International Journal of Latest Engineering Research and Applications (IJLERA) ISSN: 2455-7137

Volume – 04, Issue – 04, April 2019, PP – 49-55

Research on Thermal Properties of a Phase Change Regenerator based on parallel-flow heat exchanger

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Abstract: Phase change energy storage materials (PCM) provide an ideal solution for thermal control requirements in complex thermal environments such as deep space exploration. PCM can also provide high cooling power in a short period of time with limited power supply. In microgravity, solid or shape-stable PCM can provide high thermal conductivity without the need for fluid management. It is of great significance to understand the heat transfer process between PCM and PCM HX for the design and optimization of PCR.Based on the above requirements, the phase change regenerator (PCR) made by ourselves based on flat tube heat exchanger was studied experimentally. R134a is used as working medium to build a closed loop. The phase change regenerator stores the cold energy into the PCM through the Thermo Electric Cooler (TEC), and then takes the cold energy out through the liquid phase and two-phase R134a. The heat transfer performance is good, the liquid working medium under the thermal state heat transfer capacity of about 6.0W / ℃.Through the analysis of the experimental results under different working conditions, the cold storage and release performance of the phase change regenerator are understood. This paper also discusses the influence of different mass flow rate and quality on the performance of the regenerator. With the increase of mass flow rate and quality, the heat transfer capacity is improved, but the utilization rate of cooling capacity is decreased.

Keywords: PCM, flat-tube HX, PCR, two-phase flow

I. INTRODUCTION

Spacecraft is in a bad working environment both in launch and on-orbit operation, especially in extreme temperature environment, which can easily lead to electronic equipment damage. According to the research report, the temperature factor accounts for 55% of the electronic equipment failure, which is much higher than other environmental factors, accounting for more than half of the total[1]. In order to adapt to the development trend of multi-task and complex environment, the active thermal control which can adjust temperature independently must be continuously studied and optimized. Its core point is the design of heat exchanger[2]. The design of heat exchangers mainly considers the following factors: First, in space applications, heat exchangers must be small and light. In addition to the limited space and energy consumption inside the spacecraft, the launch cost is also one of the important reasons. The cost is as high as $20,000 per kilogram[3].Secondly, the capacity to provide a large heat transfer power in a short time. Thirdly, it is safe, non-toxic and easy to manage. Especially in manned spacecraft, it is necessary to provide safe and comfortable working environment for astronauts.

Under microgravity conditions, gas and liquid are often difficult to manage, which will increase the design cost greatly. Among the thermal control technologies, phase change thermal control technology has the advantages of large energy storage, low energy consumption, light weight and compact structure. Phase change thermal storage material (PCM) can optimize the structure size of heat exchanger and more meet the heat dissipation requirements of space equipment[4-7]. Therefore, it has received more and more attention and research in recent years. Expanded graphite-based stereotyped composite energy storage material is a kind of composite material which is prepared by melt blending, vacuum adsorption and vacuum impregnation with expanded graphite as matrix, paraffin, fatty acid and other high latent heat density organic matter as phase change material[8]. When the solid-liquid phase transition occurs, the shape of the composite material will remain solid, and the fluidity of the liquid will not occur[9]. This makes it easier to apply and manage. Through the modification and optimization of graphite matrix, the composite not only keeps the advantages of high latent heat of organic phase change materials, but also improves the thermal conductivity of materials to a large extent. In addition, expanded graphite-based shaped composite energy storage materials have the advantages of safety, stability, environmental protection and good thermal cycling.

Parallel flow microchannel flat tube is a thin-walled porous flat tube material. Its main component is aluminium, which makes it lightweight and compact in design. The microchannel structure can effectively enhance heat transfer. And the market price of aluminium is only about one third of that of copper. Compared with traditional copper heat exchangers, the weight and cost of aluminum are greatly reduced. In industrial applications, louver fins are commonly used as heat sinks for flat tubes. In the paper[10], we studied its cold storage and heat transfer characteristics in liquid flow. In this paper,we will discuss the influence of different quality on the performance of the regenerator in two-phase flow.

