Design Optimization of Tube-in-Tube Helical Heat Exchanger Used in JT Refrigerator

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ABSTRACT

TIPC of the Chinese Academy of Science has developed a compound 4.5K cryocooler using a three-stage pulse tube cooler to precool a Joule-Thomson (J-T) refrigerator. The recuperator is one of the key components which have a significant effect upon the overall system performance. A helically coiled tube-in-tube heat exchanger is used in the J-T refrigerator because of its compact structure and excellent heat transfer performance.

In this paper, the design optimization is carried out because the heat exchanger design is unfit for future space use. Experimental data is presented to confirm the validity of the calculation method. The focus is next placed on the optimization of the heat exchanger's structure, with the intent to manufacture a lighter spiral tube-in-tube heat exchanger with high heat transfer efficiency. The effects of the optimization parameter space on the heat transfer is analyzed and discussed in detail. The pressure drop of each configuration is calculated to determine the feasibility of the chosen parameters.

INTRODUCTION

In a previous study, a Joule-Thomson (JT) refrigerator precooled by a three-stage high-frequency pulse tube was been developed in our laboratory. The refrigerator can provide several milliwatts of cooling capacity at 4.5K. The recuperator, which is one of the key components of Joule-Thomson refrigerator, strongly influences the overall performance of the refrigeration system. The present heat exchangers fail to meet the needs of future application in space. Thus, a design optimization of the three heat exchangers for different temperature ranges in the JT cycle is needed to improve the overall performance. In order to reduce the mass as well as improve the efficiency of the refrigerator, the recuperator of JT cryocooler is studied in this paper.

A tube-in-tube helical heat exchanger is widely used in petroleum and chemistry industry, refrigeration systems, air-conditioning and power engineering due to its good heat transfer performance, compact structure, low cost and simple manufacture process. For this reason, it is selected as a recuperator in the JT cooler. Extensive research has been carried out on the flow and heat transfer characteristics of this type of heat exchanger by experimental and numerical means by other authors. Most of the studies are conducted by using water or steam as the working fluid. The working medium of this research is helium. Special attention is paid to theoretical analysis and practical applications in this paper.

Description of Heat Exchanger and Design Method

Three tube-in-tube helical heat exchangers are used in the above-mentioned cryocooler; Figure 1 shows the schematic of the heat exchanger. The inner and outer diameters of the inner tube are d_i and d_o, while the external tube has the inner and outer diameters d_{oi} and d_{oo}. The coil diameter is represented by 2R. High pressure flow goes through the inner pipe while low pressure flow after throttling flows in the annual channel.

Research about the influence of the structure parameters on heat transfer is carried out by varying parameters such as (i) d_i and d_o, (ii) d_{oi}, and (iii) R. In this study, a two-stage Gifford-McMahon (GM) refrigerator is used to pre-cool the JT circuit to shorten experimental time. This configuration will not influence the test of the heat exchangers.

The thermal properties of the fluid are determined by arithmetic mean temperature difference of inlet and outlet flow. The Nusselt number of the heat exchanger is calculated using correlations described below,

$$Nu_l = (1+1.77\frac{d_e}{R})(3.657+\frac{0.0668*Gz}{1+0.04*Gz^{0.67}}) \tag{1}$$

$$Nu_t = (1+1.77\frac{d_e}{R})(\frac{(f/2)(\mathrm{Re}-1000)\Pr}{1+12.7(f/2)^{0.5}(\Pr^{2/3}-1)}) \tag{2}$$

where $Gz = \mathrm{Re}*\Pr*de/L$, $\mathrm{Re} = \rho u d_e/\mu$, $\Pr = C_p\mu/\lambda$. 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.

Based on the Nusselt number, the heat transfer coefficient of each side can be calculated from equation (3)

$$h = Nu*\lambda / d_e \tag{3}$$

Then the overall heat transfer coefficient K is given by

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

The governing equation for heat transfer is expressed as follows,

$$Q = KA\Delta T_m \tag{5}$$

where ΔT_m is the logarithm mean temperature difference of the heat exchanger, A is the heat transfer area based on the outside surface area of the inner tube.

