Analysis of a Tube-in-Tube Heat Exchanger for a Space 4K Hybrid JT Cryocooler

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ABSTRACT

Hybrid JT cryocoolers are widely used in space detectors working at 4 K because of its flexibility and relatively high efficiency. With a tube-in-tube heat exchanger commonly used in the space 4 K hybrid JT coolers. The efficiency of the counter flow heat exchangers is one of the decisive factors which affect the performance of the hybrid JT cooler. This paper focuses on the influence of the arrangement of the high pressure and low pressure gas. High pressure gas flowing in the inner tube and low pressure gas flowing in the outer side is compared with low pressure gas flowing in the inner tube and high pressure gas flowing in outer side. Two different ways of the helium gas arrangement are analyzed when both of their efficiency is assumed to be 0.97. The influence of the size of the tubes is also discussed in detail.

INTRODUCTION

Cryogenics and its applications in space have made a remarkable amount of progresses over the last decades. In the area of space astronomy, some electronic detectors are cooled to 4 K levels to improve their sensitivity and reduce the background noise , so miniaturization of 4 K cryocoolers for space application has become a key field for cryogenic research at National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA) and European Space Agency (ESA). In view of its flexibility and relatively higher efficiency, hybrid JT cryocoolers are widely used in space detectors working at 4 K. In fact, nearly all the space applications of mechanical cryocoolers working at 4 K, that have been launched or are under development are hybrid JT cryocoolers. For instance, the mechanical cryocooler used on Planck is a ^{4}He JT cooler precooled by an adsorption cryocooler[1]. JWST uses a three-stage pulse tube cryocooler to precool a JT loop. In SMILES and SPICA, two-stage Stirling coolers are used to provide precooling power for JT coolers.[2-5]

Our laboratory has also developed a compound 4.5 K cryocooler using a high frequency multi-stage pulse tube cooler to precool a Joule-Thomson (J-T) loop.[6] The counter-flow heat exchanger, one of the key components of Joule-Thomson refrigerator, strongly influences the performance of the hybrid JT cooler. The tube-in-tube helical heat exchanger is commonly used in the hybrid JT refrigerator due to its good heat transfer performance, compact structure, low cost and simple manufacture process.[7-9] The arrangement of the high pressure and low pressure gas affects the performance of the counter-flow heat exchangers, and the size of the tubes should change to adapt to the state of the helium. Detail analysis are presented in this paper.

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COUNTER-FLOW HEAT EXCHANGER

The Hybrid JT Cooler

The 4 K hybrid JT cooler developed by our laboratory is illustrated in Figure 1. The JT loop is precooled by a two-stage pulse tube cooler and three counter-flow heat exchangers, Hex1-Hex3, used in the JT loop. Figure 2 gives the schematic of the heat exchanger. The inner and outer diameters of the inner tube are d_i and d_o respectively, while the inner diameter of the external tube is d_{oi}. All these parameters affect the heat transfer characteristics of the heat exchangers. Thus, different cases are analyzed, as shown in Table 1. In each case, high pressure gas flowing in the inner tube and low pressure flowing in the outer side is compared with low pressure gas flowing in the inner tube and high pressure gas flowing in outer tube.

To make it more convenient for our analysis, we define low pressure gas flowing in the inner tube and high pressure gas flowing in outer side as condition1 and high pressure gas flowing in the inner tube and low pressure flowing in the outer side as condition2. And the parameters of condition2 are all marked with superscript, such as K'. Subscript i and o represent parameters of inner and outer side and subscript numbers represent the stage of the heat exchanger. For example, ui1 means the velocity of inner side of Hex1.

