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Influence of regenerator flow resistance on stability of pulse tube cooler

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Abstract: Based on the fluid network theory, the possibility of utilizing regenerator flow resistance to suppress the direct current (DC) flow induced by the introduction of a double-inlet in a pulse tube cooler is investigated theoretically. The calculation results show that increasing regenerator flow resistance can lead to a smaller extent of DC flow. Therefore, a better stability performance of the cooler can be realized. On this basis, the stability characteristics of the cooler with various regenerator matrix arrangements are studied by experiments. By replacing 30% space of 247 screens of stainless steel mesh at the cold part of the regenerator by lead balls of 0.25 mm diameter, a long-time stable temperature output at 80 K region is achieved. This achievement provides a new way to obtain stable performance for pulse tube coolers at high temperature and is helpful for its application.

Key words: pulse tube cooler; flow resistance; stability

The introduction of the double inlet usually leads to an increased performance of the pulse tube cooler. However, the asymmetric flow impedance of the double-inlet valve causes a DC flow around the loop of the regenerator, pulse tube and double-inlet. The DC flow not only greatly deteriorates the refrigeration performance of the cooler, but also is a key factor to cause temperature instability when the cooler operates at high temperature[1-3]. People would rather use an orifice mode instead of a double-inlet one at 80 K range for this reason, which sacrifices the powerful phase shift capacity of the double-inlet configuration. In order to improve performance of the cooler, several methods have been developed to eliminate DC flow[4-8]. However, the influence of regenerator matrices on DC flow and the stability of the cooler has seldom been undertaken. Based on the fluid network theory, the possibility of utilizing regenerator flow resistance to suppress DC flow is studied theoretically and verified by the experiment in this paper. Both results show that DC flow can be suppressed to a smaller extent by increasing the regenerator flow resistance, and stable temperature at 80 K range can be achieved.

1 Effect of Regenerator Flow Resistance on DC Flow

In a double-inlet pulse tube cooler, mass flow through a double-inlet valve during the compression and expansion processes is normally not equal, which results in the presence of DC flow. We suppose that mass flow during the compression process is larger than that of the expansion one and the difference between them is M. This portion of gas M will be gathered at the hot end of the pulse tube. However, when operating in a stable state, the gas quantities through the inlet and the outlet of the cooler should be equal, so this gathered gas M will be divided into two ways shown in Fig. 1 and returns to the outlet. One part of the gas goes through the double-inlet valve indicated as M_1 and returns to the outlet together with AC gas flow. It does not exhibit DC flow characters and is called as hypothetical DC flow. The other part of the gas goes through the pulse tube and regenerator to the outlet sequentially indicated as M_2. This portion of mass flow is called DC flow or streaming which greatly deteriorates performance of the cooler and should be well suppressed.

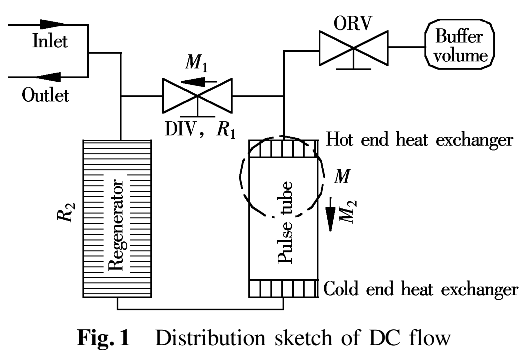

Fig. 1 Distribution sketch of DC flow

In Fig. 1, R_1 and R_2 express the flow resistances of

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the double-inlet valve and the regenerator, respectively. Supposing a linear relationship, i. e. independent of the mass flow, they can be obtained by[9]

$$R = \frac{\Delta p}{Q} \tag{1}$$

where Δp, Q are the pressure drop and the mass flow across the impedance component.

Based on the fluid network theory, DC flow M_2 can be expressed as[9]

$$M_2 = \frac{R_1}{R_1 + R_2} M \tag{2}$$

As shown in Eq. (2), M_2 can be reduced by decreasing R_1 or increasing R_2 at a constant mass flow difference M. On the other hand, keeping R_1 and R_2 constant, decreasing M can also lead to a smaller DC flow. A smaller M can be realized by reducing the mass flow coefficient asymmetry difference during the compression and expansion processes.