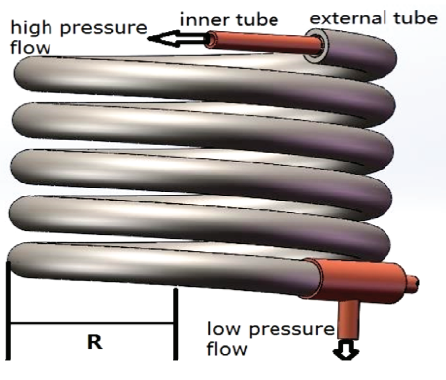

Figure 1. Schematic of tube-in-tube heat exchanger

The energy balance equations are given as follows,

$$Q = m_h C_{ph}(T_{in} - T_{out}) = m_l C_{pl}(T_{out} - T_{in}) \quad (6)$$

where m is the mass flow rate of helium, T_{in} and T_{out} are temperature of inlet and outlet flow, subscripts h and l represent high pressure flow and low pressure flow.

Combining equation (5) and equation (6), the heat transfer area A can be gained, and then the length of pipe needed is determined.

EXPERIMENTAL RESULTS AND DESIGN OPTIMIZATION

Comparison between Design Parameter and Experimental Data

The main purpose of the present study is to miniaturize the recuperator based on the successful design of a previous study. The temperature of the helium flow at the inlet and outlet of the recuperators is given in Table 2 and Table 3. The experimental results and design data match well except Hex3. The heat transfer capacity of the third heat exchanger is smaller than the design data because the cooling capacity of the second stage of pre-cooler is adequate to cool the helium flow down to about 14K. Actually, pipes shorter than the design length are sufficient to accomplish the heat recuperation of the JT cycle.

For this reason, the validity of the calculation method is verified. Using the same method, a set of much lighter and more compact helical heat exchangers are designed and analyzed. In this study, we focus on the influence of the structural parameters. Since the principle of the three heat exchangers is same, only the third recuperator's (Hex3) structural parameters are changed in this study. All the discussion and results of the third one are fit for the others.

Influence of Inner Tube

In this analysis, the helical heat exchangers with an inner diameter of the external pipe (d_{oi}) of 3.5mm and coil diameter of 50mm were considered. The material of the external pipes is stainless steel. Analyses are carried out by changing inner tube. The three kinds of inner tubes are shown in Table 1.

Table 1. Three kinds of inner tubes

	d_i(mm)	d_o(mm)	Material
condition1	0.4	0.5	stainless steel tube
condition2	0.5	1	copper tube
condition3	1	2	copper tube

Table 2. Design parameters of the three helical heat exchangers

	High pressure side		Low pressure side		Heat transfer capacity
Temperature	T_{in} (K)	T_{out}(K)	T_{in} (K)	T_{out}(K)	Q(W)
Hex1	300	103.7	97.6	293.9	9.0
Hex2	100	22.9	19.5	97.6	3.6
Hex3	20	7.9	4.5	19.54	0.72

Table 3. Experimental data of the three helical heat exchangers

	High pressure side		Low pressure side		Heat transfer capacity
Temperature	T_{in}(K)	T_{out}(K)	T_{in}(K)	T_{out}(K)	Q(W)
Hex1	300	98.5	92.3	300	9.22
Hex2	82.7	22.0	14.1	92.3	3.58
Hex3	14.3	5.1	4.5	14.1	0.54

In condition1, stainless steel is used to replace copper as the tube material, because the 0.1 mm copper wall is not able to sustain a pressure of nearly 2 MPa. The heat conduction of the wall is not the main thermal resistance. Although the thermal conductivity of stainless steel is small as compared to copper, the overall heat transfer coefficient remains is almost the same. In other words, the influence of the material of inner tube on heat transfer performance is negligible.

The heat transfer coefficients of the recuperator at different conditions are given in Figure 2. The heat transfer coefficients are influenced by d_i and d_o which determine the velocity of the fluid when mass flow rate is constant. Better heat transfer performance is achieved with a higher flow rate, and the higher flow rate can be achieved with a smaller cross-sectional area. The larger outer diameter of the inner tube (d_o) results in a smaller cross-sectional area of the annular channel while a larger inner diameter of inner tube (d_i) leads to enlargement of the cross-sectional area. The term, $h_{i,}$ drops dramatically with an increase in d_i and h_o increases as d_o increases. The overall heat transfer coefficient increases slightly because of the fact that h_o is the decisive factor of K. As a result, a much longer pipe is needed to accomplish the same amount of heat transmission, as shown in Figure 3. The flow in the inner tube of condition-3 is laminar, while it turns to turbulent flow in condition-2. This explains the fast drop in h_i drops when d_o increases from 0.5 mm to 1 mm.