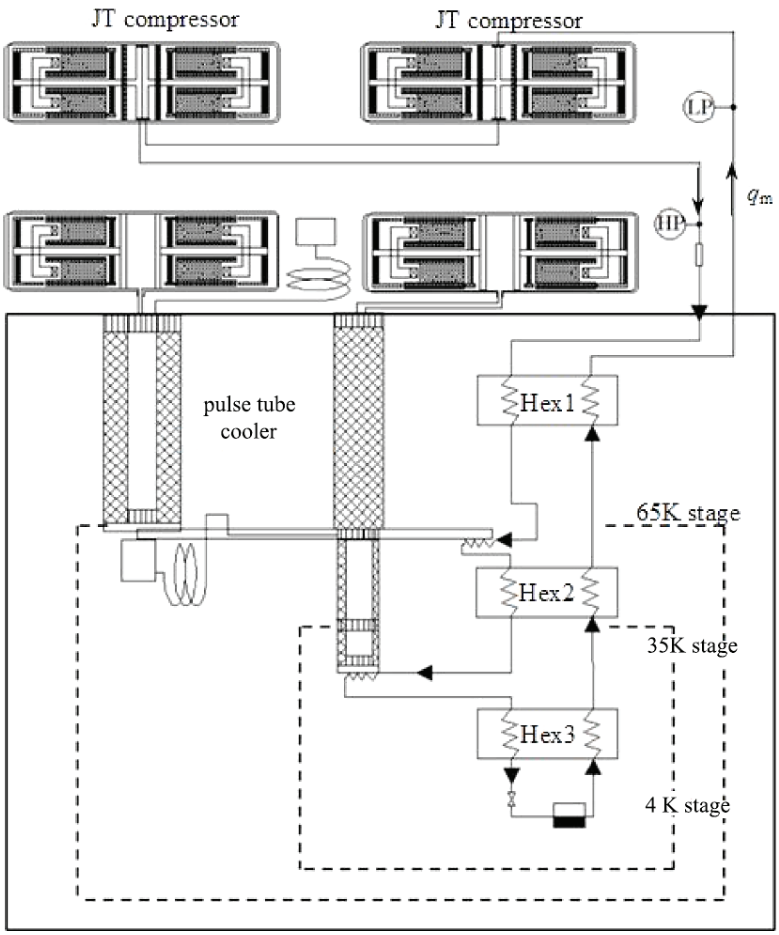

Figure 1. Schematic of the hybrid JT cooler

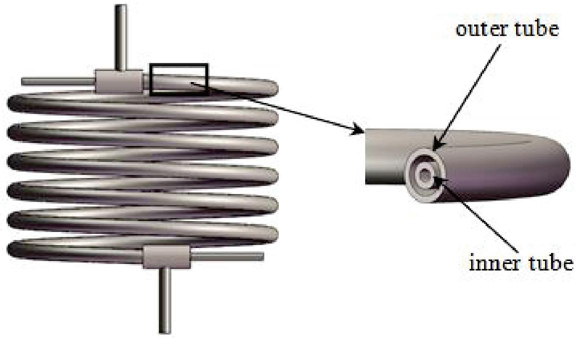

Figure 2. Schematic of tube-in-tube heat exchanger

Analysis Method

Research about the influence of the tubev parameters on heat transfer is carried out by comparing condition1 and condition2 when parameters such as d_i, d_o, and d_{oi} vary. The design method, which has already been verified to be effective, is presented as follows. The Nusselt number of the heat exchanger is calculated using correlations described below,

$$Nu_l = c_r * (3.657 + \frac{0.0668 * Gz}{1 + 0.04 * Gz^{0.67}}) \quad (1)$$

$$Nu_t = c_r * (\frac{(f/2)(\text{Re}-1000)\,\text{Pr}}{1+12.7(f/2)^{0.5}(\text{Pr}^{2/3}-1)})(1+(\frac{d_e}{l})^{2/3})c_t \quad (2)$$

where Gz=Re*Pr*d_e/L, c_r is the correction coefficient of spiral tube. Note that Nu_l is Nusselt number for laminar flow while Nu_t represents Nusselt number for turbulent flow; d_e is equivalent diameter for heat transfer. Then the overall heat transfer coefficient K can be achieved.

