Study of refrigerant circulation system and cryofan for cooling high temperature superconducting coil

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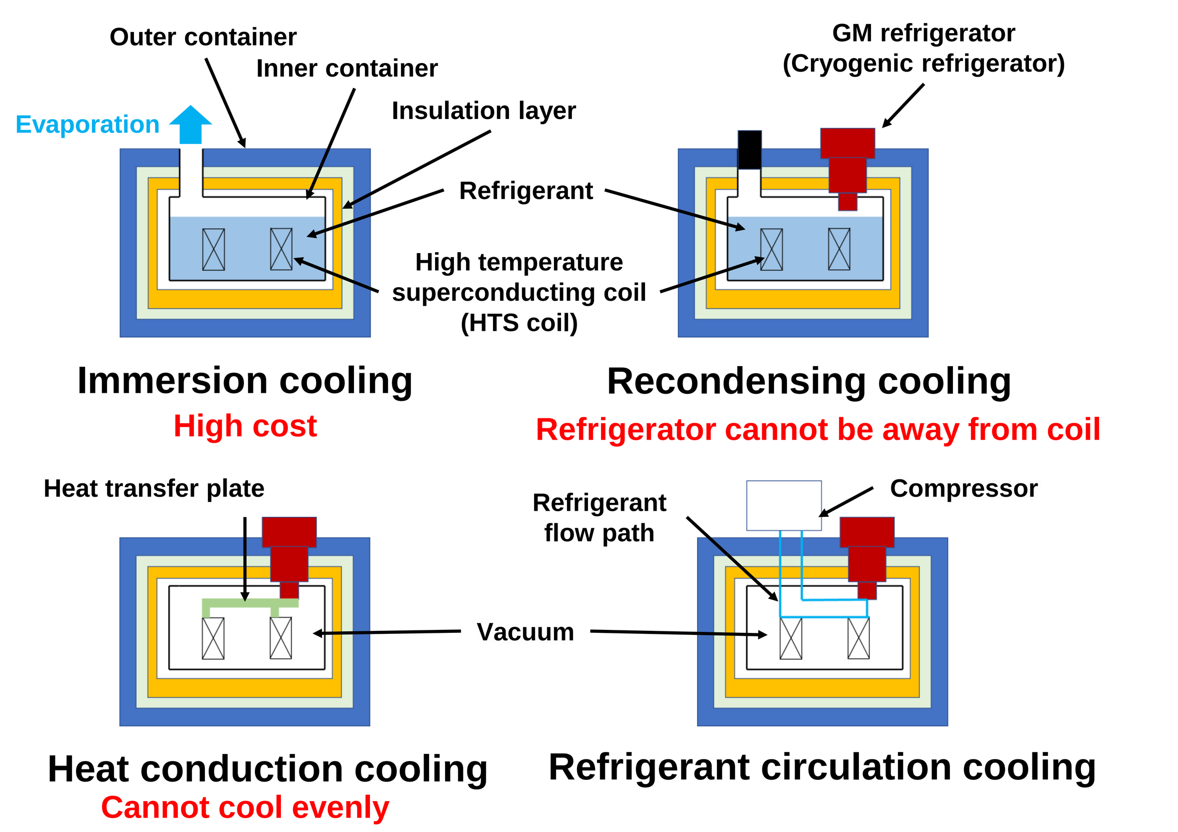
Back ground

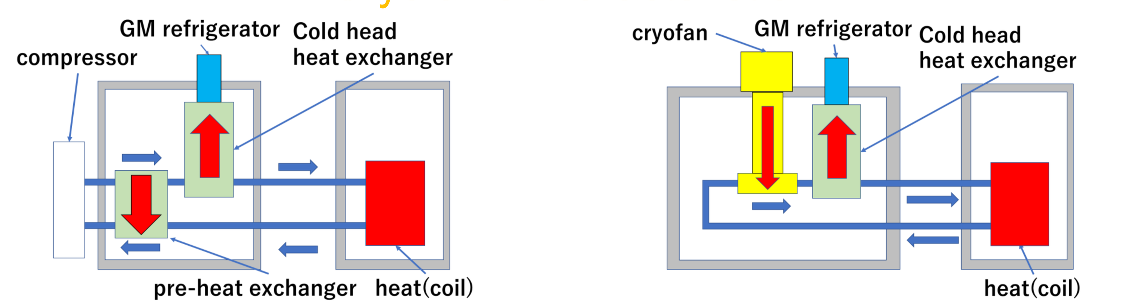
Refrigerant circulation cooling's characteristic



