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Xiaoling Yu
Xi'an Jiaotong University

Jian Li
Xi'an Jiaotong University

Quanke Feng
Xi'an Jiaotong University

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Xiao Ling YU*, Jian LI, Quan Ke FENG

School of Energy and Power Engineering, Xi'an Jiaotong University,
Xi'an, 710049, China (86-29-8266484, xlingyu@mail.xjtu.edu.cn)

ABSTRACT

Flow and heat transfer performance of the cryogenic heat exchanger is always concerned. This paper studied flow and heat transfer performance of a special cryogenic heat exchanger, which is actually a neutron moderator cell (NMC) operating in a cold neutron source (CNS) of a reactor. A 3-D numerical modeling of heat transfer in NMC was built, and the modeling was verified by a simulating experiment. In the simulating experiment the liquid hydrogen boiling in NMC was replaced by Freon-R113, the cold helium of 17.6 K flowing in the sub-cooling passage was replaced by the cold nitrogen, and the heat generated by nuclear heating was simulated by an electrical heating. The numerical modeling was used to estimate heat transfer and pressure drop of NMC in CNS operating condition.

1. INTRODUCTION

Heat exchangers are one of the most critical components of any cryogenic system. Design of these cryogenic heat exchangers demands a synthetical consideration of heat transfer ability and pressure drop. This is especially significant for some special cryogenic systems, in which pressure drop of the cryogenic heat exchanger must be strictly limited. The cold neutron source (CNS) is such a cryogenic system, which is a key component of China's Advanced Research Reactor (CARR) with nuclear power being 60MW (Ye, 1998). As shown in Figure 1, CNS is a two-phase hydrogen thermal siphon circulatory system (Shen, 2004, Bi, 2004). A neutron moderator cell (NMC), which is actually a cryogenic heat exchanger, is the heart of CNS. Liquid hydrogen is filled inner NMC and is used to moderate thermal neutrons releasing from the reactor. The cold neutron bunch with the wavelength of 4Å will be got after being moderated. The liquid hydrogen vaporizes after absorbing nuclear heat of NMC, and then flows up to a condenser, where it is condensed by the cold helium. After that, the liquid hydrogen flows back to NMC by gravity.

As shown in Figure 2, in order to improve the neutron moderating efficiency, the liquid hydrogen layer in NMC should be a crescent shape when the CNS operates (Yu, 2005). To form this shape, NMC is designed to be of a double-layer wall structure, in which an inner cup is in the core, a hydrogen vessel is in the middle, and a helium vessel is in outside. To cool NMC, a helium sub-cooling passage is set between the helium vessel and the hydrogen vessel. The cold helium coming from the refrigeration system flows into the sub-cooling passage first, and then flows into the condenser to cool the hydrogen vapor. At last, it returned to the refrigeration system. Most of nuclear heat generated from NMC was taken away by the cold helium. The helium sub-cooling passage was required to take away heat of 1200 W and pressure drop must be kept below 0.02 MPa when the CNS operates.

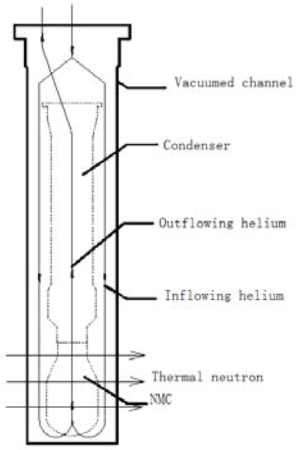

Figure 1 : Scheme of CNS

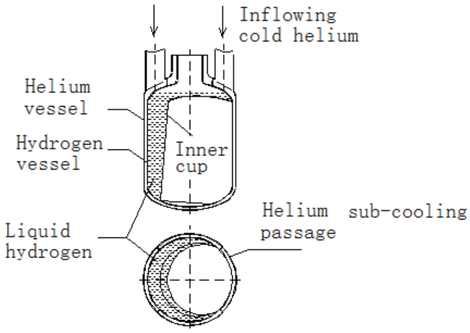

Figure 2: Structure of NMC

The heat transfer and flow performance of the helium sub-cooling passage must be calculated and experimental verified. Relationships between the heat transfer quantity and the passage geometry, helium velocity, and the pressure drop should be defined. If relevant parameters were chosen improperly, the cooling efficiency of the helium sub-cooling passage will be very low and the pressure drop will be very big, thus leading to additional load to the helium refrigerating system. Therefore, it is important to estimate heat transfer quantity and pressure drop of the helium sub-cooling passage.

