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Development of 10 kW turbo-Brayton refrigerator for HTS power applications

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Abstract. HTS power applications have been developed actively and the refrigerator requires larger cooling power. To satisfy this request we have developed 10 kW class turbo-Brayton refrigerator which has neon gas as working fluid. The refrigerator consists of a pair of turbine-compressors which have turbine, compressor and PM motor on the same shaft. The turbine-compressor has magnetic bearings with no rubbing parts, which results in a long maintenance interval. Neon gas is compressed from 0.5 MPa at inlet to 1.0 MPa at outlet by two compressors and expands through two turbines in parallel. Design cooling capacity is 10 kW at a cooling temperature of 65 K. We made a commercial model refrigerator and tested cool down characteristics, load cycles and cooling capacity using a liquid nitrogen circulation system. Specification and configuration of the refrigerator and test results are shown in this paper.

1. Introduction

High temperature superconductivity (HTS) applications such as power cable, fault current limiter and motor have been developed actively [1-4]. HTS applications need to be kept at low temperature 70 K. They are generally cooled by sub-cooled liquid nitrogen (LN) because LN is economical and has high electrical insulation advantage. Cooling capacity from 2 kW to 10 kW at 70 K is required for the cooling system, and also long maintenance interval and reliability are required. Therefore we developed 2 kW turbo-Brayton refrigerator using neon gas as working fluid in 2012 [5]. However more long HTS cables are used for demonstration in real grid recently. In SupernetNL project (Netherlands), the HTS cable is 3.4 km long and requires cooling capacity about 17 kW [6]. We have developed 10 kW class refrigerator to meet these needs for long HTS cables.

The process specifications in 10 kW refrigerator were determined by using improved process simulation for 2 kW refrigerator [7]. The 10 kW refrigerator consists of dual turbine-compressors which have compressor impeller, turbine impeller and permanent magnet motor on a single shaft. Cooling gas is compressed from 0.5 MPa to 1.0 MPa in series, and expanded by radial turbines in parallel. The turbine-compressor has magnetic bearings without rubbing parts. Magnetic bearing has basically longer maintenance interval than usual ball bearing.

The 10 kW refrigerator was launched in 2016. The commercial type 10 kW refrigerator was tested to investigate characteristics of cool down, heat load cycle and cooling power using liquid nitrogen circulation equipment. Specification, configuration and test results of the 10 kW refrigerator are shown in this paper.



2. Specification and configuration

We designed a refrigerator to satisfy 10 kW or more cooling power and long maintenance interval for long HTS cables. It also is designed to be lower cost. Therefore the refrigerator employed two turbine-compressors with magnetic bearings which are similar in configuration. The cooling power and cooling temperature are controlled automatically with the rotational speed of turbine-compressors [8].

Figure 1 shows 10 kW refrigerator schematic flow diagram. Process gas is compressed from 0.5 MPa to 1.0 MPa in series and cooled through heat exchanger and expanded in parallel by radial turbines. Specifications are determined by process simulation and shown in Table 1. Cooling capacity is 10.2 kW at 65 K of liquid nitrogen outlet temperature. Figure 2 shows assemblies of turbine-compressor. Compressor impeller and turbine impeller are attached on the each end of the shaft. Motor speed is controlled up to rated rotational speed 700 rps with variable frequency drive. Cooling power is controlled by turbine-compressor rotational speed. 10 kW refrigerator overview is shown in Figure 3.

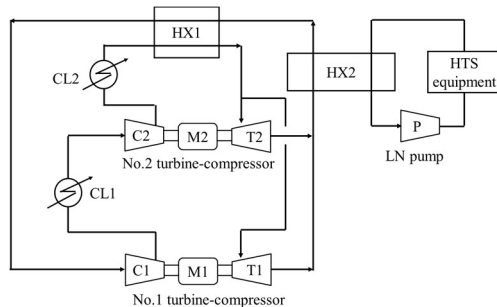


Figure 1 Schematic flow diagram

Table 1 Design specifications

Cooling temperature (LN outlet temperature)	65K
Cooling capacity	10.2 kW
Process pressure	0.5 MPa / 1.0 MPa
Gas flow rate	0.96 kg/s
Input power	162 kW
COP	0.063