As we know, the flow coefficient asymmetry of the double-inlet valve is the key point causing the DC flow. For the single-valved double-inlet configuration, the mass flow difference M between compression and expansion processes increases with the larger opening of the valve, which leads to a larger DC flow M_2 although it also brings a smaller R_1.

For the double-valved configuration as shown in Fig. 2, by fine adjusting two valves' opening settings, mass flow difference M can be reduced to a smaller value, meanwhile leading to a smaller double-inlet flow resistance R_1 for the larger valve opening[8]. Both of them contribute to a smaller DC flow M_2. Experimental results show that using a double-valved configuration, DC flow can be well suppressed to quite a small value[8]. However its ability to suppress DC flow heavily relies on valve performance and operation condition. A certain amount of mass flow difference M still exists.

As shown in Eq. (2), increasing regenerator flow resistance, DC flow M_2 can be further suppressed at a constant M. For example, suppose $R_2 = R_1/2$, the calculated DC flow $M_2 = 2M/3$. Increasing R_2 to one time R_1 ($R_2 = R_1$), M_2 can be reduced to $M/2$. This means that DC flow M_2 can be reduced to 3/4. Since a certain value of pressure ratio is necessary for achieving high performance of the cooler, in the case that regenerator flow resistance is increasing, the opening of the double-inlet valve should also be enlarged which leads to a nearly constant pressure loss of the regenerator. On this basis, increasing R_2 more than one time, DC flow M_2 can be reduced to less than 50% according to Eq. (1). From above analysis we can see that DC flow M_2 can be further suppressed by increasing regenerator flow resistance and its effect is independent of DC flow direction. By this way, temperature stability may be realized at the 80 K range.

2 Calculation of Regenerator Flow Resistance

For a GM-type pulse tube cooler, operation frequency is quite low, so the stable-flow regenerator theory can be used to approximately calculate pressure loss and flow resistance[10]. Tab. 1 lists the calculated flow resistance under orifice mode with 1. 8 Hz frequency, 1. 22 rotary valve timing and 80 K cooling temperature. Where, Δp_2, $\Delta p'_2$ are the pressure drops of the compression and expansion processes; Δp is the total pressure drop; R_2, R'_2 are the flow resistances of the compression and expansion process; SS and LD mean 247 screens of stainless steel mesh and lead balls of 0. 25 mm diameter, respectively. As shown in Tab. 1, when the regenerator is filled with 30% space of the lead balls and 70% space of the stainless steel mesh, supposing pressure loss of the regenerator keeps constant, according to Eq. (1), the DC flow can be reduced to 68% compared with that with 100% space stainless steel screen mesh. When the DC flow circulates in reverse direction, the same results can also be obtained by calculation.

Tab. 1 Pressure loss and flow resistance of the regenerator with various matrix arrangements

Regenerator matrix	Δp_2/kPa	$R_2/(\mu m \cdot s)^{-1}$	$\Delta p'_2$/kPa	$R'_2/(\mu m \cdot s)^{-1}$	Δp/kPa
100%SS	25. 8	9. 29	35. 7	15. 73	61. 5
30%LD + 70%SS	38. 7	13. 75	51. 7	22. 41	90. 4
50%LD + 50%SS	47. 1	16. 59	62. 1	26. 66	109. 2
100%LD	69. 7	23. 96	89. 8	37. 65	159. 5

3 Experimental Apparatus

Fig. 2 shows the sketch of the test cooler. This is a single GM-type double-inlet pulse tube cooler. The sizes of the pulse tube and the regenerator are ϕ28 mm × 0. 5 mm × 155 mm and ϕ32. 35 mm × 0. 5 mm × 129 mm. The buffer volume is 1 L, and the heat exchangers are filled with 90 screens of copper mesh. A 2 kW nominal supply power compressor RW2 is used to drive the cooler, and the timing of the rotary valve is 1. 22. Four PT100 thermometers are placed in the cold head, at 1/3 and 2/3 lengths of the regenerator, and the middle of the pulse tube to monitor their temperatures, which are expressed as T_1, T_2, T_3 and T_4. The cooling power is measured by applying a heat load via a resistive heater. A needle valve Nuprom with 1.4 mm maximum inside diameter is used for the orifice valve.