$$h = Nu * \lambda / d_e \quad (3)$$

$$\frac{1}{K} = \frac{1}{h_i}\frac{d_o}{d_i} + \frac{d_o}{2\lambda}\ln\frac{d_o}{d_i} + \frac{1}{h_o} \quad (4)$$

The governing equation for heat transfer and the energy balance equations are given as follows,

$$Q = KA\Delta T_m \quad (5)$$

$$Q_h = Q_l = q_m(h_{in} - h_{out}) \quad (6)$$

where ΔT_m is the log mean temperature difference of the heat exchanger, A is the heat transfer area based on the outside surface area of the inner tube, q_m is the mass flow rate of helium, h_{in} and h_{out} are enthalpy of inlet and outlet flow.

Table 1. Different sizes of tubes

	d_i (mm)	d_o (mm)	d_{oi} (mm)
case1	1.5	2.5	4.0
case2	2.0	3.0	
case3	2.5	3.5	
case4	3.0	3.75	
case5	3.0	3.5	3.75
case6	2.5		
case7	2.0		

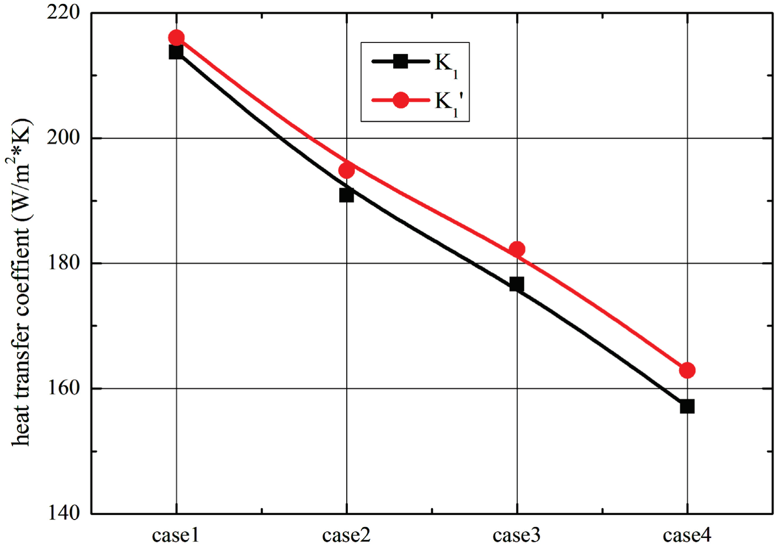

Figure 3. Heat transfer coefficient of Hex1 at different cases

The pressure drop of the heat exchanger is also influenced by the arrangement of the working helium as well as size of the tube. Pressure drop of the each case mentioned above is calculated to make sure that the flow resistance of the heat exchanger is within the allowable range[10]. The pressure drop is calculated by equation (7)-(9).

$$\Delta p = \xi f \frac{\rho u^2 l}{2d_e} \tag{7}$$

$$\xi = \{1-[1-(\frac{11.6}{K})^{0.45}]^{2.22}\}^{-1} \tag{8}$$

$$K = Re(d_e / D)^{0.5} \tag{9}$$

where ξ is correction coefficient of flow resistance, f is the resistance coefficient.

RESULTS AND DISCUSSION

In this study, the analysis is based on the following assumptions. 1) The supply pressure of the JT cooler is 2.0 MPa. 2) The low side pressure is 0.13 MPa. 3) The temperature of the first stage supply gas is 300 K. All the pressure drops of the heat exchanger are calculated based on the feature size of the tube and the total pressure drop of both the high pressure side and low pressure side should be lower than 3kPa.

Influence of Inner Tube on Hex1 and Hex2

In this part, helical heat exchangers with changing size of inner tube are considered while d_{oi} is maintained constant. The heat transfer coefficients of Hex1 and Hex2 when both the inner and outer diameter of the inner tube increases are illustrated in Figure 3 and Figure 4. As can be observed, the total heat transfer coefficients of the two heat exchangers at two conditions decrease with increasing d_i and d_o which means the heat transfer characteristics deteriorates. Although the heat transfer of the outer side can be enhanced as d_o increases, heat transfer of the inner side deteriorates. And the heat transfer coefficient of condition1 is a little higher than condition2.

