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Experimental and Computational Studies of Heat Transfer for Wall-type and Fin-type Heat Exchanger

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Abstract. Wall-type heat exchangers (WTHX) and fin-type heat exchangers (FTHX) are attached to the first and second stage cold head of two G-M crycoolers respectively in the simulating experimental platform of the internal purifier (SEPEIP). WTHX and FTHX play a significant role in SEPEIP, WTHX is designed to remove heat from helium and freeze-out extremely few impurities, FTHX is for further cooling the helium. In this study, numerical simulation and experimental results for WTHX and FTHX are carried out. According to the comparison, the numerical results have a little discrepancy with the experimental results. However, the discrepancy is within the acceptable level. Finally, it is observed that the WTHX and FTHX are suitable to apply in the experimental system and are capable of guaranteeing a purifying function.

1. Introduction

Helium demand is expected to double within the next two decades because of its significance as a cryogenic fluid and an inert gas in various technological and scientific applications. However, its production capacity only increases by 3% per year, resulting in an inevitable rising price in the near furture [1]. Recently recovering this rare source helium is becoming a must for an economical operation of cryogenic and other helium consuming applications. To ensure proper operation of the liquefier and to avoid impurities freezing in the system and blocking the tubes, it is necessary to equip such a system with an internal purifier [2].

During past decades, several researchers have put much attention on the development of purification method and progress. In 1974, Collins firstly studied the purifying method, namely, using a condensing, freezing and separation technique to acquire pure helium [3]. In 1983, technicians of Linde Kryotechnic developed the first internal purifier which was installed in the TCF type helium liquefier, which focused on the purification circuit [4]. In 2015, Lozano et. al. compared the cleaning efficiency, the energy consumption, the initial investment and the cost of maintenance of two different methods applied for the purification of recovered helium with a low level of impurities [5]. However, none of these studies has been with respect to the performance of apparatuses in the internal purifier.

In order to investigate the performance of the internal helium purifier, it is essential to establish an experimental platform to examine the purification features for each apparatus in

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the internal helium purifier. For helium recovery in the helium liquefier, the internal helium purification needs to be cooled down to below 33 K at a required pressure as impurities in the processed gas are condensed or solidified at the surface of the heat exchangers [6]. Thus, we aim to build an experimental platform that can successfully provide sufficient refrigeration power to the experimental internal purifier. In this paper, attention is concentrated on the specific presentation of the WTHXs and FTHXs that are mounted separately on the two stages of G-M cryocoolers in the experimental platform. The performance characteristics of the WTHXs and FTHXs are studied theoretically and experimentally. According to the simulation and experimental results, the feasibilities of the WTHX and FTHX for the experimental setup are verified.

2. Design and description

Two G-M cryocoolers are applied in the pilot plant to cool the cooling source helium down to a proper temperature at which the mixtures of helium-nitrogen or helium-oxygen are cooled down to below the boiling point. Thus impurities, mainly nitrogen and oxygen, will be condensed or solidified on the cold surfaces, and then by analyzing the component of the mixture gas, the purification efficiency of the internal purifier is obtained. On the basis of that reason, WTHXs and FTHXs play a significant role in the pilot plant. The specific description and detailed dimensions are given in the Figure 1.



Figure 1. A cooling source process for the experimental platform. (a) Schematic of the flow process. (b) Photograph of the coldbox. (c) The internal structures and dimensions of WTHX and FTHX.

The material of WTHXs and FTHXs is made of copper due to copper has an excellent conductivity at the cryogenic temperature. As Figure 1 shows, they both have a cavity space with the advantage of depositing traces of condensed impurities in them.

A 3 g/s of compressed helium gas flow is split into two streams by a tee coupling, which is installed at the outlet of a compressor of GM cryocooler. One flow that is 2.66 g/s goes directly into the cold head and finally returns to the compressor. The other flow that is 0.34 g/s passes through a volume flowmeter and a needle valve and enters the coldbox. Then it is cooled down to 79 K with the precooling of boil-off liquid nitrogen. After that, it is taken into the heat exchangers mounted on the cold heads, where it is further cooled down to 34 K. At last, that helium gas is warmed to ambient temperature and returned to the compressor. The specifications of GM cryocooler are given in Table 1.