II. EXPERIMENTAL

2.1 Structure of the phase change regenerator（PCR）

The Phase change material (PCM) was a composite material obtained by mixing alkane-type N-tridecane and expended graphite (EG) at a high temperature. Four chips of Thermal Electric Cooler (TEC) were applied to cool the PCM, their installation positions were shown in the **Fig. 1**[10]. Four TEC chips were thermally attached to the base plate of the PCM heat exchanger with the thermal grease. The heat was conducted from PCM to the base plate of the PCM heat exchanger, then rejected by the TECs to the cycling cooling water through the Heat Sink. Flat tubes with parallel channels were used in the PCM heat exchanger. At the same time, six thermocouples were installed on the PCM to measure its temperature change. Their installation positions are shown in the **Fig.2**[10]. They represent the positions that the closest to, and the farrest away, from the PCM HX during cold storage or cold release processes.

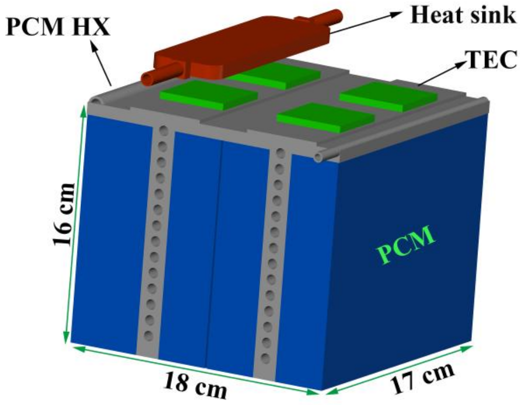

Fig. 1 The structure of the PCR with TEC chips and water cooled heat sink

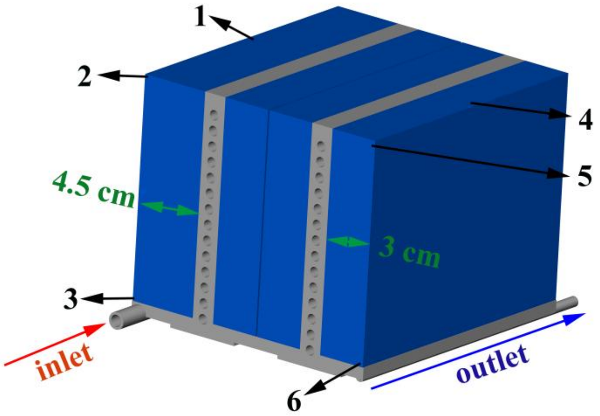

Fig. 2 The mounting positions of the thermocouples

The PCM HX is made of aluminum flat tubes with parallel channels, with the cross section shown in **Fig. 3**. To fit into the aluminum frame of the heat exchanger, those flat tubes were bent to form a π-shape (an upside down π-shape in **Fig. 4**) and vacuum brazed to fabricate the PCM heat exchanger (shown in **Fig. 5**). The π-shape design can create the space for the PCM blocks and also increase the heat transfer area between the PCM and the flat tubes. The overall mass of the PCM HX is about 1.7kg. The PCR was wrapped with thermal insulation material, and placed into an epoxy resin board shell.

