Experimental Investigation on High Performance Cryogenic Heat Transfer Based upon Natural Circulation Cooling

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A novel cryogenic heat transfer unit is proposed, which combines NCC and CHP together. The unit takes advantages of NCC and CHP, and eliminates the disadvantage of NCC for its low thermodynamic efficiency. Furthermore, it has also the merit of a self-feedback process, which makes the object come back to the objective temperature quickly. In order to verify the principle, a compound system of NCC and CHP was set up and tested. And experimental results are compared with that simply cooled by a NCC or a CHP, which show the promising potential for further applications. An application to the Power MEMS cooling is also presented.

INTRODUCTION

With the rapid developments of cryogenic engineering, it is of the most importance to build an efficient "bridge" between the cryogenic source and applications. It is always a problem to transfer heat within some distance efficiently and quickly, especially for some special occasions such as space and superconducting applications. Up to now, there are several means to solve the problem, such as thermal conduction by pure metal (e.g. copper), cryogenic heat pipe (CHP), natural circulation cooling (NCC) and so on. Recently, we have studied the principles of natural circulation cooling [1-2]. Theoretical and experimental results show that the NCC can cool down an object fleetly. Essentially, the direct driving force of NCC comes from the temperature difference between the object to be cooled and the cold source, which generates the pressure difference through the cryogenic fluid evaporation. Obviously, the driving force of NCC will gradually weaken and vanish at last during the cool-down process. So the NCC only serves for fast cooling with low efficiency instead of continuous operation. Moreover, there are some problems of temperature instability and mechanical vibration due to the exquisite evaporation of cryogenic fluid. The cryogenic heat pipe (CHP) is an acknowledged alternative to realize continuous cooling with high efficiency, because of its small axial temperature difference[3-4]. However, the cool-down process of the CHP is slow and it will not work if over-loaded.

Therefore, we proposed to combine the NCC and the CHP together and make them into a cryogenic heat transfer unit[5], which synthesizes the advantages of the NCC and the CHP. We make use of NCC to shorten the cool-down process and also simultaneously cool down the CHP. Once the NCC nearly stops, the CHP starts to work. It serves for continuous operation with high efficiency and keeps the temperature stable. Especially, once the temperature of the object sharply increases (e.g. quench), the NCC may automatically start again and cool down the object to the objective temperature fleetly. So the new cryogenic heat transfer unit has a self-feedback function, which improves the security of the whole systems. In order to verify the principle, an experimental setup was designed and tested. The preliminary results accords with those we expected. The heat transfer unit has been successfully applied to Power

MEMS as a cold source.