Table 1.	Specifications	of GM	cryocooler
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KDE210-KDC6000				
Cooling capacity (50 HZ)	Weight	Power consumption (50 HZ)		
First stage — Second stage	Coldhead — Compressor	Steady — Cooldown		
$40 \ {\rm W@45} \ {\rm K}-5 \ {\rm W@10} \ {\rm K}$	17.8 kg — 118 kg	$\mid 6.5 \; \mathrm{KW} - 7.2 \; \mathrm{KW}$		

3. Simulation and experimental results

In this investigation, the governing equations are numerically solved by commercial computer program code Ansys Fluent. The simulations are achieved in the steady state regime, using the viscous flow and standard k- ε model, which is appropriate for evaluation of helium flow and heat transfer inside the heat exchangers. We chose helium from the fluent database as the cell zone materials, the physical properties of which are kept default without being changed or modified. However, the physical properties are constant even if as the temperature varies in different conditions, which may be one of the reasons for the deviation of the simulation results from the experimental results.

The mesh of the models was realized using ANSYS-Meshing, with refinements near the walls. The boundary conditions of point T1 at the inlet sections are the boil-off temperature of liquid nitrogen and the mass flow of 0.34 g/s. For external walls, the heat flux is selected as the thermal condition according to the heat load of the cold heads of the cryocoolers.

The simulation results are presented in Figure 2. The quantitative data are revealed by contours of temperature. According to the simulation results, the temperatures of T1, T2, T3, T4, and T5 are approximately 80 K, 60 K, 58 K, 45 K, and 35 K, respectively. In addition, the locations of points T1, T2, T3, T4 and T5 are listed in Figure 1.(a). After that, we interpret the results of the experiments as in the following.

Experiments are performed on the helium refrigeration system when the purifier has not been applied. The separated helium flow is accurately controlled and measured by the volume flowmeter (shown in Figure 1), and the flow rate is approximately 0.34 g/s. Moreover, the flow rate can also be adjusted by the needle valve in the circuit. Rhodium-iron resistance thermometers are used to measure the temperature at T1, T2, T3, T4, and T5. Then the test results on two different days with respect to time are presented in Figure 3. One of them was tested on June 29th, 2016; the other was recorded on July 6th, 2017. The experimental results are both summarized as follows. The process of testing is approximately divided into three periods, namely, cooling period, helium flow adjustment period and warming period. Firstly, in the cooling time, we intended to keep the mass flow of the helium source at a certain value. The results, nonetheless, are challenging for us to fix the mass flow of the helium source, partly because of the density of the helium increasing as the temperature reduces. Therefore, the mass



Figure 2. Temperature contours of two type heat exchangers. (a) Temperature contours of the left WTHX in Figure 1(a). (b) Temperature contours of the right WTHX in Figure 1 (a). (c) Temperature contours of the right FTHX in Figure 1(a). (d) Temperature contours of the left FTHX in Figure 1(a).

flow rate decreases gradually over time, which is revealed in the green flow line in Figure 3 (a) & (b). Above all, if we want to keep the mass flow rate at a constant value, it is necessary for us to adjust the openness of the needle valve. Secondly, during the adjustment period, which means that the temperature of every individual point vill not change over time except increasing or decreasing the mass flow rate of the helium source through the needle valve, we hold the mass flow of the helium source at a constant value of about 0.34 g/s by controlling the needle valve. Then the slight variation of the temperature is observed. However, the variation only occured when the mass flow rate of the helium source is suddenly changed. On the whole, the temperature at each point is roughly steady when the mass flow of the helium source is constant as shown in Figure 3. According to the experimental results (Figure 3 (a) & (b)), when the helium mass flow is roughly 0.34 g/s, T1, T2, T3, T4, and T5 are around 80 K, 63 K, 56 K, 45 K, and 38 K, respectively. When the second time experiment was performed on July 6th, 2017, T1, T2, T3, T4 and T5 are approximately 80 K, 65 K, 55 K, 45 K and 36 K, respectively. Among them, T5 at the second time is lower than the first time, probably because of the installation of a radiation shield at the point 5. Finally, for the warming period, the GM cryocoolers are shot down, then the temperature at each point begins to increase.