- Stable superconductivity → Coil temperature < 50K
- Keep costs down → Cooling multiple coils with one refrigerator
- Placement of equipment in the factory → Can extend the distance between refrigerator and coil

In this research, we analyzed the case where a compressor was used in case of multiple coils were actually cooled and the case where a cryofan was used, including the case where helium and hydrogen were used as the refrigerant, and the change in cooling performance was studied. We also analyzed and studied the effect of the heat generated by the motor on the cooling performance if it were present in the circulation flow path for the motor used for the cryofan.

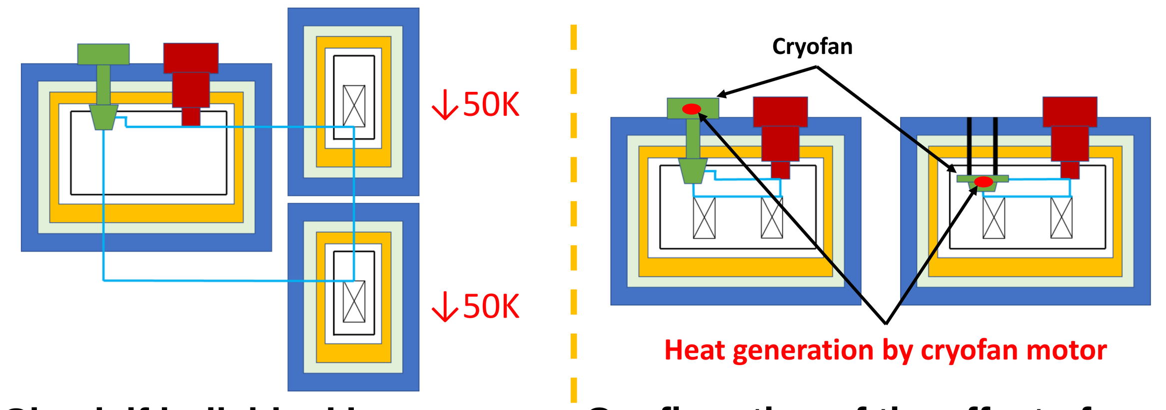
Cryofan's characteristic



Merit
- The precooling heat exchanger can be removed, and the length of the flow path can be reduced by 80% or more of the total.
- There is no need to bring the refrigerant back to room temperature at compressor.

Demerit
- A new heat intrusion occurs from the cryofan.
- Heat generation due to viscosity occurs in the cryofan impeller part.

Research target



Check if individual long distance coils can be cooled in series.

Confirmation of the effect of heat generation when the cryofan motor is in the flow path.

