Optimization of the Counter-Flow Heat Exchangers of Space 2.5 K Hybrid Joule-Thomson Cryocooler

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ABSTRACT

Heat exchangers are, among others, the key components of hybrid Joule-Thomson (JT) cryocoolers. Three tube-in-tube counter-flow heat exchangers (CFHX) are used in our hybrid JT cooler. Among them, the 3rd stage counter-flow heat exchanger of JT cycle has the important role of precooling high pressure gas before throttling. To make the structure of hybrid JT cryocooler more compact, a new high-efficiency 3rd stage counter-flow heat exchanger is designed and will be used in a JT cryocooler.

INTRODUCTION

In recent years, it is becoming more prevalent for JT cryocoolers to be used in space exploration. JT cryocoolers have higher efficiency at temperatures near and below 4 K than other kinds of mechanical cryocoolers and can isolate vibration and shield electromagnetic interference easily because there are no moving parts at the cryocoolers' cold ends.

Counter-flow heat exchangers which have high efficiency and compact structures are principal components of hybrid JT cryocoolers. This kind of heat exchanger can be compactly integrated with the pre-cooling stages, such as multi-stage pulse tube or Stirling cryocooler. In addition, counterflow heat exchangers make full use of the cooling capacity of recuperated cold helium to pre-cool the high pressure incoming helium.

In 2018, a 2.65 K hybrid JT cooler using ^{4}He as working medium were developed by the Key Laboratory of Space Energy Conversion Technology, CAS. This hybrid JT cryocooler obtained the temperature of 2.65 K with total power consumption of 317.3 W and cooling capacity of 1.48 mW at 2.71 K [1]. The three counter-flow heat exchangers used in this hybrid JT cryocooler are spiral tube-in-tube design as Figure 1 shows. The high pressure helium which comes out from the 3rd stage

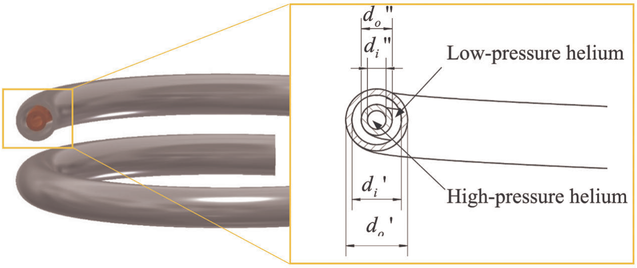

Figure 1. Diameters of tubes of the counter-flow heat exchanger.

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Table 1. The estimated parameters of the 3rd stage CFHX when JT cycle obtained 3K.

Parameters	Outer tube	Inner tube
Inlet pressure (MPa)	0.025*	0.9
Inlet temperature (K)	3	18
Length (m)	1~2	
Spiral diameter (cm)	3~6	
Mass flow rate (mg/s)	1.0~1.8	
Pressure drop (kPa)	<3	

*The saturated vapor pressure of helium is 0.02373 MPa at 3K. Due to the distance between the evaporator and the inlet of inner tube, it is conservatively estimated that the inlet pressure of the inner tube is 0.025 MPa.

counter-flow exchanger directly enters in the JT valve for throttling. So, the efficiency of the 3rd stage counter-flow heat exchanger directly impacts the performance of the JT cycle.

In this paper, a new compact 3rd stage CFHX is designed, which will improve the performance of the hybrid JT cryocooler.

MATHEMATICAL MODELING AND COMPUTATION

Flow regime of the fluid in CFHXs

The 3rd stage CFHX is directly connected with the JT valve, and its heat exchange efficiency directly impacts the cooling performance of the JT cycle. The previous 3rd stage heat exchanger has a large spiral radius taking up a lot of volume. To reduce the volume and improve the efficiency of the 3rd stage heat exchanger, we can reduce the spiral diameter, increase the heat exchanger length, and reduce tube diameter.

According to our previous experiments, when this JT cryocooler obtains a temperature of 3 K, the parameters of the 3rd stage CFHX are estimated and shown in the Table 1.

The first step of optimizing the 3rd stage CFHX is determining the proper tube diameter of CFHX with a certain spiral diameter of 40 mm. According to our previous study, six groups of CFHXs are discussed, as Table 2 shows. Then, the spiral diameter will be optimized.