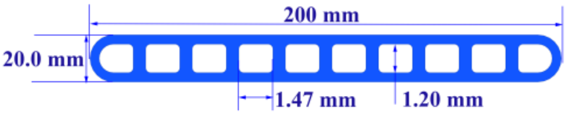

Fig. 3 Cross section diagram

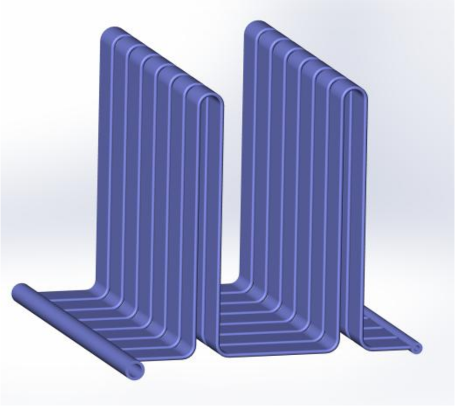

Fig. 4 π-shape flat tubes with parallel channels

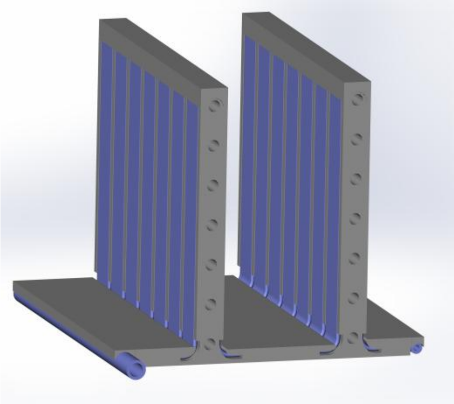

Fig. 5 the structure of the PCM HX

2.2 Loop principle

The Schematic drawing of experimental was shown in the **Fig 6**. The main components contain pump, flowmeter, preheater, PCR, condenser, accumulator, TEC and TEC heat sink. The working fluid of the loop is R134a. By controlling the temperature of accumulator, the saturation pressure of the R134a in the loop can be stabilized. The flowmeter can measure and control the mass flow of the R134a.Conderder can protect the pump from cavitation. Temperature and quality of working fluid at the entrance of PCR can be changed by adjusting preheater power.

The experiment consists of two stages: "cold storage " and "cold release ". The process of "cold storage" refers to the extraction of heat from PCM by means of Thermal Electric Cooler (TEC), so as to achieve the purpose of cold storage. In the process of cold storage, the valve and pump in the loop are closed. TECs transport the heat from PCM to the PCM HX, and then the heat is taken out by the working fluid in the thermostatic water bath. The material of the PCM HX is also aluminum, which can reduce the overall weight of the system.

"Cold release" refers to stopping the TEC cooling after the process of "cold storage ", then the high-temperature refrigerant (such as R134a) was pumped into the PCM heat exchanger, and lowered its temperature by transferring its heat to the PCM. The APS_{acc} measured the pressure of the accumulator, and the APS_{sat} measure the inlet pressure of the PCR. It can be judged by comparing their values that whether the refrigerant is heated to the vapor-liquid phase flow state. Some thermocouples are placed in PCM and the loop .The experiment ended when the refrigerant's temperature at the outlet of the heat exchanger reached 5°C