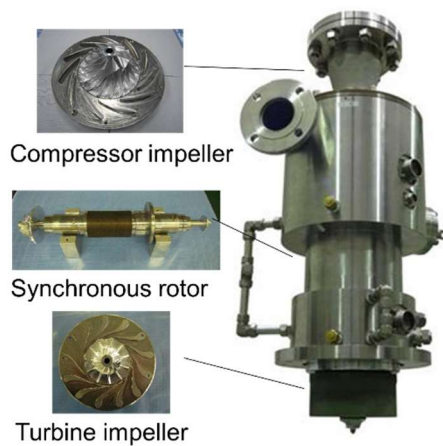


Figure 2 Turbine-compressor



Figure 3 10 kW refrigerator overview

3. Performance test procedure

Refrigerator performance tests were carried out to investigate characteristics of cool down, heat load cycle and cooling power with liquid nitrogen circulation equipment in Figure 4. The liquid nitrogen circulation equipment consists of pressure builder, circulation pump and electric heater. Liquid nitrogen pressure is kept constant by pressure builder in lower than 1.0 MPa. Heater power output is 15 kW because it needs to be larger than refrigerator maximum cooling power. Refrigerator and liquid nitrogen circulation equipment are connected with transfer tubes which are flexible and have vacuum insulation layer to decrease heat loss. Performance test flow diagram is shown in Figure 5.

3.1. Cool down test

Turbine inlet temperature T_{in} is preset at 78 K. Cool down time is defined as the time between room temperature to 78 K at T_{in} . Cool down time is measured without liquid nitrogen circulation to confirm cool down curve characteristics by stand-alone refrigerator.

3.2. Load cycle test

One load cycle is done added heat load of 11.2 kW during 8 hours using heat load heater and no heat load during 16 hours. Load cycle test is carried out 20 cycles to show stable operation of refrigerator. A part of heating, input power of the heater is adjusted manually to keep liquid nitrogen outlet temperature T_1 and maximum motor speed of the turbine-compressor.

3.3. Cooling capacity and COP test

The condition of cooling temperature for cooling capacity test and COP test is 66, 69, 72 and 77 K. The refrigerator is operated on maximum motor speed of the turbine-compressor and heater power is adjusted manually to keep cooling temperature constantly. Cooling capacity Q and COP is calculated as below;

$$Q = \dot{m} \times (H_2(P_2, T_2) - H_1(P_1, T_1))$$

$$COP = Q / W_{total}$$

Where \dot{m} is liquid nitrogen mass flow rate, H is enthalpy, P is pressure, T is temperature and W_{total} is all of input electrical power for refrigerator including control electrical device and any electrical losses.

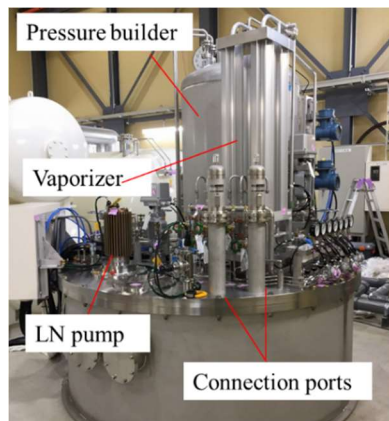


Figure 4 Liquid nitrogen circulation equipment

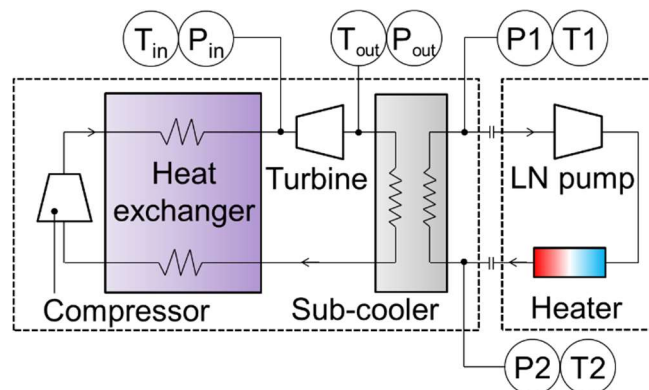


Figure 5 Flow diagram of performance test

4. Performance test result

Figure 6 shows the temperature at the turbine inlet and outlet as the test result of cool down test. At the started operation of the refrigerator is 0 minute and system temperature is almost same of room temperature. Turbine inlet temperature achieved to 78 K less than 3 hours. After cooling temperature archived to 78 K, turbine-compressor rotational speed is adjusted by PID control to keep cooling temperature constantly. The cooling power is 0 kW after 3 hours.

Figure 7 shows one of the heat load cycle with input heater power of 11.2 kW to operate of the refrigerator on maximum cooling power for 8 hours and no heat load for 16 hours. Liquid nitrogen inlet and outlet temperature increase rapidly with turning on the heater power. The turbine-compressor rotational speed increases to make cooling power and to reduce temperature difference between set cooling temperature and liquid nitrogen outlet temperature. The under-shoot and overshoot from liquid

nitrogen outlet setting temperature is within 3 K and the temperature is got stable situation of 69 K within two hours. Figure 8 shows liquid nitrogen inlet and outlet temperature of 20 load cycles. The liquid nitrogen outlet temperature is stable during all cycles.