Reynolds number is commonly used to judge the flow regime of fluid. The critical Reynolds number of the spiral tube is calculated with the following formula [2]. This calculation ignores the pressure drop inside the heat exchanger.

$$\mathrm{Re}_c = 2300(1 + 8.6(\frac{d_i}{D})^{0.45}) \tag{1}$$

where Re_c is critical Reynolds number, D is spiral diameter of CFHX.

According to calculation results of Reynolds numbers in different tubes with mass flow rate from 1.0 mg/s to 2.0 mg/s, the flow regime is summarized in the Table 2. The flow regime of the fluid inside these six CFHXs is laminar.

Table 2. The parameters of six CFHXs.

Group	d_o ' (mm)	d_i ' (mm)	d_o " (mm)	d_i " (mm)	D (mm)	Flow regime of inner tube	Flow regime of outer tube
1	6	4	2	1	40	laminar flow	laminar flow
2	4	3	2	1			
3	4	3	2	1.6			
4	4	3	1	0.6			
5	3	2	1	0.6			
6	2	1.6	1	0.6			

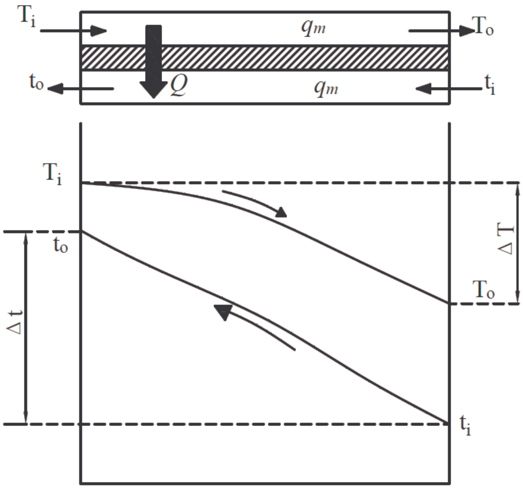

Figure 2. Schematic diagram of fluid temperature in CFHX.

The effectiveness of CFHXs and the temperature of outlets

Figure 2 shows the schematic diagram of CFHX. T_i and T_o are the temperatures of high pressure helium of inlet and outlet, respectively. t_i and t_o are the temperatures of low pressure helium of inlet and outlet, respectively.

The specific heat capacity at 0.9 MPa and 0.025 MPa are shown in the Figure 3. The effectiveness of the heat exchanger is the ratio of the actual heat flow to the theoretical maximum heat flow, which is set to 97%.

$$\varepsilon = \frac{Q'}{Q_S} = \frac{Q''}{Q_S} = 97\% \tag{2}$$

$$Q_S = \left\{ q_m \int_{t_i}^{T_i} c_p'(T)dT, q_m \int_{t_i}^{T_i} c_p''(T)dT \right\}_{\min} \tag{3}$$

where Q' is the heat flow of high pressure helium released, Q'' is the heat flow of low pressure helium absorbed, **ε** is effectiveness of heat exchanger and Q_s is the smaller value between Q' and Q''.

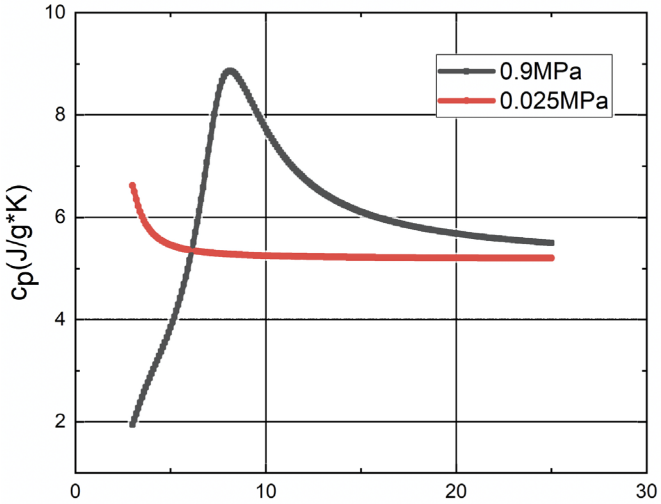

Figure 3. The specific heat capacity of helium at 0.9 MPa and 0.025 MPa.

Table 3. The calculation results of temperature of CFHX.

