Experimental investigation on DC flow suppression and refrigeration characteristics of a high-performance single-stage GM-type PTC

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The influence of DC flow induced by the introduction of double-inlet on the refrigeration performance of the pulse tube cooler is experimentally examined. A double-valved double-inlet configuration instead of conventional single-valved one is successfully used in experiments to reduce the DC flow. Besides, the performance of the cooler with various regenerator matrices and supply power of compressors has been extensively investigated under different operation modes. Operating under double-inlet mode, 18.4K and 14.7K minimum temperature has been reached driven by RW2 and CP4000 compressor respectively.

INTRODUCTION

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, regenerator and pulse tube will cause a DC flow around the loop of them. The DC flow from the warm end to the cold end adds an additional thermal load to the cold end of the cooler, and greatly deteriorates the refrigeration performance due to the large temperature difference between two ends, although its value is quite small compared with AC flow [1]. In addition, the DC flow is also a key point to induce the temperature instability of the cooler in some cases [2]. For the better performance of the cooler, the DC flow should be well suppressed to a certain small extent by several ways [3-4]. Based on the detailed analysis and comparison for all kinds of the suppression ways, two parallel-placed needle valves with opposite flow direction referred as two-valved configuration instead of traditional single-valved one as double-inlet are introduced in the paper to eliminate the DC flow and are proved to be a successful way. Besides, the performance of the cooler with various regenerator matrices and supply power of compressors has been extensively investigated under different operation modes. Operating under double-inlet mode, 18.4K and 14.7K minimum temperature has been reached driven by RW2 and CP4000 compressor respectively. Further optimization of the regenerator matrix and operation parameters, better performance of the cooler could be possible. This development will lead the single-stage pulse tube cooler to be used in 20K temperature range instead of the multi-stage pulse tube cooler using at present.

EXPRIMENTAL DETAILS

Figure.1 shows the sketch of the test cooler. This is a single double-inlet pulse tube cooler. The sizes of the pulse tube and regenerator are $\Phi 28\times 0.5\times 155$ and $\Phi 32.35\times 0.5\times 129$ respectively. Two different regenerator matrices are tested. matrix1: all space of the regenerator filled with 247 screens of stainless steel mesh and matrix2: 1/3 space of the stainless steel mesh at the cold part of the regenerator was replaced by lead balls of 0.25mm diameter. A calibrated carbon-glass resistance thermometer is used to monitor the temperature at the cold end of the pulse tube. The cooling power is measured by applying a heat load via a resistive heater.

For the flow asymmetry of a needle valve, the DC flow direction will be opposite when the valve placed in opposite flow direction. So the structure shown in Figure.1 with two parallel-placed needle valves with opposite flow direction called as double-valved configuration, instead of conventional single-valved configuration as the double-inlet is used in this experiment to eliminate the DC flow. In Figure.1 DIV1 expresses the main flow direction of the valve from the regenerator to the pulse tube as indicated with arrow by the manufacturer, DIV2 means the reverse direction.