Figure 3. Temperature and mass flow of helium with time during the experiment. The F denotes the mass flow of the helium. (a) Experimental data on June 29th, 2016. (b) Experimental data on July 6th, 2017.

4. Discussion

The two experimental results and the simulation results are simply graphed in Figure 4. According to the comparison, it shows that there is a little discrepancy between the experimental results and the simulation results. In other words, all the errors are almost within 5 percent except the errors of point 2 and point 5. More specifically, the error between the simulation and the experiment of T2 on July 6th, 2017 is about 8.3 percent, while the error of T5 on June 29th, 2016 is approximately 8.5 percent. To sum up, the discrepancy is within an acceptable level.

The errors between the simulation and the experiment may come from several aspects, containing the uncertainties in the model and the measurements. The influence of the radiation heat from surroundings could also lead to the discrepancy. However, according to the above comparison, the deviations between the simulation results and the experimental results are

acceptable. Therefore, we confirm that the simulation model and results are suitable for us to investigate the performance characteristics of the WTHXs and FTHXs. It can provide some guidance information for improvement of the WTHXs and FTHXs. We have found that the helium temperature in the inner layer temperature zone of the WTHX is much lower than outer layer temperature zone. According the color distribution at the legend (shown in Figure 2), the differences between the highest temperature and the lowest for the WTHXs are separately 34 K and 30 K. The temperature difference between the inner layer and the outer layer partly attributs to the stagnation of the inner layer zone. In other words, the flow irregularity in the WTHX causes the stagnation phenomenon and then leads to the heat transfer deterioration.

Similarly, the same phenomenon has occured in the FTHX. It is shown in Figure 2(c) & (d) that heat transfer in the dark blue zone of the FTHX in not as good as at the right place. There is few steamline distributed on the left side of the FTHX. That means the flow to the left of the FTHX is almost stagnant, which causes an inefficiency of nearly half the heat transfer area of the FTHX. The results may be due to the outlet was located at the center of the FTHX. Therefore, we believe if the outlet was located at the left of the FTHX, then the heat transfer would be more uniform.

It should be noted that this simulation does not consider the variation of the physical properties of helium as the temperature changes. If we use the real gas model in the simulation, namely, the physical properties data of helium are all from NIST database, the simulation will encounter an unknown error. Consequently, we keep the physical properties of helium constant during simulation. It is known to all that the accuracy of physical properties play a significant role in the calculation and simulation of the heat exchanger. However, due to the constant physical properties, the accuracy of the simulation is not as excellent as possible. Regardless of its limitation, this simulation does provide the temperature distribution of the WTHXs and FTHXs. In addition, it points out the imperfection of the WTHXs and FTHXs and the locations of the flow irregularity.

5. Conclusion



Figure 4. Results of experiment and simulation

A helium refrigeration system for the experimental investigation of an internal purifier has

been built and tested. A simulation of the WTHXs and FTHXs has also been carried out. Results show that the simulation and experiment have a good consistency. The comparion results also reveal that the errors between them are no more than 10 percent, at some points the errors are less than 5 percent. The experiment has been tested twice. The temperatures of key point T5 are 38 K and 36 K respectively, which are separately 3 K and 1 K bigger than the simulation result 35 K. Nonetheless, it is capable of providing sufficient cooling power to make the contaminants condense on the surface of the purifier. The deficiency of the WTHXs and FTHXs has also been pointed out and the further improvement is required. Notwithstanding the limitations of the WTHXs and FTHXs, it is concluded that they are suitable to be applied in the refrigeration system and are capable of guaranteeing a purifying function.

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