As is known, the low pressure gas needs more flow area than high pressure gas. Thus, the low pressure gas should flow in larger cross section area. It is more reasonable to compare case5 at condition1 with case1 at condition2 whose cross section area of the high pressure side and low pressure side is about the same. As shown in Table 2, the overall heat transfer coefficient of condition2 is better than condition1. What's more, its velocity of the return low pressure gas is lower. As a result, the pressure drop of condition2 is lower than condition1 which is preferred for the JT cooler.

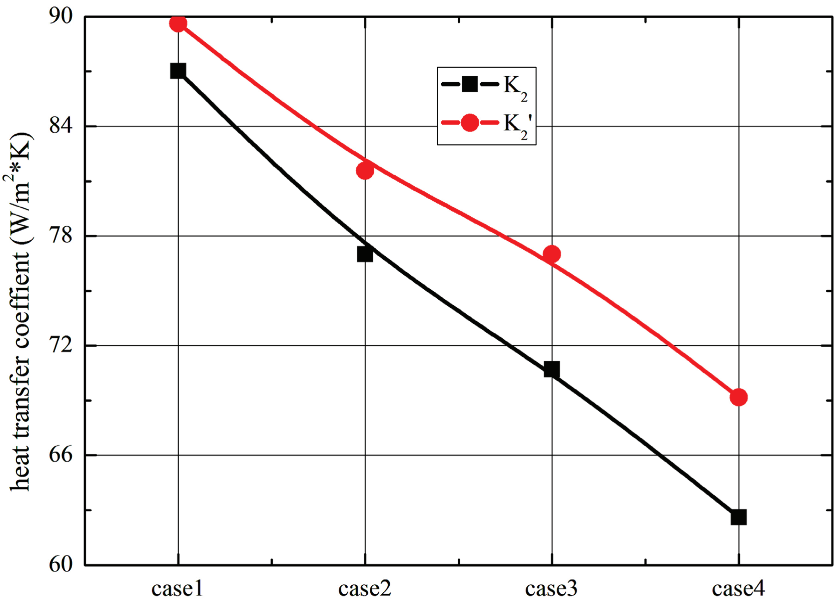

Figure 4. Heat transfer coefficient of Hex2 at different cases

As can be observed in Table 2 and Table 3, the heat transfer enhancement of the low pressure side can improve the performance of the heat exchanger efficiently for both conditions. Therefore, high pressure gas flows in the inner tube is preferred based on the analysis above.

Influence of Diameter of Inner Tube

The heat transfer coefficient increases with decreasing d_i, as shown in Figure 1 and Figure 2. In this section, the cross-sectional area of the annular channel remains constant and the influence of d_i is discussed at condition1. The heat transfer is enhanced with faster flow, and faster flow can be achieved with smaller cross-sectional area, as illustrated in Figure 5. Then, a shorter tube is required to accomplish the same amount of heat transmission. However the pressure drop of the low pressure side increases dramatically with decreasing d_i. When d_i is 1.5 mm, the pressure drop goes up to 3365 kPa which is not acceptable for the JT loop. However, Hex3 may use a smaller tube because of the fact that the viscosity of the helium is very low at temperatures below 20 K.

The pressure drop of the Hex3 at two conditions is shown in Table 4. The two conditions have about the same flow area for the high pressure gas as well as the low pressure gas when d_i=1.5mm, d_{io}=1.8 mm, d_{oi}=2.0 mm and d_i'=0.8 mm, d_{io}'=1.5 mm, d_{oi}=2.5 mm. Although the diameters of the tubes are much smaller than Hex1 and Hex2, the pressure drop is still very low. The pressure drop of Hex3 at condition1 is lower than condition2.