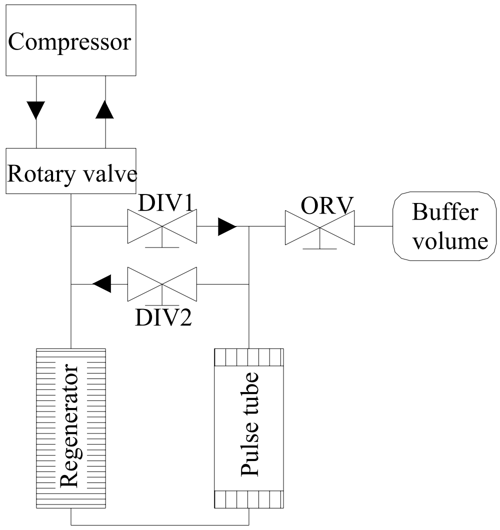


Figure.1 sketch of the pulse tube cooler

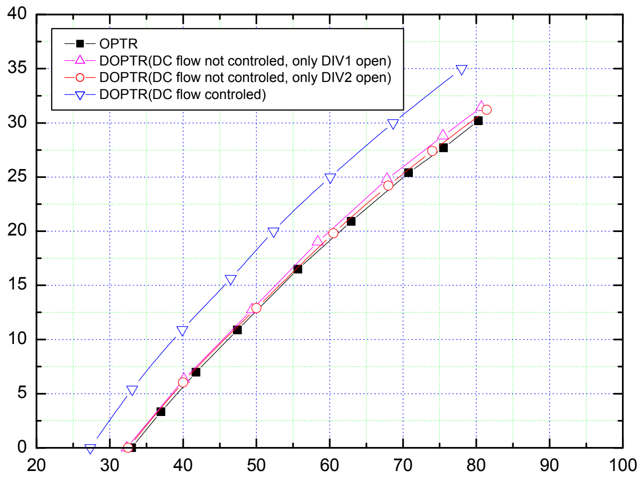
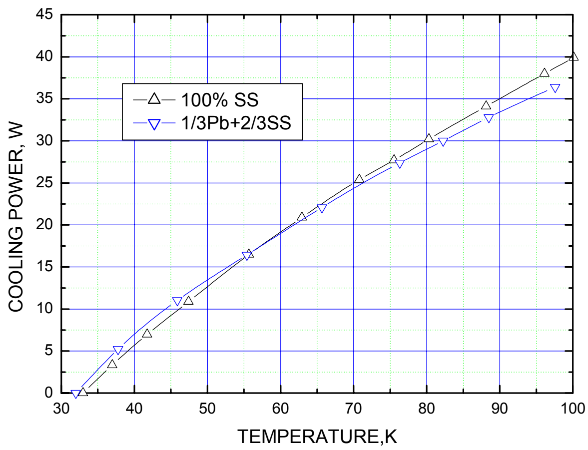


Figure.2 Cooling power under different operation mode

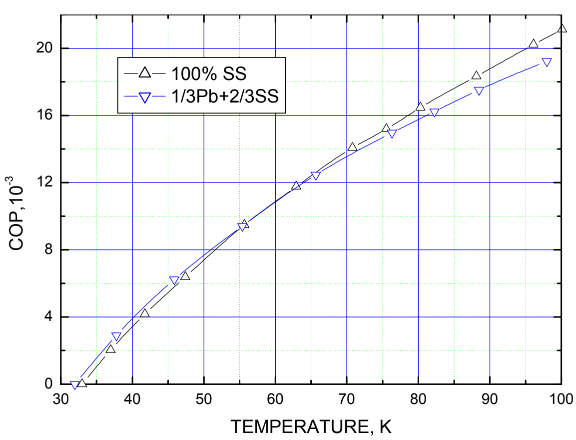
RESULTS AND ANALYSIS

Figure.2 shows the cooling power of the cooler with double-valved configuration compared to single-valve one with matrix1 driven by RW2 compressor. As it is shown in Figure.2, with the single-valve configuration, the minimum temperature obtained is 31.5K, which is only 1.0K lower than that of the orifice mode, while the minimum temperature of about 27K could be reached with the double-valved configuration. Besides, a 5W more cooling power in the measured temperature range has been obtained for the double-valved arrangement. These results show that the double-valved configuration is an effective way to suppress the DC flow.

When the temperature is below 70K, the volumetric specific heat of the stainless steel mesh is lower than the helium. Matrix1's regeneration capacity will greatly degrade, which hamper the temperature further lowering. Replacing 1/3 space of the stainless steel mesh by lead balls (matrix2), which provide larger volumetric specific heat at the cold part of regenerator, maybe leads to a lower temperature and larger cooling power. Due to the difference of the orifice and double-inlet pulse cooler in operating principles, the effect of the matrix arrangements on cooling performance will also be some different.