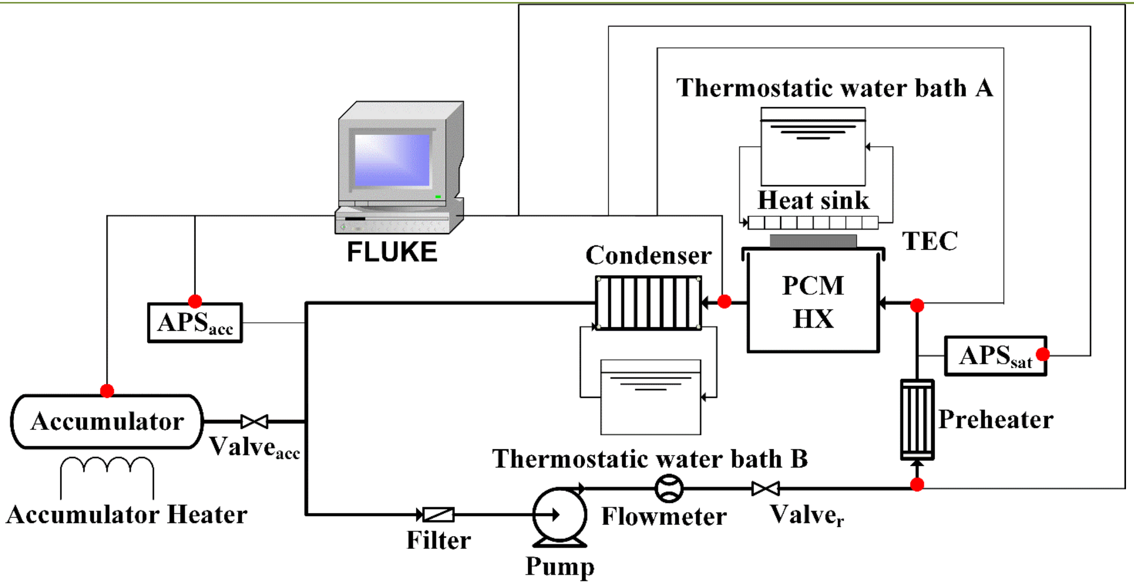

Fig. 6 Schematicdrawingof theexperimental bench

III. DATA ANALYSIS METHODOLOGY

3.1 Cold release capacity

The cold release capacity is defined as the thermalpower of the heat exchange under certain temperature difference betweenthe PCM cold end and the fluid through the PCR. In the "cold release" process, the cold release power (P_{cr}) can be calculated if we know the mass flow rate ($\dot{m}$) and the specific heat (c_p) of the liquid through the PRC, and the temperature difference of the liquid between the inlet of the preheater and the outlet of the PCR. Then the cold release capacity of the regenerator can be obtained as:

$$\frac{dP_{cr}}{dT}=\frac{\dot{W}-\dot{m}c_p(T_{out}-T_{pre\_in})}{\bar{T}_H-\bar{T}_L} \qquad 1)$$

where $\dot{W}$ is the heating power of the preheater,$\dot{m}$and c_p is respectively the mass flow rate and the specific heatof the fluid,T_{pre_in} is the temperature at the inlet of the preheater, $\bar{T}_H=\frac{1}{2}(T_{out}+T_{in})$ is theaverage temperature of the fluid through the PCR, and $\bar{T}_L=\frac{1}{4}(T_1+T_2+T_4+T_5)$ is the average temperature over the PCM cold ends,T_{out} and T_{in} is respectively the fluid temperature at the outlet and the inlet of the PCR.

For two-phase flow, the quality of the two-phase flow x is obtained:

$$x=\frac{\dot{W}-\dot{m}c_p(T_{pre\_out}-T_{pre\_in})}{\dot{m}(h_v-h_l)} \qquad 2)$$

whereT_{pre_out} is the temperature at the outlet of the preheater, $h_l$and h_v is respectively the enthalpy of saturated liquid and the saturated vapor of R134a at the corresponding saturation pressure. For liquid flow, when $\dot{W}=0$and $T_{in}=T_{pre\_in}$, the cold release capacity can be simplified as:

$$\frac{dP_{crl}}{dT}=\dot{m}c_p\frac{T_{in}-T_{out}}{\bar{T}_H-\bar{T}_L} \qquad 3)$$

3.2 Cold utilization rate

In the cold release process, the outlet temperature of PCR kept rising. The cold release process was considered to be over when the temperature of the liquid at the outlet of the PCR rise to 5 °C. Yet at this moment, the cold energy in the PCR was not used up. We thus define the cold utilization rate η_{cu} as follow:

$$\eta_{cu}=\frac{1}{Q_{cs}}\int_{t_i}^{t_o}\dot{m}\Delta H dt \qquad 4)$$

where t_o is the time when the out-flowing liquid reaches 5 ℃,ΔH is the enthalpy difference of the fluid between the inlet and the outlet of the PCR, for both liquid flows and two-phase flows. $Q_{cs}$is the cold storage quantity of the PCR, about 346kJ.

3.3 Average usable cold release power

We define the average usable cold release power as:

$$P_{avg} = \frac{1}{t_o - t_i}\int_{t_i}^{t_o} \dot{m}\Delta H dt \qquad 5)$$

to characterize the overall cold release power of the PCR for any flow.