EXPERIMENTAL SETUP

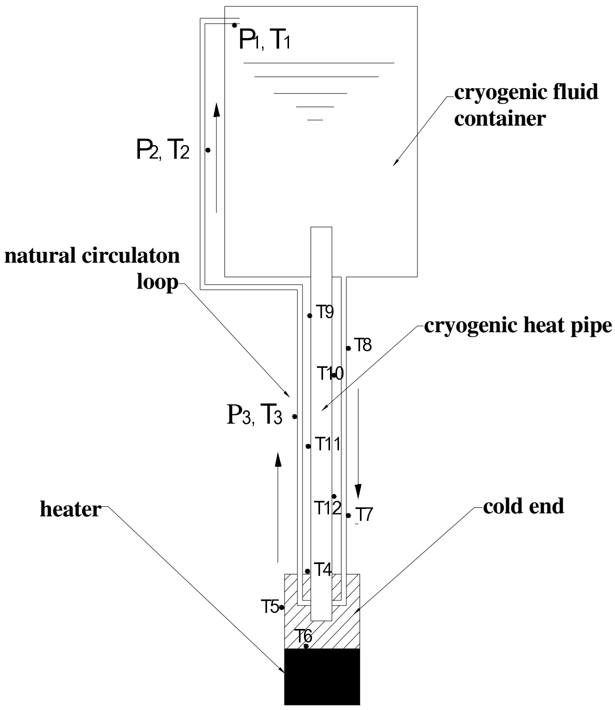

Figure 1 Schematic of the experiment set-up and photograph

The NCC+CHP unit consists of cold source, cryogenic heat pipe, natural circulation loop and heater. For convenience, liquid nitrogen is used for the cold source. The liquid nitrogen is stored in a stainless steel (1Cr18Ni9Ti) container with volume 5×10^{-4} m^3. The insulation material surrounded the container is polyurethane foam whose thermal conductivity is around 0.0026 to 0.028 W/m•K. The thickness of insulation material is 3×10^{-2} m. Two copper thermosyphons with a length of 0.2 m and inner diameter of 6×10^{-3} m are used. The condensation section of the thermosyphon is immersed in the bottom of liquid nitrogen container, while the evaporation section shares the same copper body with the cold end as shown in Figure 1. The working fluid in the thermosyphon is nitrogen with high purity. The natural circulation loop (inner diameter of 4×10^{-3} m, length of 0.8 m) is made of stainless steel to decrease the axial thermal conduction. The inlet of the natural circulation loop is located at the bottom of the container, while the outlet is above the liquid nitrogen level. Themosyphons, the natural circulation loop and the cold end are also insulated. A heater with maximum input power of 50 W is installed at the bottom of the cold end. The input power to heaters is measured by a digital power-meter.

Twelve calibrated copper-constantan thermocouples are arranged along the natural circulation loop (T1, T2, T3, T7, T8), the thermosyphon (T9, T10, T11, T12), and the cold end (T4, T5, T6), as show in Figure 1. A Keithley 2700 digital multi-meter is used to acquire the temperature signal. Three piezoelectic pressure sensors (Siemens, KPY-45R) are installed along the natural circulation loop to observe the fluid flow (see Figure.1). Pressure and temperature data are processed by a computer with the software of Labview 6.1 and a DAQ card (NI 6023E).

EXPERIMENTAL RESULTS AND DISCUSSION

Figures 2 shows the cool-down process of the cold end with Q_0＝0 W. Q_0 is the initial heating power applied to the cold end. It takes about 22, 30 and 47 minutes to reach stable states at 81, 83 and 87 K for the NCC+CHP, the NCC and the CHP, respectively. In respect of the cool-down time and the final objective temperature, the NCC＋CHP is the best. For NCC+CHP, the NCC cools down not only the cold end but also the CHP, which enhances the heat transfer performance of CHP. Simultaneously, the CHP directly transfers heat from the cold end to the cold source, which improves the flow of cryogenic liquid in natural circulation loop. Because the CHP is filled with gas at the beginning and needs more time to pre-cool itself as well as the cold end, the cool-down time is much longer and the final objective temperature is higher than those of NCC+CHP.

Figures 3 shows the cool-down process of the cold end with Q_0＝10 W. The tendency of cool-down processes is similar with those in Figure 2. The effect of initial heating power on the heat transfer performance of the NCC+CHP and the NCC is not significant. The final objective temperatures at the cold end are almost the same for the NCC+CHP and the NCC. The cool-down time is a little longer than those in Figure 1 only because of the initial heating power. The effect of initial heating power Q_0 on the heat transfer performance of CHP is remarkable. Because there is a reservoir connected with thermosyphons (Figure 1), the CHP needs more time to cool down the gas besides the cold end. It is estimated that the cool-down time will be shortened and the objective temperature will be lower if we cut the connection between the reservoir and thermosyphons.

