Cryogenic Oscillating Heat Pipe for Conduction-cooled Superconducting Magnets

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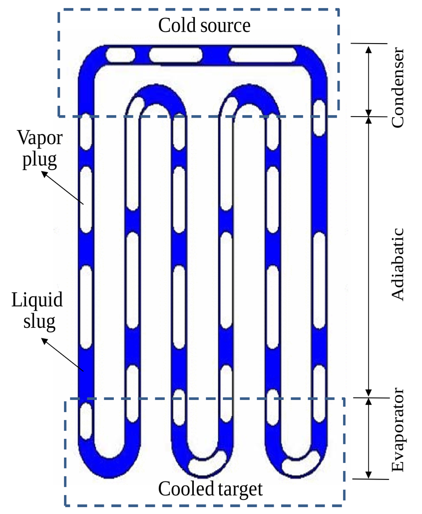
Background



Oscillating Heat Pipe

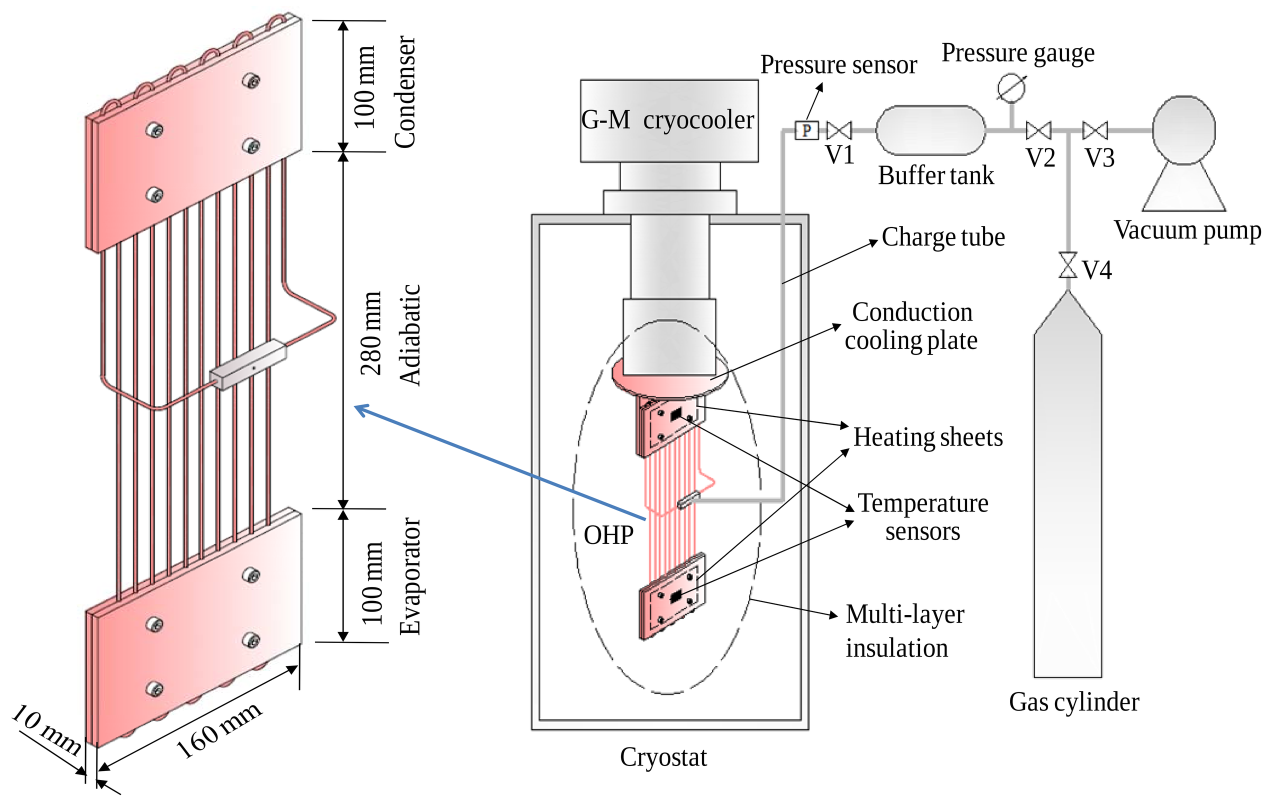
- ❖ The oscillating heat pipe (OHP)] is formed by bending a metallic capillary tube into many turns and divided into the condenser section, the adiabatic section and the evaporator section.
- ❖ The condenser section connects with the cold source, while the evaporator section connects with the cooled target.
- ❖ The working fluid filled in the OHP distributes in the form of liquid slugs and vapor plugs due to of surface tension effects.
- ❖ The instant pressure imbalance among the different turns will drive the flow of the liquid slugs and vapor plugs and lead to heat transfer between the cooled target and the cold source.
- ❖ The employment of flexible capillary tube makes the OHP more convenient as the thermal link in the cooling system.