ε	T_i (K)	T_o (K)	t_i (K)	t_o (K)	Δt_m (K)
97%	18	6.84	3	17.54	12.77

According to the effectiveness of heat exchanger and design parameters, outlet temperatures of inner and outer tubes can be calculated as Table 3 shows.

Then, according to these four temperatures of inner and outer tubes, the logarithmic mean temperature difference (LMTD) can be obtained [5].

$$\Delta t_m = \frac{\Delta t_{\max} - \Delta t_{\min}}{\ln \dfrac{\Delta t_{\max}}{\Delta t_{\min}}} \tag{4}$$

$$\Delta t_{\max} = \left\{T_i - t_o, T_o - t_i\right\}_{\max} \tag{5}$$

$$\Delta t_{\min} = \left\{T_i - t_o, T_o - t_i\right\}_{\min} \tag{6}$$

where Δt_m is the logarithmic mean temperature difference.

Heat transfer coefficient of CFHXs

The Nusselt number of a spiral tube using gas as working fluid can be obtained by multiplying the Nusselt number of a straight tube by a correction factor – c_r. The heat transfer coefficient of CFHX are calculated by these following formulas [2-5].

$$\frac{1}{K} = \frac{1}{\alpha''}\frac{d_o''}{d_i''} + \frac{d_o''}{2\lambda_s}\ln\frac{d_o''}{d_i''} + \frac{1}{\alpha'} \tag{7}$$

$$\alpha = Nu\frac{\lambda}{d_e} \tag{8}$$

$$Nu^* = 3.657 + \frac{0.0668Gz}{1 + 0.04Gz^{0.67}} \tag{9}$$

$$Nu = c_r\frac{\int_{t_1}^{t_2} Nu^*(t)dt}{t_2 - t_1} \tag{10}$$

$$c_r = 1 + 1.77\frac{d}{R} \tag{11}$$

where K is the total heat transfer coefficient, α' and α'' are the convective heat transfer coefficient of outer and inner tube respectively, λ is heat conductivity coefficient of fluid, λ_s is heat conductivity coefficient of the material of tubes. Nu is Nusselt number of a straight tube, and Gz is the Graetz number.

Table 4. The calculation results of heat transfer coefficient.

Group	t_o (K)	T_o (K)	D (mm)	d_o' (mm)	d_i' (mm)	d_o'' (mm)	d_i'' (mm)	K $(W/m^2 \cdot K)$
1	17.54	6.84	40	6	4	2	1	1.7071
2				4	3	2	1	2.3869
3				4	3	2	1.6	2.4507
4				4	3	1	0.6	1.9937
5				3	2	1	0.6	3.0879
6				2	1.6	1	0.6	4.0799

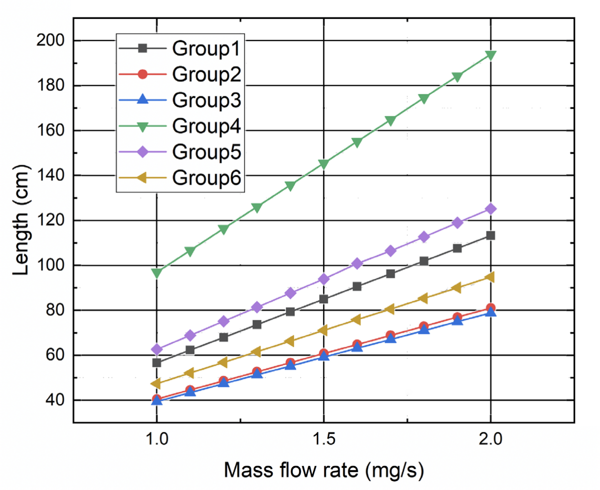

Figure 4. The calculation results of length of six CFHXs.

The heat transfer coefficient of the six CFHXs are shown in Table 4. It can be seen that the heat transfer coefficient has a close relationship with hydraulic diameters of outer and inner tubes. The smaller the hydraulic diameter, the greater the heat transfer coefficient.

The length of CFHXs

After obtaining the total heat transfer coefficient, the required heat transfer area can be obtained. The length of CFHXs with different mass flow rate can be calculated by these following formulas.

$$S=\frac{Q}{K\Delta t} \tag{12}$$

$$L=\frac{S}{\pi d_o''} \tag{13}$$

where S is the heat transfer area of CFHX. L is the length of heat exchanger.