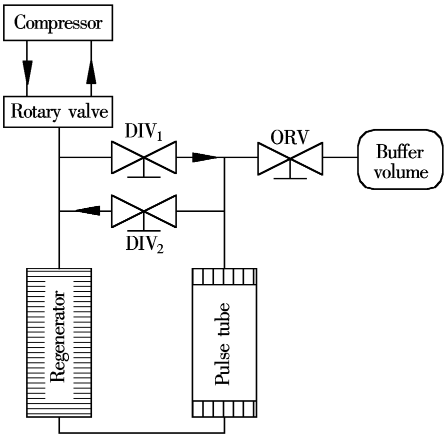

Fig. 2 Sketch of the pulse tube cooler

For the flow asymmetry of a needle valve, the DC flow direction will change when the valve is placed in the opposite flow direction. So a double-valved double-inlet structure instead of conventional single-valved one is used in the experiment to eliminate the DC flow. In Fig. 2, DIV_1 expresses the main flow direction of the valve from the regenerator to the pulse tube as indicated with arrow by the manufacturer, and DIV_2 means the reverse direction. Both DIV_1 and DIV_2 are WHITEY SS-ORS-3MM, whose maximum flow diameter is 2.0 mm.

4 Analysis of Experimental Results

Figs. 3(a) and (b) show the temperature history of the cooler imposed 23 W and 37 W heat load respectively when the regenerator is filled with 100% space stainless steel mesh. As shown in Fig. 3, the temperature can keep stable with 23 W heat load, while it becomes unstable under 37 W heat load. The detailed operational behavior is that the temperature in the middle of the pulse tube decreases, while the cold end temperature increases step by step. The concavities of the cures in Fig. 3 (b) were caused by the small performance fluctuation of the compressor. The induced gas turbulence by DC flow is a key reason to cause this temperature instability. As we know, there is gas in the middle portion of the pulse tube which never leaves the pulse tube and forms a temperature gradient that insulates the two ends. It acts like a displacer but consists of gas rather than a solid material. For this gas plug to effectively insulate the two ends of the pulse tube, turbulence in the pulse tube must be minimized. However, for the circulation of DC flow, additional gas turbulence will be induced. The laminar flow character of the gas piston will be destroyed and cause temperature instability. When the cooler is operating under lower heat load, motion of the gas molecules in the pulse tube is not strong enough to destroy the performance of the gas piston, so a stable temperature can be realized. By increasing heat load to a certain high level, gas temperature in pulse tube will also rise which will intensify the molecular motion and stronger gas turbulence will be induced by DC flow. Therefore, the laminar flow character of the gas piston will be partially destroyed and temperature instability will occur. If the DC flow is suppressed to a smaller extent, the induced gas turbulence will be smaller. By