Table 2. Heat transfer and pressure drop of Hex1

condition1 (case5)	h_{i1}(W/m²K) 166.95	h_{o1}(W/m²K) 2138.65	K_1(W/m²K) 156.47	ΔP_{i1}(Pa) 265.91	ΔP_{o1}(Pa) 343.90
condition2 (case1)	h_{i1}' (W/m²K) 347.864	h_{o1}' (W/m²K) 342.14	K_1' (W/m²K) 216.04	ΔP_{i1}' (Pa) 241.67	ΔP_{o1}' (Pa) 247.62

Table 3. Heat transfer and pressure drop of Hex2

condition1 (case5)	h_{i2}(W/m²K) 66.24	h_{o2}(W/m²K) 912.41	K_2(W/m²K) 62.36	ΔP_{i2}(Pa) 58.22	ΔP_{o2}(Pa) 80.35
condition2 (case1)	h_{i2}' (W/m²K) 148.40	h_{o2}' (W/m²K) 135.76	K_2' (W/m²K) 89.62	ΔP_{i2}' (Pa) 61.17	ΔP_{o2}' (Pa) 58.20

Table 4. Pressure drop of Hex3

condition1	ΔP_{i3} (Pa) 228.19	ΔP_{o3} (Pa) 92.89
condition2	ΔP_{i3}' 320.80	ΔP_{o3}' 160.26

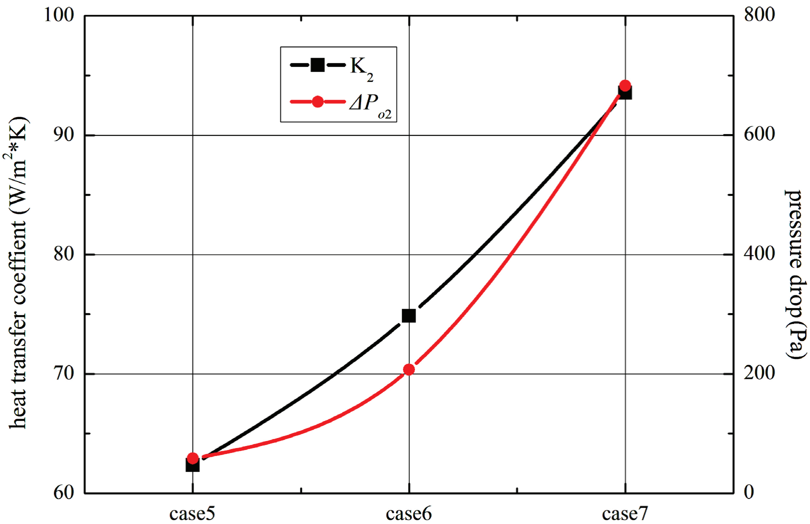

Figure 5. Heat transfer coefficient and pressure drop of Hex2 at different d_i

DISCUSSION

Based on all the discussion above, it is obvious that the heat transfer characteristics of the tube-in-tube heat exchangers are affected by the size of the tubes and the arrangement of the gas. The enhancement of heat transfer in the low pressure side is an effective way to improve the overall performance of the heat exchanger. Better heat transfer performance can be achieved by using smaller diameter tubes, but the pressure drop will increase dramatically as gas flow area decreases. Besides, the tubes must be chosen on the premise of ensuring that the pressure drop is in the acceptable range. The gas arrangement of condition1 performs better at Hex1 and Hex2 while condition2 is preferred in low temperature range.

CONCLUSIONS

The influence of the size of the tubes and the gas arrangement on heat transfer characteristics of the tube-in-tube heat exchangers are demonstrated and analyzed. The performance of the heat exchanger can be improved by employing smaller tubes, but its pressure drop increases at the same time. With high pressure gas flowing in the inner tube and low pressure gas flowing in the annular channel performs better in high temperature range while the third stage heat exchanger performs better with high pressure gas flowing in annular tube.

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