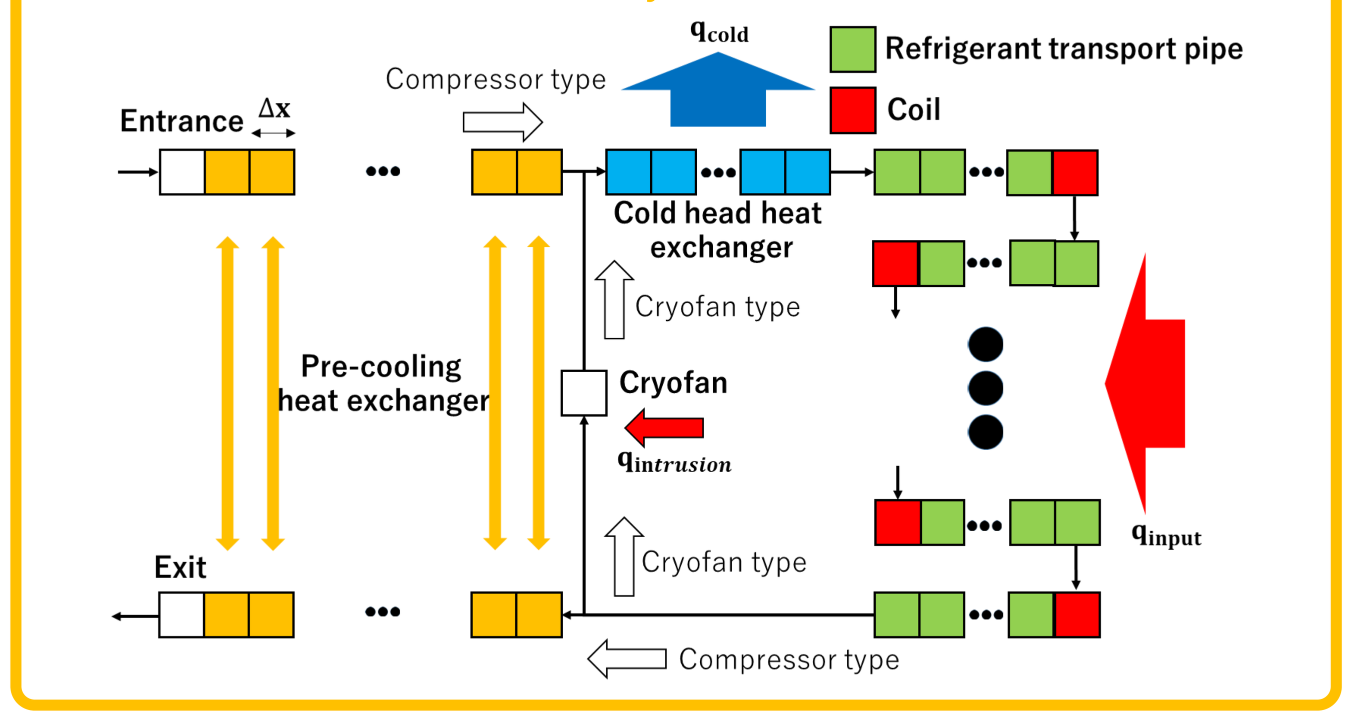
Analysis model, method

Governing equation

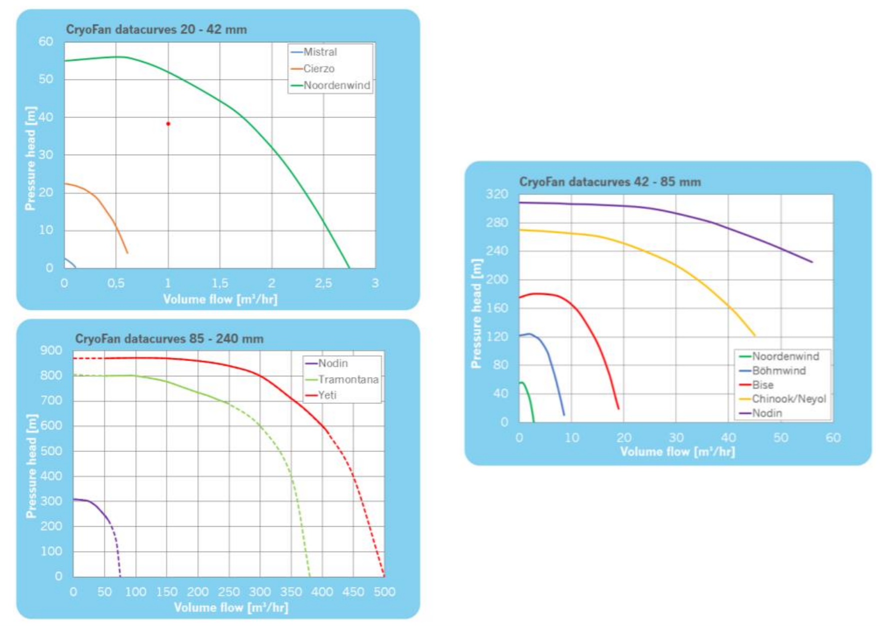
$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=k\frac{\partial^2 T}{\partial x^2}-\frac{1}{2}\rho u\frac{\partial u^2}{\partial x}+\frac{4}{3}\mu\left(\frac{\partial u}{\partial x}\right)^2-\frac{q_{ex}}{Sdx}-\frac{q_{lat}}{Sdx}-\frac{q_{rad}}{Sdx}$$