The helium temperature is below 17.6K when the CNS operates. Even though in the operating condition the heat transfer quantity and pressure drop of the helium sub-cooling passage can be calculated by a numerical model, the simulation results need to be verified by experiments because the cryogenic helium flowing in and out of the helium sub-cooling passage was in a small temperature difference. However, the operating temperature is too low to reach in the experimental condition. Therefore, in this paper a simulating experiment for the flow in the helium sub-cooling passage was proposed. The numerical model was verified by the simulating experiment first, and then the numerical model was used to simulate the flow in the helium sub-cooling passage to judge whether it can satisfy the cooling requirements.

2. EXPERIMENTS

In the simulating experiment, the liquid hydrogen boiling in NMC was replaced by Freon-R113, and the helium of 17.6K flowing in the sub-cooling passage was replaced by normal atmospheric temperature nitrogen and normal atmospheric temperature helium. The scheme of the simulating experiment was shown in Figure 3. It included three major parts: NMC, a blower and a refrigeration system. The cold nitrogen or helium cooled by the refrigeration system flows into the sub-cooling passage. It is heated in the passage and then flows to the blower, which drives the gas circulating in the experiment system.

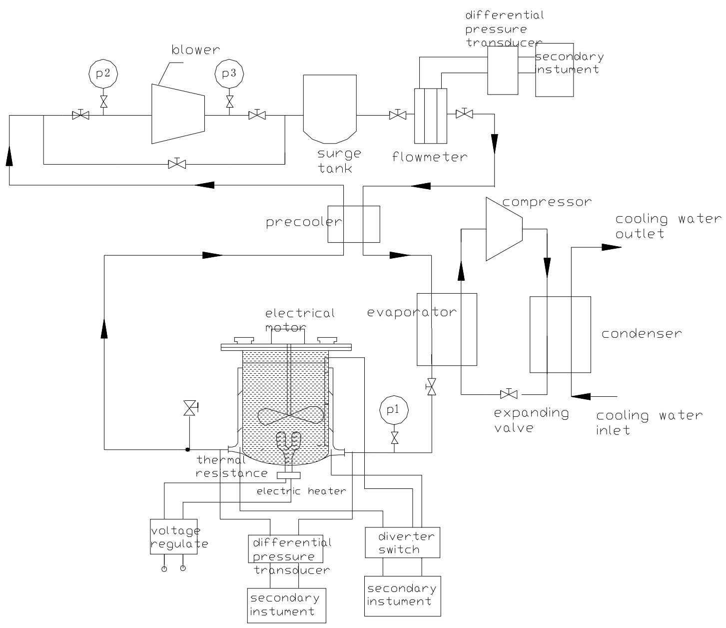

Figure 3: Scheme of the simulating experiment

NMC in the simulating experiment is made of aluminum-magnesium alloy. Its structure and size are shown as Figure 4. The nitrogen or helium flew into the sub-cooling passage from the entrance, and then went out from the exit. Liquid Freon-R113 filled into NMC was heated to boiling by a heating rod immersed in it. The heating power can be regulated by changing the voltage. An agitator was used to make NMC be heated uniformly.

The gas velocity flowing in the sub-cooling passage was measured by a nozzle flow meter of a 0.2 grade accuracy in the pipeline. Three groups of platinum resistance temperature sensors of a 0.2 grade accuracy were used to measure temperatures of the basis of NMC, temperature of Freon, and temperature of the gas flowing in and out of the sub-cooling passage. The pressure drop through the sub-cooling passage was measured by a differential gauge with a high degree of accuracy. A digital voltmeter with a 0.05 grade accuracy measures the heating voltage.

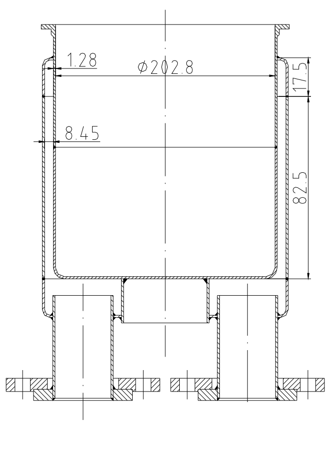

Figure 4 : NMC in the simulating experiment

3. RESULTS AND DISCUSSION

3.1 Results of the Simulating Experiment

If heat leakage was ignored, all of the heat generated by the heating rod in NMC was taken away by the gas passing through the sub-cooling passage. Thus, Equation (1) was got:

$$C_p \times Q_m \times (T_{out} - T_{in}) = h \times A \times (T_{wall} - T_{gas}) \tag{1}$$

where C_p, Q_m , T_{in} and T_{out} is the specific heat, mass flow rate, inlet temperature and outlet temperature of the gas respectively, T_{gas} is the mean temperature of the inlet temperature and outlet temperature, T_{wall} is the mean temperature of the inner wall of the sub-cooling passage, A is the inner wall area of the sub-cooling passage, and *h* is heat transfer coefficient between the gas and the inner wall of the sub-cooling passage. According to experiment data *h* can be calculated from this equation.