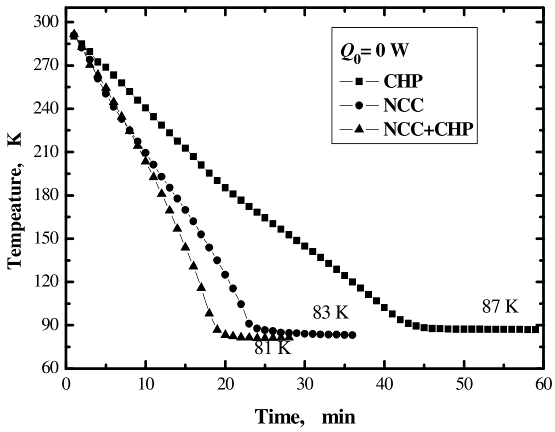

Figure 2 Cool-down process of cold end with Q_0＝0 W

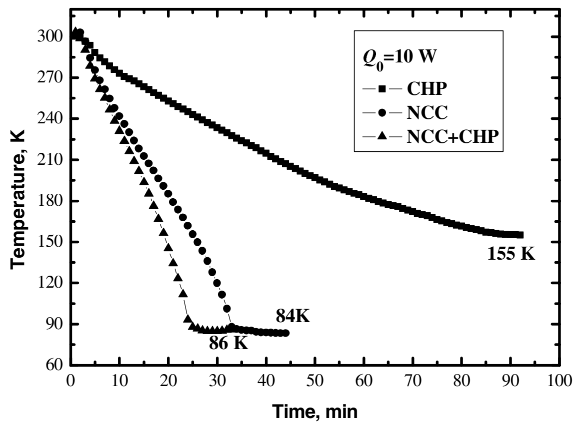

Figure 3 Cool-down process of cold end with Q_0＝10 W

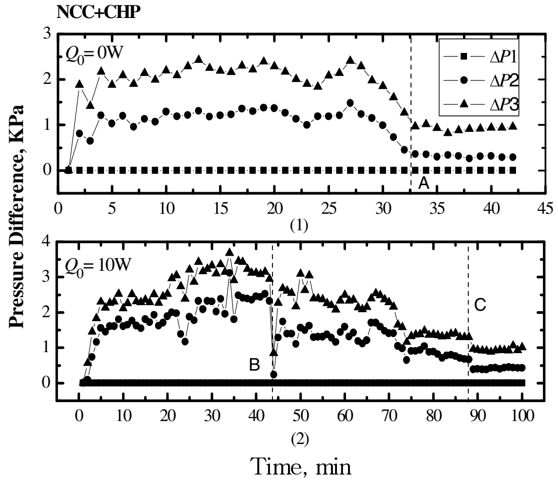

Figure 4 Pressure difference variations of NCC+CHP during cool-down process

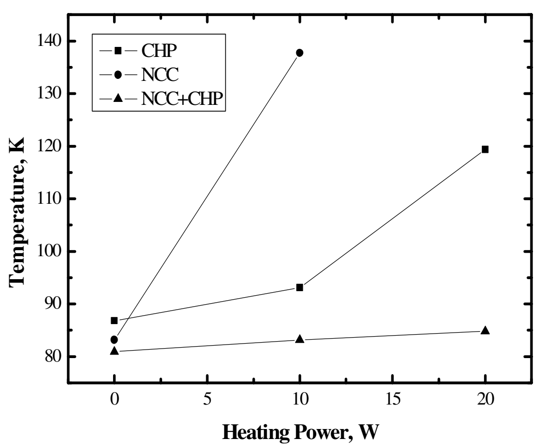

Figure 5 Cooling performance of CHP, NCC and NCC+CHP

Figure 4 shows the pressure difference variation along the NCC during the cool-down process of NCC+CHP. The benchmark of the pressure difference is based on P1 as shown in Figure 1. The pressure difference gradually attenuates and reaches the minimum, such as the point A, B and C (Figure 4) which means the NCC can hardly circulate. In Figure 4(2), the NCC may circulate again from point B when some nitrogen gas at room temperature is charged into the circulation pipe. And the circulation still terminates finally.

Figure 5 shows the comparison of the cooling performance among CHP, NCC and NCC+CHP. The heating power was applied to the cold end after the cold end cooled down without heat load. With the same heat load, the NCC+CHP reaches the lowest temperature, where the NCC is the highest (except $Q_0 = 0$ W). The driving force of NCC greatly reduces after the cool-down process. Once heated, the temperature of cold end increases rapidly, which means that the NCC is not good for steady operation. On the contrary, the CHP works well to transfer heat from the cold end to the cold source and keeps the temperature of cold end lower after the cool-down process for the NCC+CHP.

Furthermore, the new cryogenic heat transfer unit was successfully applied to the research of power MEMS, which makes use of Seebeck effect to generate electricity by semiconductor chips. The cryogenic heat transfer unit serves as a cold source and ensures the temperature difference between the two sides of the semiconductor chip. With a temperature difference of 400 K, 4.9 V is produced by two pieces of semiconductors with the size of 25×25mm.

CONCLUSIONS

1. A new type of cryogenic heat transfer unit is proposed, which makes full use of the advantages of natural circulation cooling and cryogenic heat pipe. It can not only cool down an object fleetly but also keep the object temperature stable with high efficiency. The NCC may automatically circulate again when the object temperature increases sharply.
2. The NCC plays important role during the cool-down process, while the CHP is primary during the steady operation to maintain the cold end at a lower temperature.

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