The test results of cooling capacity and COP at each cooling temperature is shown in Figure 9. Cooling capacity at 66 K is 10.4 kW. This result is very close to design value of 10.2 kW at 65 K in Table 1. At the cooling temperature 69 K, cooling capacity is 11.2 kW and COP is 0.067. A Carnot refrigerator operating between 69 K and 300 K, the coefficient of performance is

$$COP_i = \frac{T_c}{T_H - T_c} = \frac{69}{300 - 69} = 0.299$$

The percent Carnot for refrigerator at 69 K is

$$\%Carnot = \frac{COP}{COP_i} \times 100 = \frac{0.067}{0.299} \times 100 = 22.4$$

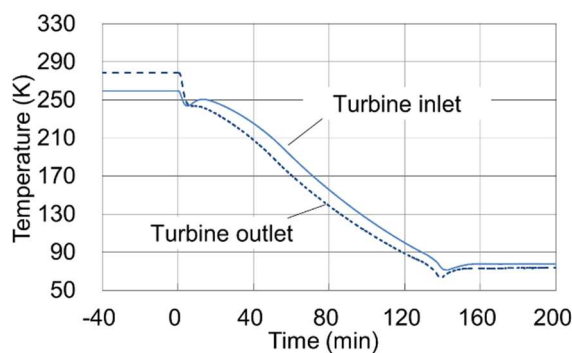


Figure 6 Cool down curve of stand-alone

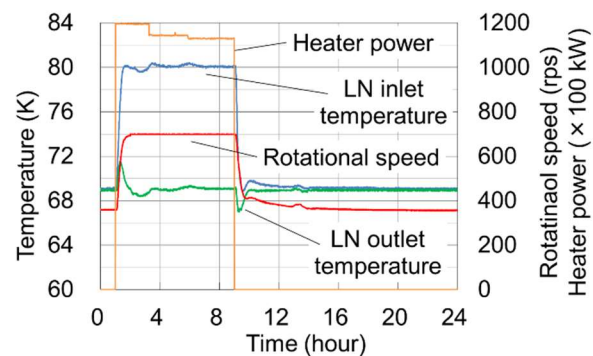


Figure 7 Load cycle test (one cycles)

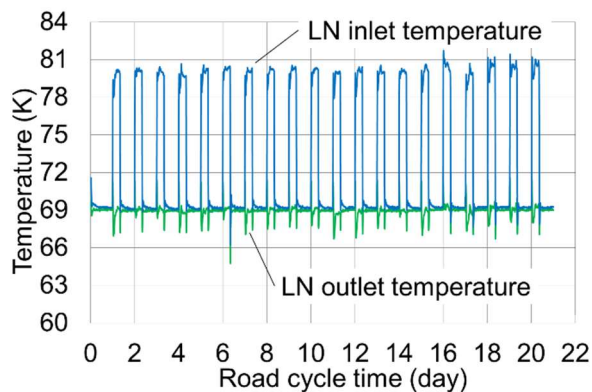


Figure 8 Load cycle test (20 cycles)

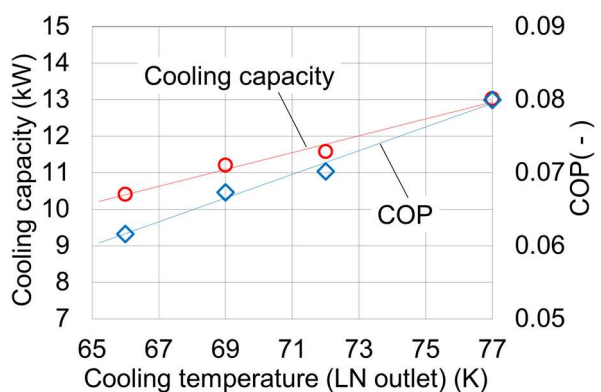


Figure 9 Cooling capacity and COP of test result

5. Conclusion

A 10 kW refrigerator was designed and launched in 2016. The performance test of the refrigerator was carried out using liquid nitrogen circulation equipment.

Cool down test is done with setting of turbine inlet temperature of 78 K. Cool down time of achieving to 78 K from room temperature is less than 3 hours.

The refrigerator operation is stable for 20 load cycles. Liquid nitrogen temperature increased rapidly at the heater power turn on. The turbine-compressor rotating speed is adjusted to get stable situation of liquid nitrogen outlet temperature. During the load cycle test, difference between the setting temperature and liquid nitrogen temperature is kept within 3 K.

The cooling capacity at 66 K is obtained 10.4 kW and the test result close to the design value of 10.2 kW at 65 K in Table 1. At the cooling temperature 69 K, cooling capacity is 11.2 kW, COP is 0.067 and percent Carnot is 22.4.

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