Figure 5 and Figure 6 show respectively the relationships of the heat transfer coefficient and the pressure drop versus the flowing velocity when nitrogen gas flew in the sub-cooling passage in different heating power. It can be seen that both the heat transfer coefficient and the pressure drop increases with the flowing velocity under various heating power. Under the experimental conditions, the range of heat transfer coefficient is from 200 W/ (m^2·K) to 270W/ (m^2·K), and the range of pressure drop is from 3500 Pa to 5500 Pa. The relationships of the heat transfer coefficient and pressure drop versus the heating power is not obvious.

Figure 7 and Figure 8 shows respectively the relationships of the heat transfer coefficient and the pressure drop versus flowing velocity when helium flows in the sub-cooling passage in different heating power. Similar to nitrogen, the heat transfer coefficient and the pressure drop of helium also increases with the flowing velocity under various heating powers. Especially, the pressure drop is independent of the heating power. Under the experimental condition, the range of heat transfer coefficient is from 240 W/ (m^2·K) to 340W/ (m^2·K), and the range of pressure drop is from 600 Pa to 2000 Pa, much smaller than that of nitrogen.

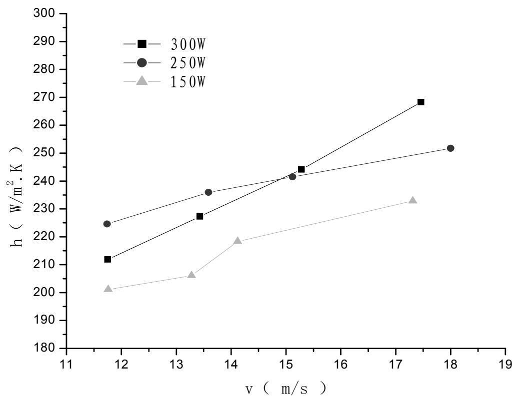

Figure 5 Heat transfer coefficients VS. flowing velocity for nitrogen

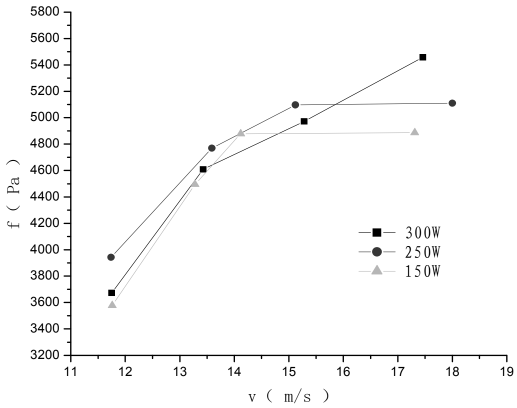

Figure 6 Pressure drop VS. Flowing velocity for Nitrogen

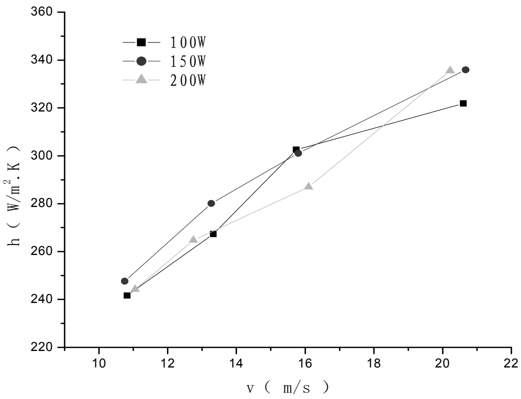

Figure 7 : Heat transfer coefficients VS. flowing velocity for helium

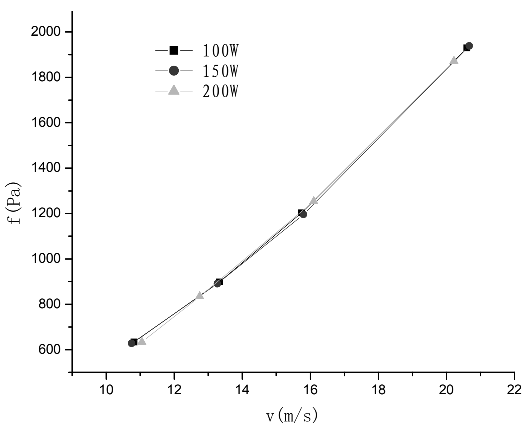

Figure 8 : Pressure drop VS. flowing velocity for helium

3.2 Extrapolation

The numerical model of heat transfer of the gas flowing in the sub-cooling passage was solved by a commercial software. The experiment and simulation results of heat transfer coefficient and pressure drop of helium in the simulating experiment condition were respectively shown in Figure 9 and Figure 10.

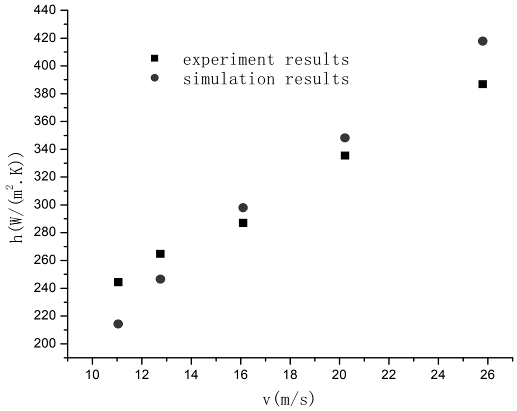

Figure 9 : Heat transfer coefficient of helium in the simulating experiment condition

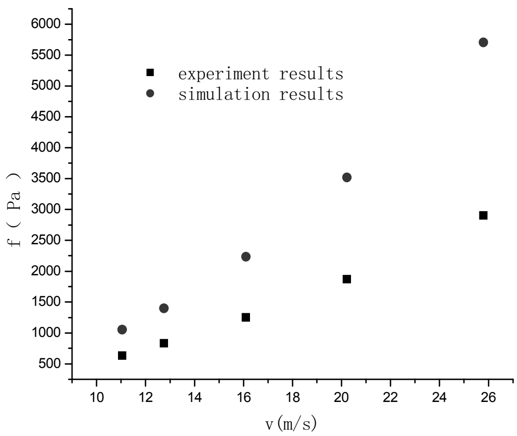

Figure 10 Pressure drop of helium in the simulating experiment condition