- ρ : Density of refrigerant[kg/m^3]
- c_p : Constant pressure specific heat of refrigerant [J/(kg・K)]
- k : Thermal conductivity of refrigerant[W/(m・K)]
- T : Temperature of refrigerant[K]
- q_{ex} : Exchanging heat at every mesh[W]
- q_{lat} : Change of latent at every mesh[W]
- q_{rad} : Radiant heat at every mesh[W]
- u : Flow velocity of refrigerant[m/s]
- S : Area of cross section[m^2]

Analysis model



Here, the one used for the analysis will be described. The analysis conditions are described on the analysis result of the poster. For the governing equation, the energy equation on the upper left was used. The symbols used in the equation are as described below the governing equation.
The analysis model is placed in the lower left. As an analysis model, when a compressor is used, the refrigerant flows from the inlet of the double heat exchanger and the flow path inside the pre-heat exchanger, and when a cryofan is used, it flows from the discharge side of the cryofan. The flowing refrigerant is cooled in the cold head heat exchanger, and then one or more coils connected in series by the refrigerant transport pipe are cooled and heat is input. After heat is input, when a cryofan is used, the refrigerant flows through the cryofan, and when a compressor is used, it flows through the pre-heat exchanger and returns to the compressor. The figure below is a performance table that partially describes the model of the cryofan used.[1]



Analysis in case of multi coil cooling

Analysis condition

Common data
- Heat input : 20 x (Number of coils) W
- Number of coils : 1,2,3
- Refrigerant transport pipe : 1.0 m
- Inlet pressure : 0.5, 1.0, 1.5, 2.0 MPa

Compressor
- Inlet temperature : 295 K
- Mass flow rate : 0.1, 0.5 ,1.0 g / s
- Outlet pressure : Calculated based on the pressure loss of the entire flow
- Outlet temperature : Same temperature as 1 mesh on the upstream side

Cryofan
- Inlet temperature : Based on the temperature of cryofan
- Mass flow rate : Calculated every hour
- Outlet pressure : Based on the mesh on the discharge side of the cryofan
- Outlet temperature : Based on the temperature of the refrigerant in the cryofan