Research Contents

- ❖ The cooling capacity of the cryogenic OHP during the cooling down process of the superconducting magnet.
- ❖ The heat transfer performance of the cryogenic OHP during the operation process of the superconducting magnet.

Experimental Setup

- ❖ Inner diameter: 1.0 mm; outer diameter: 2.0 mm
- ❖ The condenser section
  - Copper blocks: connect with the cryocooler head
  - Heading sheet: control the condenser temperature
- ❖ The evaporator section
  - Copper blocks: mock-up superconducting magnet
  - Heading sheet: simulate the heat generation of the superconducting magnet
- ❖ The working fluid charging system: connects with the OHP
- ❖ The working fluid : nitrogen
- ❖ liquid filling ratio of 33.5%



Data Reduction

- ❖ The cooling power Q_c and the thermal conductivity k_c during the cooling process:

$$Q_c = -mC_p \frac{dT_e}{dt} \quad \text{and} \quad k_c = \frac{Q_c}{T_e - T_c}\frac{L}{S}$$

- ❖ The average cooling power $\overline{Q}_c$ and the average thermal conductivity $\overline{k}_c$ from time t_1 to t_2 during the cooling process:

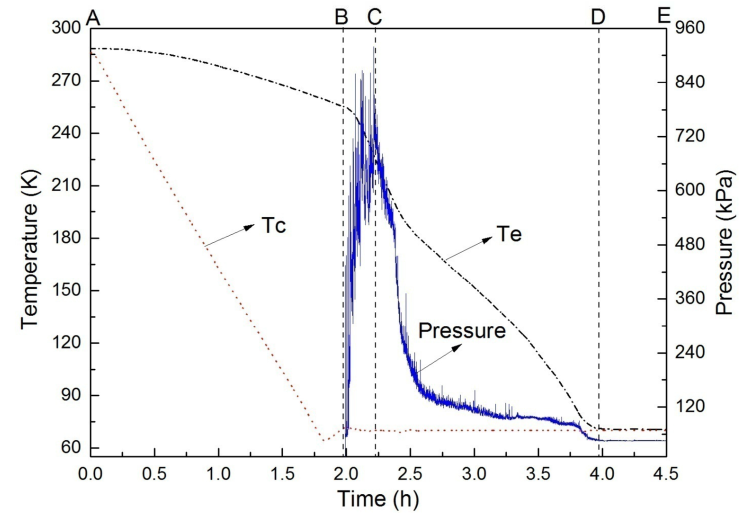
$$\overline{Q}_c = \frac{\int_{t_1}^{t_2} Q_c dt}{t_2 - t_1} \quad \text{and} \quad \overline{k}_c = \frac{\int_{t_1}^{t_2} k_c dt}{t_2 - t_1}$$

- ❖ The thermal resistance $\overline{R}_t$ and the thermal conductivity $\overline{k}_t$ during the operation process:

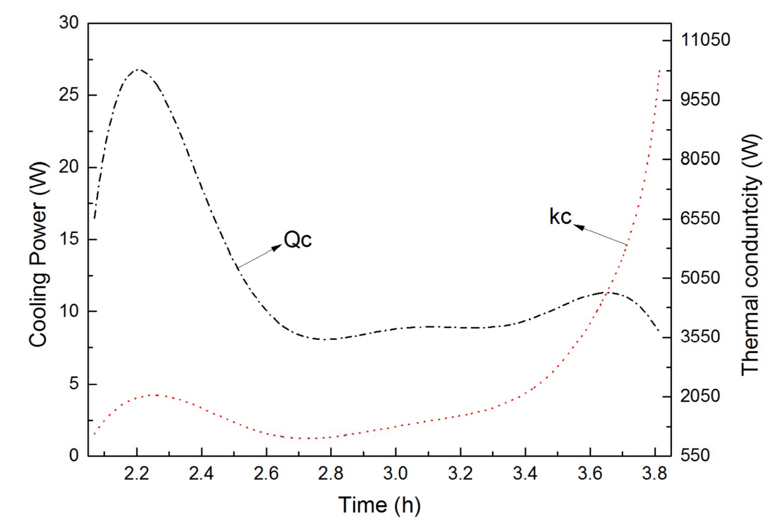
$$\overline{R}_t = \frac{\overline{T}_e - \overline{T}_c}{Q_i} \quad \text{and} \quad \overline{k}_t = \frac{Q_i}{\overline{T}_e - \overline{T}_c}\frac{L}{S} = \frac{1}{\overline{R}_t}\frac{L}{S}$$

- T_e —— the evaporator temperature (K)
- T_c —— the condenser temperature (K)
- m —— the total mass of the copper blocks on the evaporator section (kg)
- C_p —— the specific heat of copper at the evaporator temperature ($Jkg^{-1}K^{-1}$)
- t —— the cooling time (s)
- L —— the distance of the two centers of the evaporator and the condenser (m)
- S —— the total outer cross sectional area of the capillary tubes connecting the evaporator with the condenser (m^2)