From Figure 9 and Figure 10, it can be seen that the difference of heat transfer coefficient between simulation and experiment result is about 10%, but the difference of pressure drop is much bigger, even reach 50%. This is because some assumptions were made in the numerical model and measurement errors mainly exist in the three parameters: gas temperature in the entrance and exit of the sub-cooling passage and mass flow rate. Especially, it is very difficult to measure the gas temperature in the entrance and exit of the sub-cooling passage accurately, because the gas temperature difference of the entrance and exit is very small, even smaller than 1 ℃, but the measurement error of platinum resistance temperature sensor reaches 0.2 ℃. Anyway, the heat transfer coefficient can be calculated accurately by the numerical model, and it can be used to simulate the heat transfer and flow in the sub-cooling passage in the working condition.

The key input parameters and simulation results of the helium flowing in the sub-cooling passage in CNS working condition were listed in Table 1. The simulation results of heat transfer of helium is 2118W, 76.5% higher than the heat transfer requirement of 1200 W. Even considering heat transfer simulation error of 10%, the sub-cooling passage can satisfy the heat transfer requirement very well. For the pressure drop, the simulation result is 3833 Pa, much lower than the pressure drop limit of 0.2 MPa. Therefore, the sub-cooling passage can meet the cooling requirements.

Table 1 : Input parameters and simulation results in CNS operating condition

Input parameters		**Simulation results**	
Helium temperature of entrance（K）	17.57	Pressure drop（Pa）	3833
Helium pressure of entrance（MPa）	0.17	Heat transfer（W）	2118
Mass flow rate（m^3/h）	5700		

5. CONCLUSIONS

(1) Under the simulating experiment condition, the range of heat transfer coefficients for helium flowing in the sub-cooling passage is from 240 W/ (m^2·K) to 340W/ (m^2·K), the range of pressure drop is from 600 Pa to 2000 Pa.

(2) Simulation results of heat transfer coefficient can be calculated more accurately than pressure drop by the numerical model, which can be used to estimate the heat transfer and flow in the sub-cooling passage in CNS working condition.

(3) The simulation results show that the sub-cooling passage can meet both the heat transfer and pressure drop requirements.

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