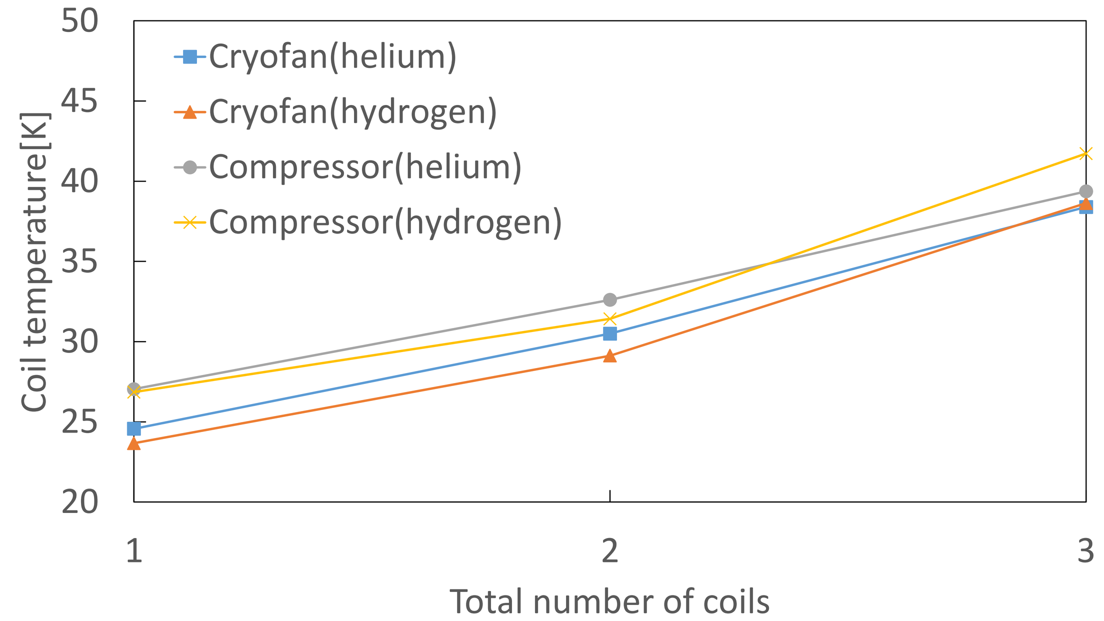


Fig.1 The lowest temperature of each coil in each condition

Here, we analyzed the coil temperature in case of circulating cooling was performed for multiple HTS coils. The analysis results are as shown in the graph on the right. It is occurred a total of four condition by whether a compressor or cryofan was used as the circulation device, and whether helium or hydrogen was used as the refrigerant. And the graph described the conditions under which the hottest coil at each heat input was cooled.

As a result of the analysis, it was shown that the cryofan has higher cooling performance than the compressor in multiple cooling. It is considered that this is because a high mass flow rate can be flowed with a low pressure loss. It was shown that hydrogen as a refrigerant has better cooling performance than helium. This is thought to be because hydrogen has a higher specific heat than helium and causes a relatively low temperature change with respect to a high-load heat input. In addition, from this result, it was shown that it is less than 50K even in case of there are three coils.

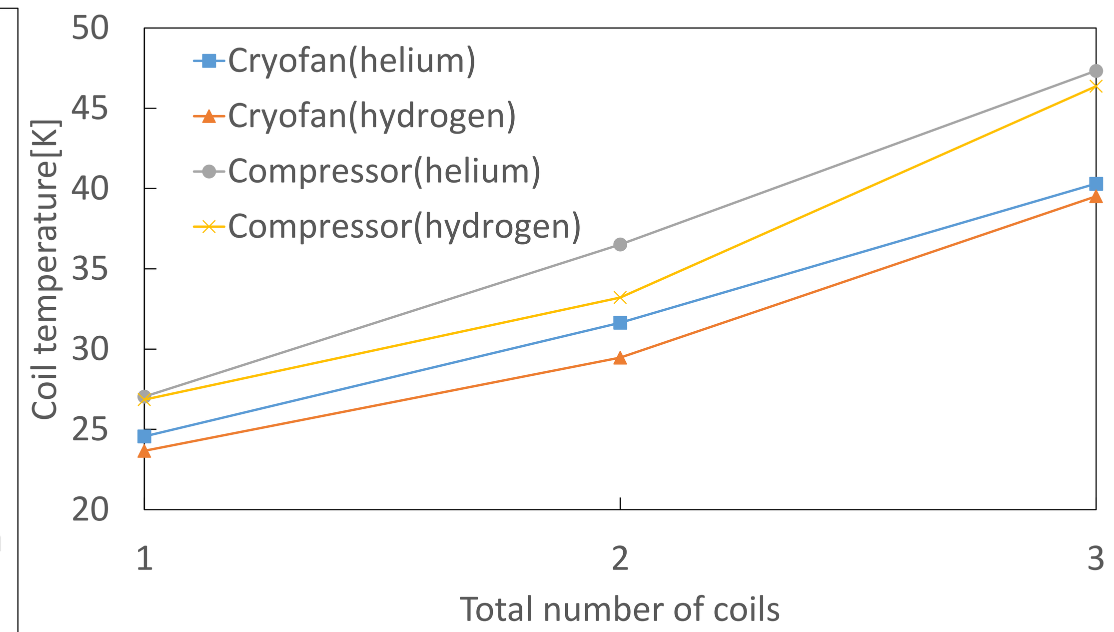


Fig.2 The highest temperature of each coil in each condition

Analysis in case of heat generation is occurred by motor

Analysis condition

Common data
- Heat input : 0.0 ～ 30.0W (every 1.0W)
- Number of coils : 1
- Refrigerant transport pipe 1.0 m
- Inlet pressure : 2.0 MPa

Compressor
- Inlet temperature : 295 K
- Mass flow rate : 0.1～1.5 g /s (every 0.1g/s)
- Outlet pressure : By the pressure loss of the entire flow
- Outlet temperature : Same temperature as 1 mesh on before side