Figure 4 shows the calculation results of the length of CFHXs at different mass flow rates. As the mass flow rate increases, to maintain the same efficiency of heat exchange, the length of the heat exchanger will also increase. At a certain flow rate, the lengths of 2nd and 3rd group are shorter than others, which proves that these two groups of CFHXs take up less space. Because the hydraulic diameter of outer tube of the 4th group is relatively large and the outer diameter of inner tube is small, the 4th group is much longer than others.

However, all the calculation are performed under ideal conditions without considering pressure changes.

The pressure drop of CFHXs

The resistance of fluid in spiral tubes is different from that in straight tubes. The pressure drop in spiral tubes can be calculated by multiplying the pressure drop of straight tubes by a correction factor - c_f[2].

$$\Delta p=f\frac{L}{d_e}\frac{\rho v^2}{2} \tag{14}$$

$$c_f=\left(1-\left(1-\left(\frac{11.6}{\mathrm{Re}\left(\frac{d_e}{D}\right)^{0.5}}\right)^{0.45}\right)^{2.22}\right)^{-1} \tag{15}$$

where Δp is the pressure drop of CFHX, f is friction coefficient of laminar flow.

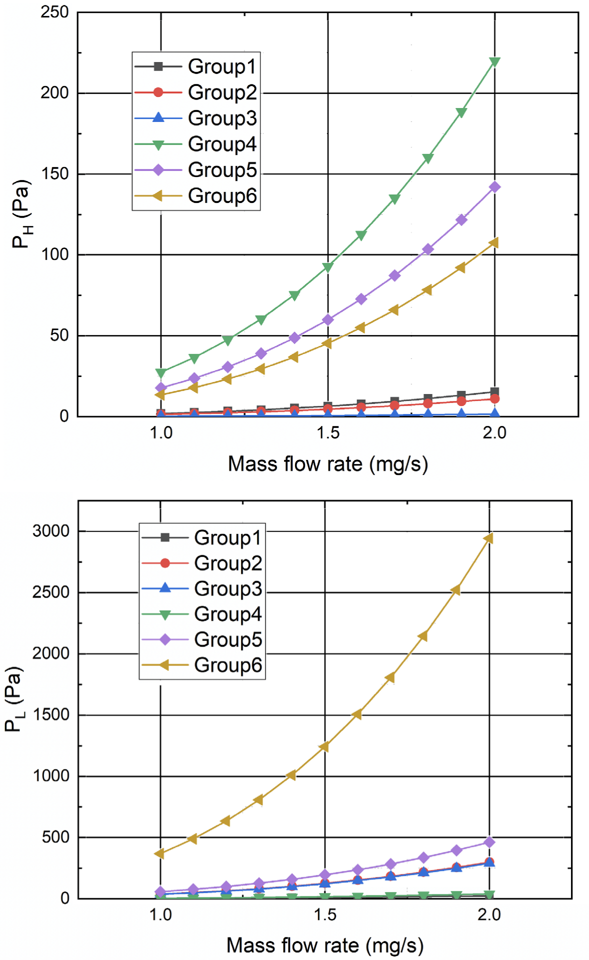

Figure 5. The calculation results of pressure drop in outer and inner tubes.

Figure 5 shows the calculation results of pressure drop of these 6 groups. With the decrease of hydraulic diameter, the pressure drop of the tube also decreases. Only the pressure drop of the outer tube of the 6th group exceeds 1 kPa. Relative to the pressure in tubes, 0.9 MPa and 0.025 MPa, the pressure drop can be acceptable.

The selection of proper diameters of CFHX

According to the above analysis, the hydraulic diameter is one of the key factors impacting the heat transfer coefficient. With the decrease of hydraulic diameter, the heat transfer coefficient increases, which means the required heat transfer area decrease. But the length of CFHX is not only determined by heat transfer coefficient but also impacted by the outer diameter of the inner tube.

Table 5. The comparison of spiral diameters and heat transfer coefficient.