Cooling Down Process

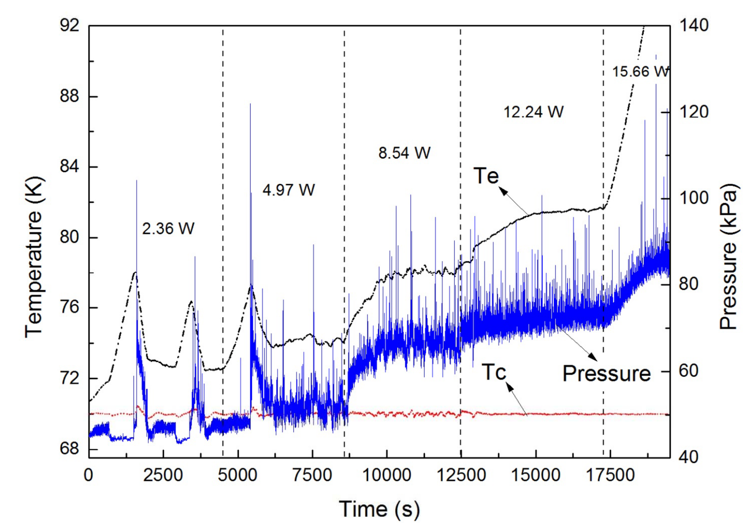


- ❖ AB: The cryocooler is started and the condenser temperature drops quickly.
  The temperature decrease in the evaporator is very small since the heat transfer mechanism in the OHP is only wall conduction.
- ❖ BC: The condenser temperature is controlled at 70 K and the nitrogen gas is introduced into the OHP.
- ❖ CD: The cooling process of the evaporator copper blocks is significantly accelerated by charging with nitrogen.
- ❖ DE: The evaporator temperature decreases to 70 K.

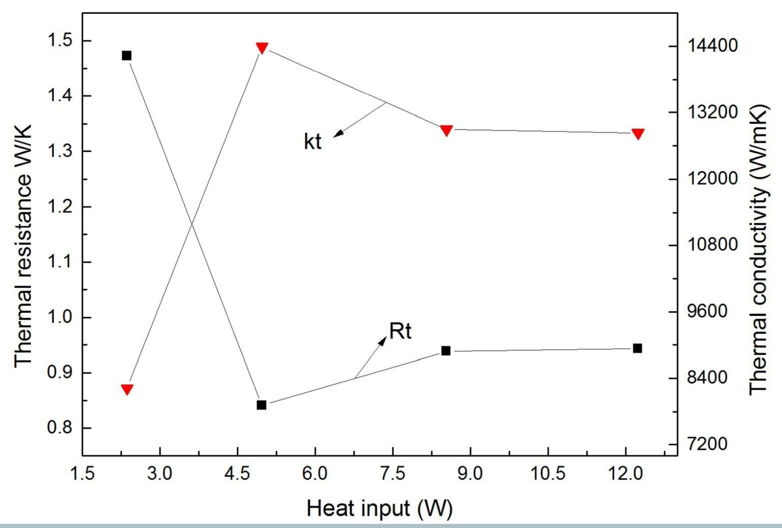


- ❖ At the beginning, the cooling power and the thermal conductivity increase.
- ❖ At 2.22 h, they start to decrease due to a rapid decrease in the pressure.
- ❖ At 2.75 h, they increase again since liquid slugs and vapor plugs oscillate between the condenser section and the adiabatic section.
- ❖ At 3.36 h, the thermal conductivity of increases quickly with time, while the cooling power increases at first and then decreases.
- ❖ The average cooling power and the average thermal conductivity are **12.56** W and **2227** W/m K, respectively.

Operation Characteristics



- ❖ As the heat input increases from 0 to 12.24 W, the evaporator temperature increases from 70 to 81.5 K, and the pressure of the OHP increases from 45 to 75 kPa
- ❖ At 2.36 W, the evaporator temperature and the pressure of the OHP have large amplitude.
- ❖ At 4.97 W, they increase firstly and then decrease to a relatively stable state.
- ❖ At 8.54 W and 12.24 W, they increase gradually and then attain the steady state.
- ❖ At 15.66 W, the evaporator temperature keeps going up quickly and the dry out occurs in the evaporator.



- ❖ The average thermal resistances decrease from 1.47 to 0.84 W/K and then increases to 0.94 W/K.
- ❖ The average thermal conductivity increases from **8215** to **14,388** W/m K and then decreases to **12,834** W/m K.
- ❖ The average thermal conductivity during the operation process is much larger than that of during the cooling down process and copper.
  (The thermal conductivity of copper with a RRR of 100 is about 604 and 401 W/m K at 70 and 250 K, respectively.)

Conclusion

- ❖ The cryogenic OHP has large cooling capacity during the cooling down process.
  —— It can reduce the cooldown time of superconducting magnet from room temperature to operational temperature.
- ❖ The cryogenic OHP has excellent heat transfer performance during the operation process.
  —— It can promptly remove the heat generation during the operation of superconducting magnet system..

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