The sensitivity analysis of average cold release power is as fllowed:

One minute before the outlet temperature reaches 5.0 C.

$$P_{avg-} = \frac{1}{t_o - 1 - t_i}\int_{t_i}^{t_o - 1} \dot{m}\Delta H dt \qquad (6)$$

One minute after the outlet temperature reaches 5.0 C.

$$P_{avg+} = \frac{1}{t_o + 1 - t_i}\int_{t_i}^{t_o + 1} \dot{m}\Delta H dt \qquad (7)$$

IV. DISSCUSSION OF RESULTS

4.1 Cold release capacity

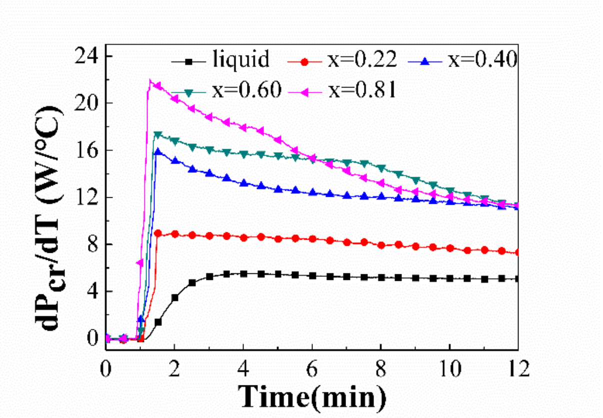

Fig.7 Cold release capacity of two-phase flow at the mass flow rate of 2.0 g/s, and different quality of R134a, within the process that the first PCM block did not totally melt.

The cold release capacity of the two-phase flow at different quality was measured.Thelooppressurewas stabilized at 660 kPawhen the accumulator temperature was adjusted to 25 ℃. Theinlettemperature of the PCM HX was heated up to 25 ℃ tomakesurethattheinletflowwas in vapor-liquid two-phase. Themass flow rate of the fluid was 2.0 g/s. The temperature at the inlet of the PCM HX were compared with saturated temperature corresponding to the local pressure to judge whether the R134a at the inlet reached the two-phase state. Asshownin Fig. 6, with the increase of quality at the inlet of the PCR, the cold release capacity has been significantly improved; but it decreases faster with the cold release time. For the flow quality of 0.8, the cold release capacity reaches the top to 22 W/℃ at the beginning, about four times as much as that of the liquid flow at the same flow rate of 2.0 g/s. It then decreases gradually to about 11 W/℃. The cold release powers of the two-phase flow at quality higher than 0.4 tend to converge to this point. Except for the case with flow quality of 0.81, the fluid in the outlet of the PCR is in subcooled liquid state. This means that the so-called cold release capacity of two-phase flow (defined by equation (1)) includes that of liquid flow (defined by equation (3)). It is a combined value depending on the condensation length.

For two-phase flow, at the beginning of the cold release process, the cold energy in the PCM is adequate. Yet because of a much higher heat exchange coefficient of two-phase flow than liquid flow, the cold release capacity is much higher (supported by data in Figure 7), and the cold energy is removed from the PCM much quicker. The PCM near the PCM HX melts much quicker at the beginning, especially near the inlet of the PCR. Then the increasing thermal resistance of the PCM becomes dominant of the cold release process, resulting in the decreasing cold release capacity. The higher the quality of the R134a in the inlet is, the faster the PCM melts. At last, the cold release capacityis limited by the thermal resistanceof the PCM. The measurement error from the instruments was less than 4%. Themain uncertainty was from the definition of the cold release capacity, in which the temperatures measured by the thermal couples were the temperatures on the corners or the edges of the PCM blocks.

4.2 Cold release time and cold utilization rate

The cold release time for the vapor-liquid two-phase fluid was much shorter than that for the liquid at the same mass flow rate and the same saturation temperature (shown in the **Table 1**). Increasing the quality of the R134a could also shorten the cold release time greatly. The shortest time was 6 minutes when the mass flow and the quality is respectively 2.0g/s and 0.81. Altogether, the cold release time decreased with increasing vapor quality except for the quality near 0.60. The cold utilization rate is also low for the vapor-liquid two-phase fluid except for the quality near 0.6. Both the cold release time and the cold utilization rate are higher than those with the quality near 0.4.