(a) Cooling power

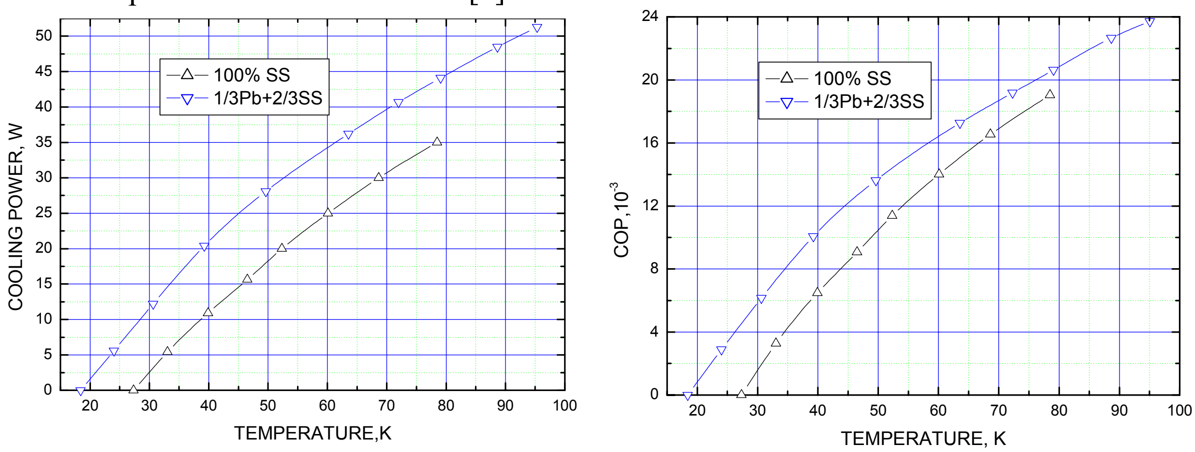


(b) COP

Figure.3 Cooling power and COP vs. temperature with various regenerator matrices (Orifice mode,RW2)

Figure.3 gives the cooling power and COP of the cooler operating under orifice mode with various regenerator matrices. As it is shown in figures, the minimum temperature with matrix2 is only little lower than that with matrix1. And the cooling power and COP is little higher than that with matrix1 when the temperature below 54K, while temperature above 54K, it is lower than that with matrix1, which could be well explained with conventional regeneration theory.

From the phase shift and fluid network theories, the introduction of the double-inlet, not only increases the phase shift capacity of the mass flow and pressure, but also the flow impedance could be reduced. Both of them lead to a better performance of the cooler. As we see in Figure.4, when the cooler operating under double-inlet mode, the temperature drops from 27K to 18.4K with matrix2 and 11.5W cooling-power at 30K could be obtained. At 40K and 50K, the COP with matrix2 could be 56% and 31% more than that with matrix1. These results show that with matrix2 the positive effect of the lead balls on regeneration capacity will take dominant position than the passive effect in consequence of increased flow resistance. We also could see in Figure.4b, when the temperature is higher than 40K, the slope of the COP decreases quite sharp and at 50K it will be lower than that with matrix1. This change tendency is the same as the orifice case, which depends on the thermo-property of the lead balls. While for the measured temperature range, with matrix2 the COP is always higher than the case with matrix1. The possible reason of the refrigeration characteristics difference is: operating under double-inlet mode, the DC flow plays a great role on the performance of the cooler, with matrix2 the DC flow could be better suppressed which leads to a better performance of the cooler [5].



(a) Cooling power (b) COP

Figure.4 Cooling power and COP vs. temperature with various regenerator matrices (double-inlet mode,RW2)

