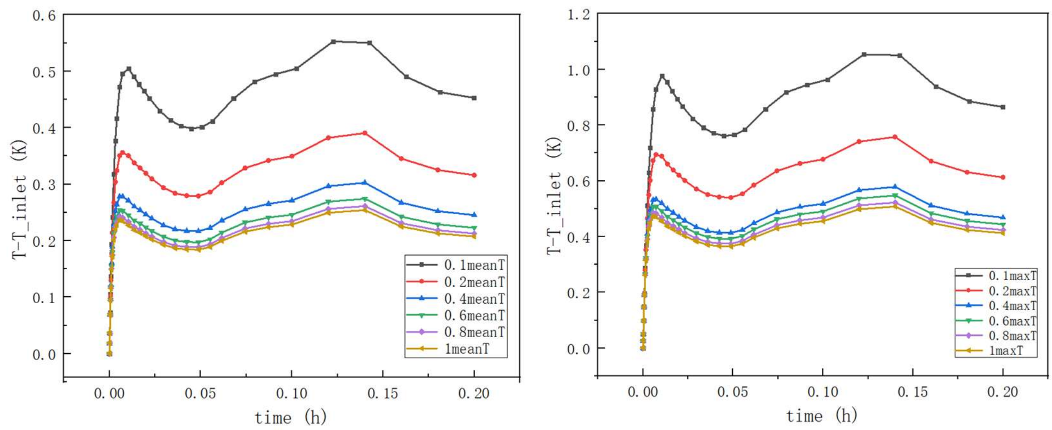


Fig. 5 the temperature variation of four interfaces.

The temperature curve in Fig.5 shown the temperature change process of the cooling effect of the four different interfaces. The difference between the four interfaces was not obvious during the cooling process, because that the mass flow rate was too small, there was little change in the overall flow field. It can be seen from the diagram that the overall cooling effect was the best compared with the other three when the cylindrical interface design was used in the bottom right-hand corner, and the circular interface is also easy to product, therefore, other factors were studied using cb interfaces.

3.3 Effects of PCS's Mass Flow Rate

The mass flow rate of PCS is an important factor in the BTMS based on PCS. In order to find out the comprehensive effect of this important factor on the cooling performance of the battery in microgravity field, the temperature field of the battery under different mass flow rate was simulated, the result of the simulation is shown in the temperature cloud image below:



(a) (b)

Fig 6. (a) average temperature variation at different flow rate within 0.2h,(b) the maximum temperature variation at different flow rates within 0.2 h

As shown in Fig.6, the relationship between the cooling effect of the battery and the flow rate. The cooling effect is shown in the form of temperature difference. The average and maximum temperature curves show that as the flow rate increases, the average temperature and the maximum temperature decrease with the increase of the fluid velocity, because the higher convective heat transfer coefficient between the fluid and the cell wall, the stronger the convective heat transfer effect, and the better the heat transfer effect. However, the fluid velocity couldn't be increased blindly, improve the fluid velocity means that the system needs more work to input, in the design of spacecraft battery pack, every part of energy and every part of space is worth cherishing, when the mass flow rate was 3.0 E-4 kg/s, the system temperature was about 308K, which is in the best working temperature range of the battery, so the mass flow rate of 3.0 E-4 kg/s was chosen as the best mass flow rate parameter in this paper.

4. Conclusion

In this paper, a liquid cooling scheme of PCS for direct cooling of battery pack under microgravity conditions was studied, and through comparative analysis and optimization design, selected the appropriate interface, mass flow rate, the cooling performance was compared with that of other cooling mediums, and the cooling effect of normal gravity and microgravity was analyzed. The main conclusions are as follows:

1) Comparing the cooling effect of the battery in normal gravity with that in microgravity, because of the influence of natural convection in gravity, the temperature field of the battery in normal gravity with three cooling mediums (air, pure water, PCS) was lower than that in microgravity, and the temperature field control of the battery in four kinds of gravity fields all meet the design requirements. The pressure drop in the microgravity field was smaller than that in the normal gravity field, which indicated that the energy consumption of the microgravity field system was smaller than that in the normal gravity field.

2) Four kinds of interfaces were designed, and the best one is that the cylinder is located in the bottom right position. Because the research object belongs to the field of low flow rate, the cylindrical interface located at the bottom right can make the cooling medium fill the whole cooling cavity well, so that the battery can be fully cooled.

3) The higher flow rate of PCS was, the better the cooling effect was. However, the higher flow rate is, the higher pump power consumption is. Considering the effect of energy consumption, the optimal mass flow rate was 3.0 E-4 kg/s, and the inlet flow rate was 1.2 e-3 m/s, at this low flow rate, the latent heat absorption performance of PCS can be exerted and the energy consumption for cooling the batteries can be minimized.

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