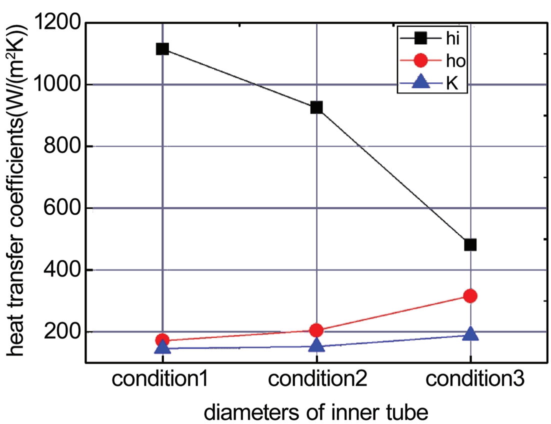

Figure 2. Effect of inner tube on heat transfer coefficient of Hex3

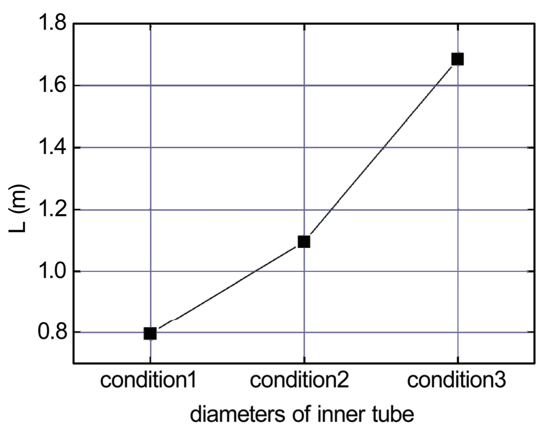

Figure 3. Effect of inner tube on the length of Hex3

Influence of External Tube

In this section, the effect of inner diameter of outer pipe (d_{oi}) on heat transfer is considered. The pipe diameters considered here were d_i=0.4mm, d_o=0.5mm. For all these cases, the coil diameter (R) is 50mm.

As shown in Table 4, h_i is much larger than h_o and does not change as d_{oi} decreases. The recuperator heat transfer is actually constraint by h_o. Therefore, in the following discussion, special attention is paid to the change in h_o. In Figure 4, both h_o and K increase with decreasing d_{oi} due to the increase of velocity in the annular channel, and their growth rates are almost identical. More important is that the length of the tube decreases nearly linearly with an increase in the inner diameter of outer tube (d_{oi}). As can be seen, only half of the tube length is needed when d_{oi} decreases from 4.5mm to 2.5mm without regard to other factors.

Influence of Coil

In this analysis, the influence diameter of the coil diameter (R) on heat transfer is considered. The pipe diameters considered here were: d_i=0.4mm, d_o=0.5mm, d_{oi}=1.5mm. The coil diameter varies from 10mm to 30mm.

In Figure 5, the convective heat transfer coefficient of both sides of the inner tube decrease marginally as the value of the coil diameter (R) increases. The root cause of this is that coil diameter affects the centrifugal force of the moving helium flow in the spiral pipe and this will in turn influence secondary flows along the pipe.

The centrifugal force is dominated by the curvature of the coil which is represented by a coil diameter R. As a result of curvature effect, the helium streams in the outer part of the pipe flow faster than helium streams in the inner part. The difference in the velocity brings about the secondary flow. The development of the secondary flow results in the enhancement of the heat transfer in the heat exchangers. Better heat transfer performance is achieved with smaller R and eventually the length of pipe needed is cut down. The relationship between L and R is given in Figure 5.

Table 4. The convective heat transfer coefficient of Hex3

d_{oi}(mm)	4.5	4	3.5	3	2.5
h_i(W/(m^2 • K))	925.85	925.85	925.85	925.85	925.85
h_o(W/(m^2 • K))	22.87	25.46	28.92	33.776	40.21
K(W/(m^2 • K))	22.61	25.13	28.48	33.18	40.22