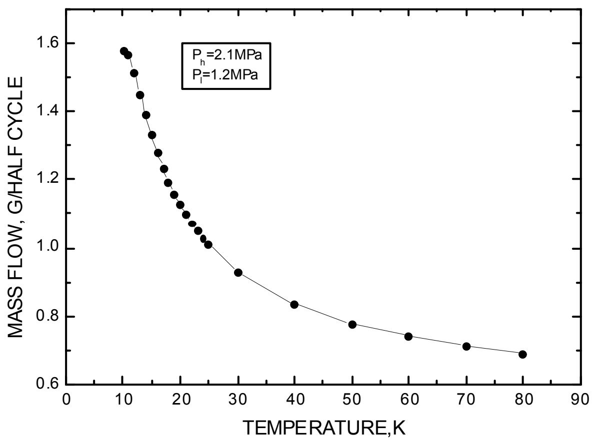
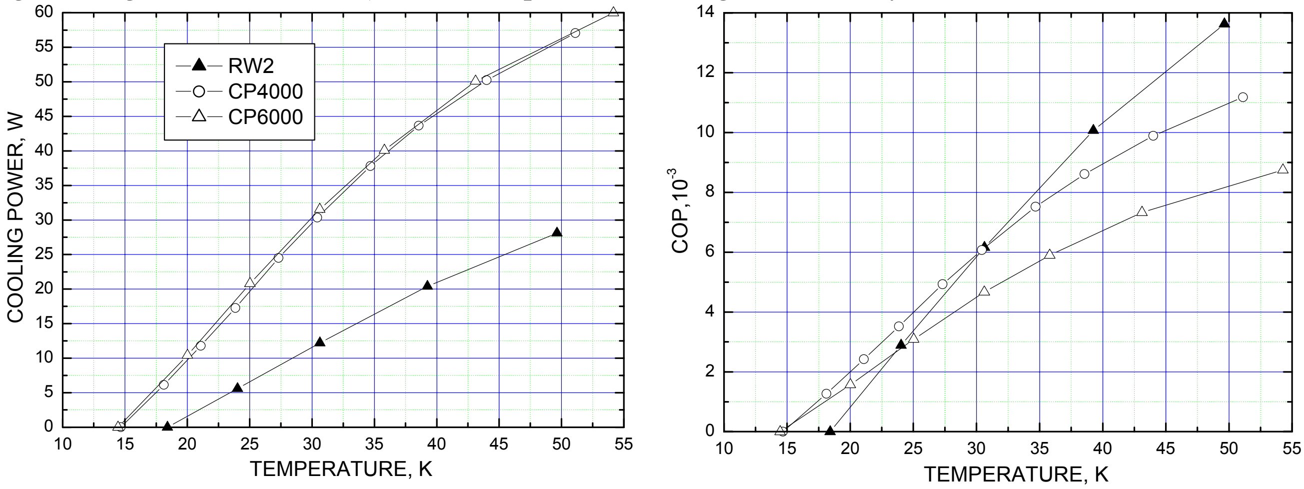


Figure.5 Calculated gas flow per half cycle vs. temperature

As we know, when refrigeration temperature below 20K, the real gas property of helium will impose a great influence on the performance of the cooler, which needs more mass flow to further increase its performance. Figure.5 shows the required mass flow to maintain the high- and low-pressure 2.1Mpa and 1.2Mpa respectively for a half cycle of the cooler. The calculation was carried out based on the temperature profiles of the regenerator and pulse tube are linear. In 300K-80K temperature range, we calculate the gas properties with mean temperature and then the mass flow; while for the range from 80K to minimum temperature the gas properties of 20 differential temperature segments are used to calculate the mass flow. From Figure.5, we can see that with temperature decreases, especially for a temperature below 20K, the required gas of the cooler increases very fast.

Figure.6 shows the cooling power and COP curves vs. temperatures driven by different compressors. It is seen in Figure.6a that the minimum temperature of the cooler is as low as 14.7K, and 29.5W cooling power has been obtained at 30K driven by CP4000. This is one of the best results for a single stage pulse tube cooler could reach so far. However, the slope of the COP is not as steep as the case driven by RW2 shown in Figure.6b. Especially when the temperature higher than 31K, with RW2 could get higher COP than that driven by CP4000. This means the cooler which uses a compressor with low power supply could get higher efficiency.

We also tested the performance of the cooler with CP6000 compressor. As shown in Figure.6a, no more cooling power than that of CP4000 has been obtained driven by CP6000, while the COP are much lower. One of the possible reasons causing this result is that the larger gas flow provided by CP6000, leads to too large pressure ratio in pulse tube to expand sufficiently. So a proper compressor selection is very important for a certain cooler to obtain good performance when the required cooling power is fulfilled. The other possible reason is that, when the temperature below 20K, the volumetric specific heat of the helium is higher than that of lead balls, the regenerative efficiency of the regenerator is very low. More gas flow will further deteriorate regenerator performance, and as a results the cooling performance are limited. In this case, through further optimization of the regenerator filling matrix (for example, using magnetic regenerative material), lower temperature and higher COP may be obtained.



(a) Cooling power (b) COP

Figure.6 Cooling power and COP vs. temperature with matrix2 driven by various compressors

CONCLUSIONS

The existence of DC flow deteriorates refrigeration performance of a double-inlet pulse tube cooler greatly. A double-valved configuration instead of conventional single-valved one is successfully used in experiments to suppress the DC flow to a small extent. The effect of the regenerator matrices on performance of the cooler not only depends on the material thermodynamic property, but also the operation mode of the cooler. Operating under double-inlet mode, 18.4K and 14.7K minimum temperature has been reached driven by RW2 and CP4000 compressor respectively.

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