Group	d_o ' (mm)	d_i ' (mm)	d_o '' (mm)	d_i '' (mm)	D (mm)	K $(W/m^2 \cdot K)$
3	4	3	2	1.6	40	2.4507
7					30	2.5864
8					50	2.3689

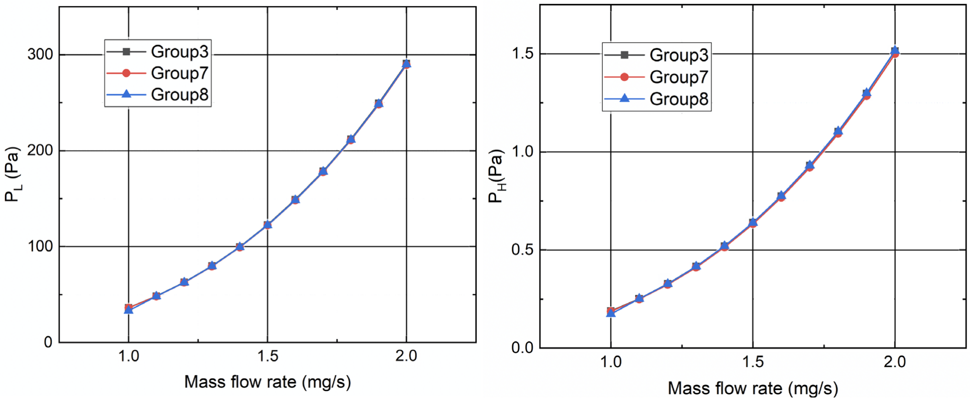

Figure 6. The calculation results of pressure drop of group 3, 7 and 8.

In addition, the hydraulic diameter also influences the pressure drop in the tubes. The pressure drop is the key parameter for JT cryocoolers, which directly influence the performance of JT cycle. Considering the heat transfer coefficient, length and the pressure drop, the 3rd group diameters are the best choice in these 6 groups.

The optimization of spiral diameter of CFHX

The spiral diameter of CFHX can impact the convection heat transfer coefficient and resistance coefficient of the fluid in the tubes. To investigate the influence of spiral diameter on the design of the length of CFHX, the other 2 sets of spiral diameters are selected to compare with the 3rd group diameter. The diameters and transfer coefficient of three groups are shown in Table 5. The tube diameters of groups 7 and 8 are the same as that of group 3.

The calculation results of pressure drop and length are shown in Figures 6 and 7. The pressure drop of tubes with different spiral diameter has no significant difference. But the heat transfer coefficients have a more obvious change, which causes the change of lengths of CFHXs.

As we can see, the CFHX of group 7 has better heat transfer performance, which is shorter and lighter than the other two groups. However, when the spiral diameter is 30 mm or smaller, the two tubes of CFHX are more likely to be in contact, which will impact the actual heat transfer coefficient. Considering the manufacture difficulty and heat-exchanging performance, the spiral diameter can be selected as 40mm and the length of CFHX is set to 1 m for leaving a margin.

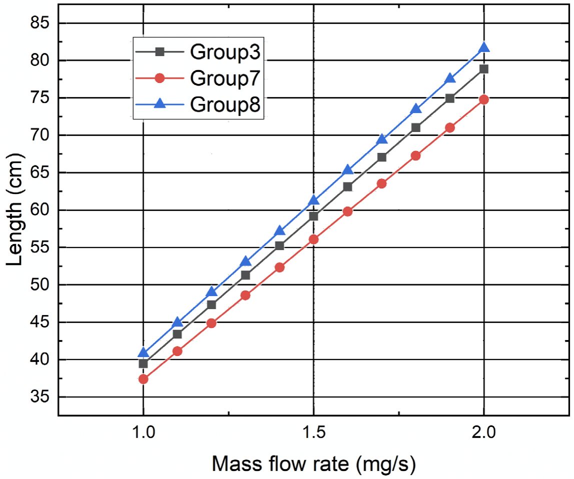

Figure 7. The calculation results of lengths of group 3, 7 and 8.

Table 6. Parameters of 3rd stage CFHX new design.

d_o' (mm)	d_i' (mm)	d_o'' (mm)	d_i'' (mm)	D (mm)	L (m)
4	3	2	1.6	40	1

CONCLUSION

The heat exchange efficiency of 3rd stage CFHX directly impact the cooling performance of the JT cycle. Through analyzing the heat transfer coefficient and the pressure drop, a new 3rd stage CFHX which can be used in hybrid JT cryocoolers is designed (Table 6). The 3rd stage CFHX becomes more compact and lighter after optimization. When the new 3rd stage CFHX is connected with a JT cooler, it is expected that the performance of the hybrid JT cryocooler will be improved.

ACKNOWLEDGMENT

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