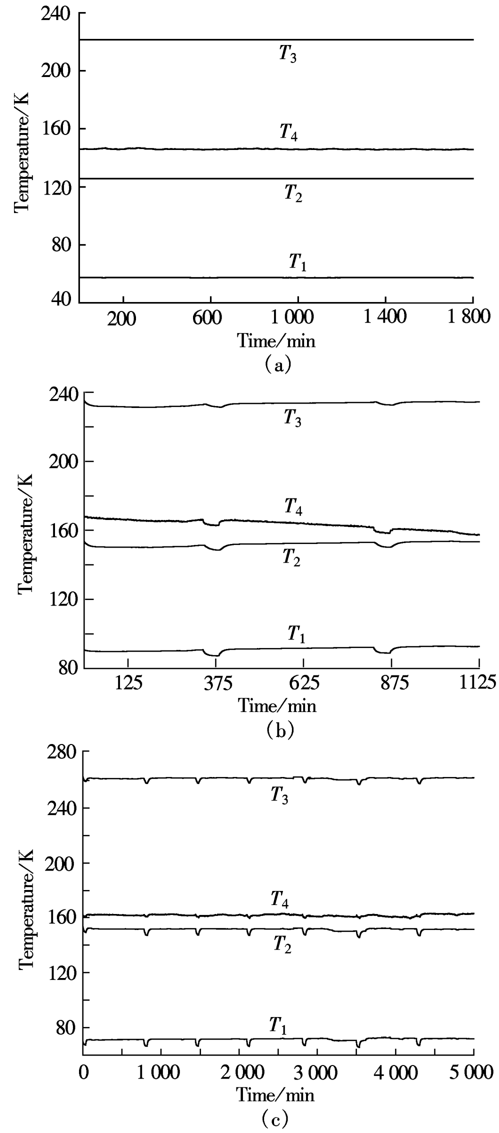

Fig. 3 Temperature history under various heat loads. (a) 23 W heat load; (b) 37 W heat load; (c) 40 W heat load

this means, temperature stability of the cooler can be carried out.

Based on the above analysis, we replaced 30% stainless steel mesh at the cold part of the regenerator by lead balls of 0.25 mm diameter. Operating under orifice mode, the measured pressure drop of the regenerator is 145 kPa, which is 80 kPa higher before modification. While under double-inlet mode, pressure loss of the regenerator is about 70 kPa which is very close to 55 kPa as the regenerator is filled with 100% SS. Calculating by Eq. (1) shows that at a constant mass flow difference M, after modification the DC flow can be reduced to about 50% of the former. Fig. 3(c) shows the experimental results of temperature history with 40 W heat load. As shown in Fig. 3(c), temperatures of the cooler keep stable for a long time run. The slight temperature oscillation comes from small heat load oscillation. The experimental results show that with a larger regenerator flow resistance, the cooler can operate stably at a higher temperature region.

Fig. 4 and Fig. 5 also show the temperature profiles and performance of the cooler filled with various regenerator matrix arrangements. As shown in Fig. 4, with 30% LD + 70% SS regenerator arrangement, the temperature profile is more linear than that of 100% SS. And the performance of the cooler along the measured temperature range is also improved as shown in Fig. 5, which contradicts the conventional regenerator theory and also differs to orifice mode. As shown in Fig. 6, operating under orifice mode, volumetric specific heat of the lead balls is lower than stainless

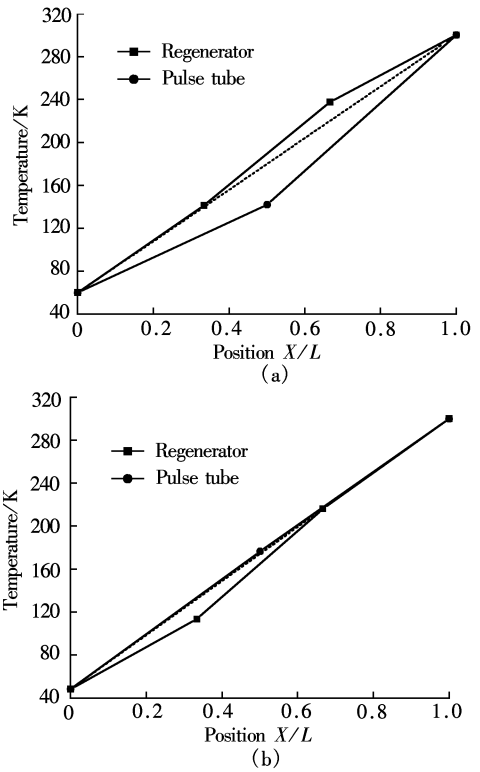

Fig. 4 Temperature profiles for various regenerator arrangements with 25 W heat load. (a) 100% SS; (b) 30% LD + 70% SS