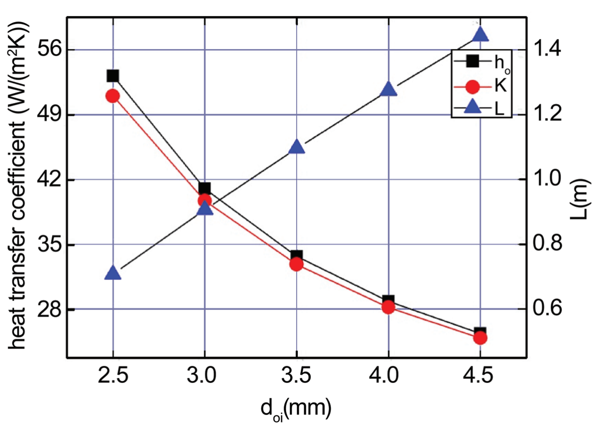

Figure 4. Effect of inner diameter of external tube

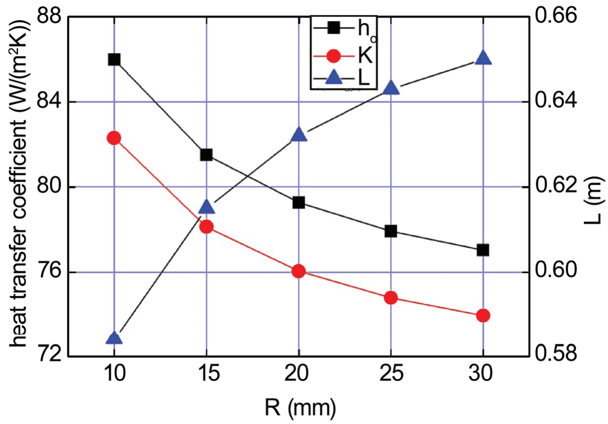

Figure 5. Heat transfer coefficient and length of pipe versus the coil diameter

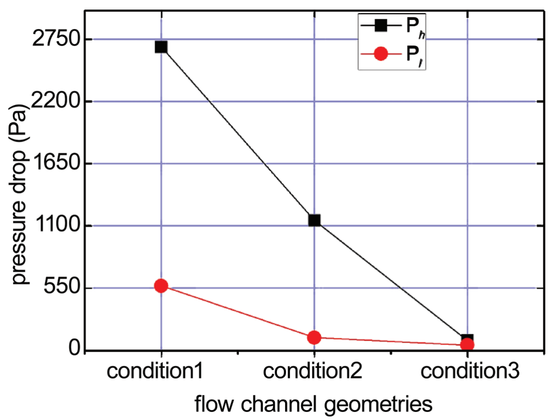

Figure 6. Pressure drops of different tube diameters

Pressure Drop of the Recuperator

The fact that the pressure drop of the heat exchanger increases as the cross-sectional area is lowered cannot be ignored. The pressure drop for the three conditions mentioned above is calculated and the inner diameter of external tube (d_{oi}) of each condition is fixed at 4mm, 2.5mm, and 1.5mm, respectively. As can be seen in Figure 6, the pressure drop rises sharply when smaller tubes are used, especially the pressure drop of high pressure side (P_h). The velocity of the flow increases with a decrease in the cross-sectional area while the pressure drop is proportional to the square of the speed. Although a dramatic change occurs when the tube diameters decrease, the pressure drops are still in the acceptable range.

It must be mentioned that the pressure drop is also a function of the properties of helium which changes significantly with temperature, so the heat exchangers of different stages have to be analyzed separately.

Optimization Design Results

Based on all the discussion above, it is obvious that the heat transfer of the recuperator is affected by geometries of inner and external tube. The enhancement of heat transfer in annular channel is an effective way to improve the overall performance of the heat exchanger. Improved performance of the heat transfer can be achieved by using small pipes with small coil diameter. However, the pressure drop increases dramatically as the cross-sectional area declines and the coil diameter cannot be too small in consideration of the space available. The tubes must be chosen on the premise of ensuring that the pressure drop is in the acceptable range. In addition, the pipe used must be able to sustain pressure up to nearly 2MPa.

Taking all the limitations mentioned above into consideration, the structure parameters of third heat exchanger (Hex3) are fixed at di=0.4mm, do= 0.5mm, doi=1.5mm, R=15mm and L=0.6m.

CONCLUSIONS

The influence of the geometries of the inner and external tube on heat transfer and flow characteristics of tube-in-tube helical heat exchangers is demonstrated and analyzed. The performance of the heat exchanger is improved by employing tubes with smaller diameter. The overall heat transfer coefficient increases with an increase of d_o and a decrease of d_{oi}, but the pressure drop increases sharply. In addition, as the value of the coil diameter (2R) declines, the heat transfer of both side of the inner tube is enhanced slightly. Shorter pipes are needed when heat transfer is enhanced. After design optimization, a new set of lighter and more compact recuperators are manufactured and ready to be tested by experiment.

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