Table 1 Main data of cold release

Massflow(g/s)	Quality(x)	cold release time t_r(min)	cold utilization rate η_{cu}
0.60	0.00(liquid)	159	1.0
	0.20	89	0.70
	0.40	69	0.80
	0.59	53	0.80
	0.81	44	0.81
1.0	0.00(liquid)	98	1.0
	0.23	51	0.72
	0.42	21	0.45
	0.62	25	0.67
	0.82	13	0.45
2.0	0.00(liquid)	43	0.50
	0.22	16	0.43
	0.40	10	0.36
	0.60	11	0.58
	0.81	6	0.42

4.3Average usable cold release power

Theresult of the P_{avg} was shown in the **Fig. 8**. P_{avg} is almost linear relation with quality, and also increases with the mass flow rate, up to 400 W. The measurement error from the instruments was less than 2%, even the uncertainty of the cold release time is one minute.

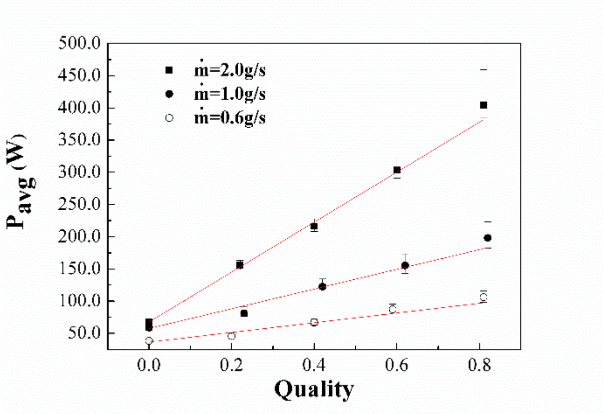

Fig. 8 The average usable cold release power at different quality.

When the mass flow rate is 0.6, 1.0, and 2.0g/s, the slopes of the fitting curves are 75.4, 153.6, and 387.9W, respectively. The higher the mass flow rate is, the higher the average heat transfer capacity is. For high quality, due to the low utilization rate of cooling capacity, the used cooling capacity is in the low thermal resistance area, while the unused cooling capacity is in the high thermal resistance area. Therefore, it appears that the heat transfer efficiency is higher and the average cooling power is higher.

In the case of low flow rate and low quality, one minute before and after the cooling time has little influence on the average heat transfer power. With the increase of quality and flow rate, its sensitivity becomes greater. At low flow rate and low quality, the cooling time is longer, and the one-minute heat transfer has little effect on the whole. However, when the flow quality increases, the cooling time becomes shorter, and the proportion of one minute is much larger than before, which has a great impact on the average heat transfer power.

V. CONCLUSION

In this paper, the thermal performance of a phase change cooler consisting of an aluminium parallel flow microchannel flat tube heat exchanger and an expanded graphite-based shaped composite energy storage material is discussed. By adding TEC and TEC water-cooled circuit to form a cold storage system, the electric energy is transformed into heat energy. By building a closed cycle of R134a, the liquid phase and gas-liquid phase refrigeration tests are carried out for phase change cold storage.

For liquid phase R134a with mass flow rate of 2.0g/s, its heat transfer capacity is about 6.0W/C. For the two-phase flow with the same mass flow rate, the heat transfer capacity is several times higher, and the heat transfer capacity increases with the increase of the dryness of the two-phase refrigerant. When the mass flow rate is 2.0g/s and the dryness is 0.2, the heat transfer capacity is about 9.0W/C. When the dryness rises to 0.8, the heat transfer capacity is about 22W/C, which is about 2.4 times of that when the dryness is 0.2.

The average heat transfer power increases with the increase of dryness, almost linearly. When mass flow rate is 0.6, 1.0 and 2.0 g/s, the slope of fitting curve is 75.4, 153.6 and 387.94 W, respectively. However, the utilization rate of cooling capacity of two-phase flow is low and decreases with the increase of dryness. When mass flow rate is 2.0 g/s, the dryness of working substance increases from 0 to 0.81, and the utilization rate of cooling capacity decreases from 0.76 to 0.42.

In summary, the phase change cooler has good cold storage and cooling release performance, compact structure and easy to use and manage, and has great application potential in space applications. The experimental results show that the phase change cooler designed in this paper is more suitable for liquid phase cooling, especially in the case of small flow rate, this design can provide a higher cooling efficiency.

Acknowledgements

This work was supported by the Project of China Manned Space Station Engineering.

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