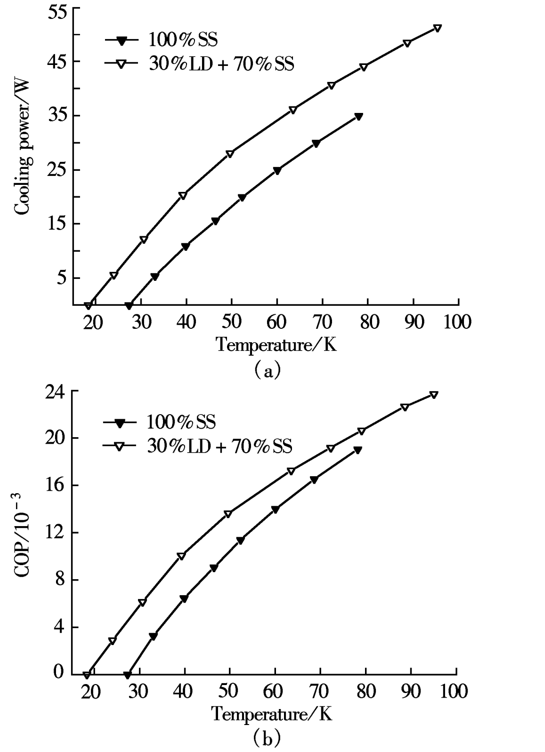

Fig. 5 Cooling power and COP vs. temperature operating under double-inlet mode. (a) Cooling power; (b) COP

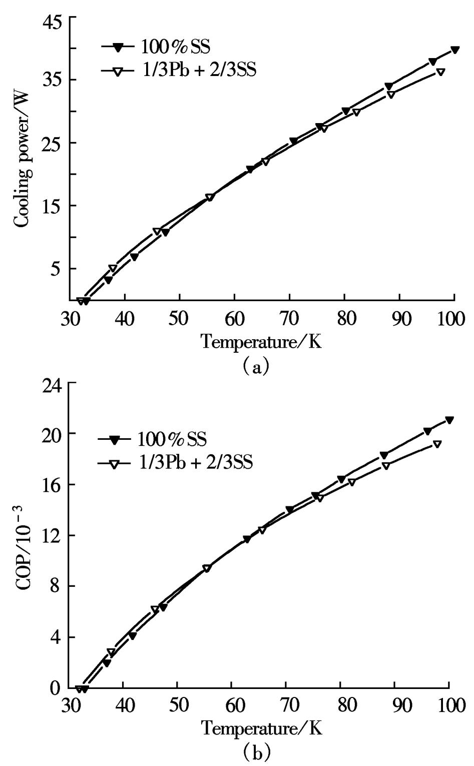

Fig. 6 Cooling power and COP vs. temperature operating under orifice mode. (a) Cooling power; (b) COP

steel mesh when the temperature is higher than 54 K, therefore the performance of the cooler is lower than that with 100% SS. These results further show that increasing regenerator flow resistance, DC flow can be further suppressed. Thereby the temperature stability and higher performance of the cooler at high temperature can be carried out.

5 Conclusion

The DC flow induced by the introduction of the double-inlet not only deteriorates cooling performance of the cooler, but also causes temperature instability. Both theoretical analysis and experimental results show that with a larger regenerator flow resistance, DC flow can be further suppressed and a long-time stable operation of the cooler at 80 K temperature region can be realized. This achievement provides a new way to obtain stable performance at high temperature for a pulse tube cooler and is helpful to its application research.

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回热器流阻对脉管制冷机稳定特性的影响

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摘要:基于流体网络理论,研究了通过改变回热器流阻对由双向进气阀诱发的直流流动进行抑制的可行性,计算结果表明,增加回热器流阻可以有效地抑制直流,进而有望提高脉管制冷机在高温区的稳定性能. 在此基础上,采用不同的回热器填料布置方式,对脉管制冷机的稳定特性开展实验研究,通过采用直径0. 25 mm 的铅丸代替回热器冷端(0. 3 回热器长度)247 目不锈钢丝网的方法,实现了制冷机在 80 K 温区长时间稳定工作. 该研究为解决脉管制冷机存在的高温区性能不稳定提供了新的途径.

关键词:脉管制冷机;流阻;稳定性
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