Cryofan
- Inlet temperature : Based on the temperature of cryofan
- Mass flow rate : Calculated every hour
- Outlet pressure : Based on the mesh on the discharge side of the cryofan
- Outlet temperature : Based on the temperature of the cryofan
- Heat generating at cryofan : 0.00 ～ 100 W (every 1W)

Here, the analysis was performed assuming that the motor required to move the cryofan was in the circulation path. Here, heat intrusion from the outside via the cryofan body is not assumed, but instead, the heat generated in the coil part of the motor body is considered to transfer heat to the refrigerant inside. For the purpose of analysis, it is necessary to estimate how much calorific value is balanced to have the same cooling performance as the compressor.

As a result, as shown in the graph on the upper right, it was found that a cooling performance equivalent to that of a compressor can be obtained with a calorific value of about 10 W to 50 W. In particular, it was shown that if there is a heat input with a coil of 20 W or more, a motor with a calorific value of up to 40 W can be expected to have cooling performance equal to or better than that of a compressor.

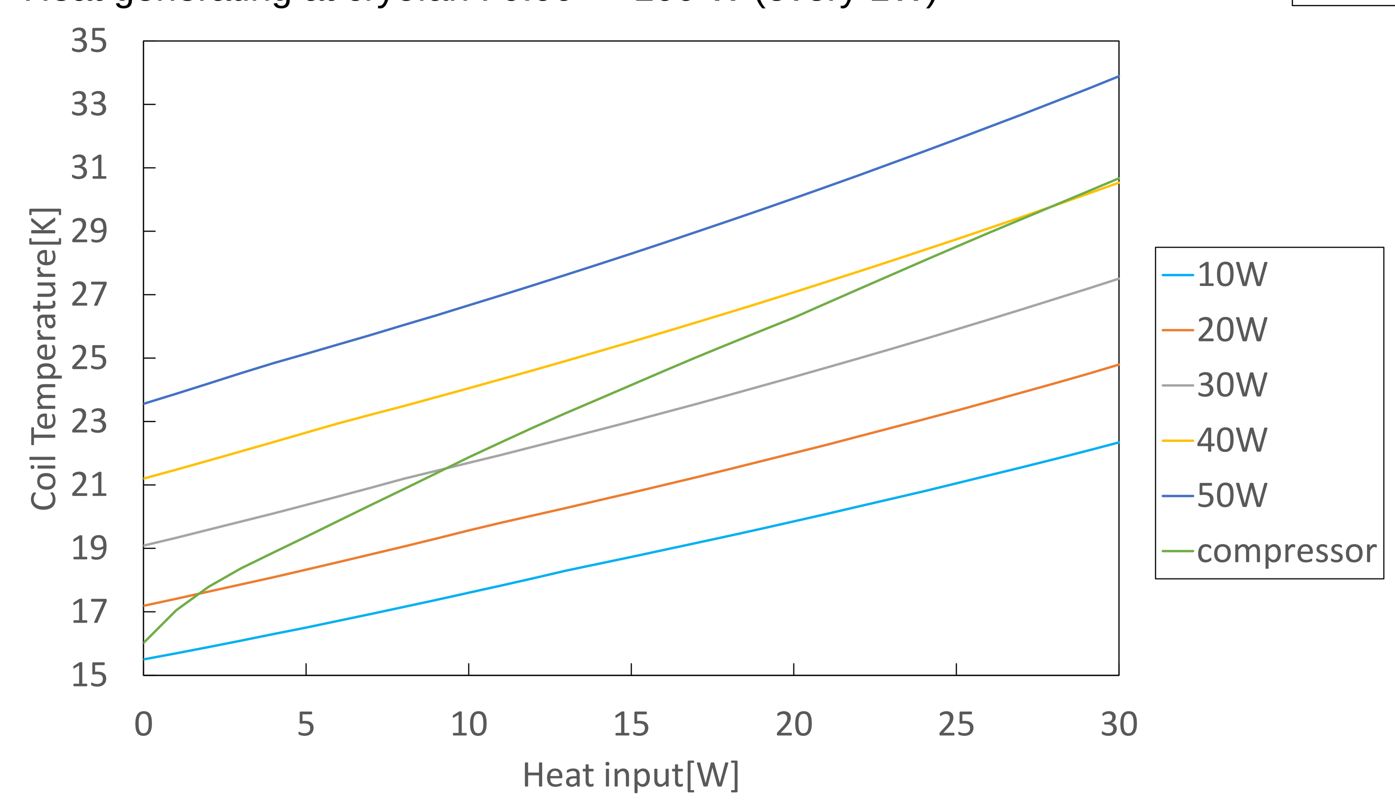


Fig.3 Comparison of analysis results considering heat generation from 10W to 50W and the case of compressor

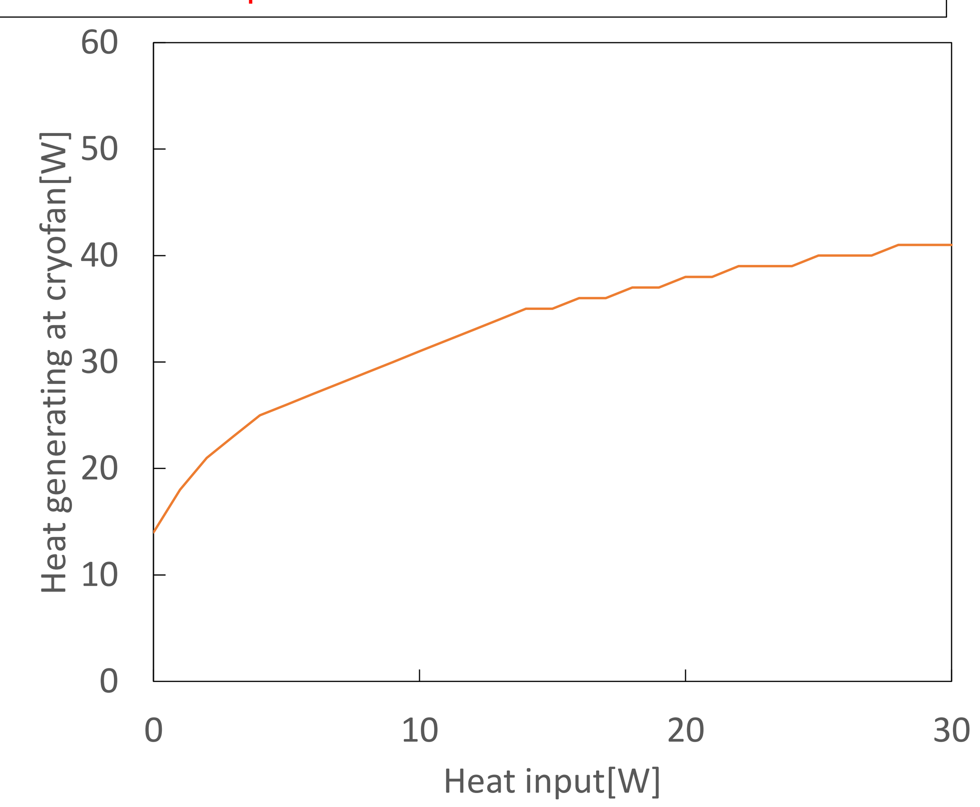


Fig.4 Amount of heat generated when it has the same cooling performance as a compressor

Summary and future prospects

It was shown that in the circulation cooling of multiple coils, it is possible to cool up to 50K or less in series with up to three coils.
In this case, it was confirmed that the cryofan as a circulation device has higher cooling performance than the compressor.
Similarly, it was confirmed that even when hydrogen was used as the refrigerant, the cooling performance was higher than that of helium.
It was shown that in case of the cryofan motor is placed in the circulation flow path, its output should be about 40W.
In the future, in addition to proceeding with analysis on the cooling of multiple coils in parallel, we will proceed with the planning of an experiment for circulating cooling that actually uses a cryofan.

Reference

[1] STIRLING CRYOGENICS, Cryofan Datasheet,https://www.stirlingcryogenics.eu/files/__documents/1/CryofansDatasheet.pdf, <2021.11.05>