§4. Superfluid Refrigeration Technologies for Large Superconducting Magnet

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So far, the superconducting magnets of helical coil for large helical device (LHD) have been cooled down by normal fluid helium (He I) at 4.4K. However, we have a plan of cooling down the superconducting magnets of the helical coils by superfluid helium (He II) at 1.8K in the near future. On that occasion, the method of refrigeration will be changed without significant change of inner cryogenic component such as the helical coils and the support structure. This is why size, structure, and arrangement of pipes and circulation systems for He II will be restricted strongly in space. Therefore, the heat transport characteristics of pressurized He II will be influenced seriously. On the other hand, huge He II refrigeration systems will be needed because of record-breaking scale of the superconducting magnets for the LHD. In the present study, we try to take numerical simulations on He II heat transport of cooling channels and pipes to heat exchangers. Up to this point, the numerical analogies of He II heat transport problems have been taken without its mass flow in consideration of high heat conductivity of He II. However, it is necessary to investigate sufficiently with including its mass flow as to large scale devices like helical coils.

To use He II for cooling the superconducting magnets of the helical coils, it is necessary to examine the heat transport characteristics in the cooling channels of the helical coils and in the pipes to heat exchangers from the viewpoints of the cryogenic stability and the quench protection. The heat generated in the helical coils are removed through the cooling channels, so it is especially important to understand the heat transport characteristics of the He II in the cooling channels of the helical coils. However, the helical coils for the LHD is so huge that the heat transport characteristics are investigated experimentally. So we investigated the heat transport characteristics by means of the numerical simulations.

In general the transport properties of the He II is described by the two fluid model. A set of the basic equations solved in the present simulations follows. 1)

Continuity equation;

$$\nabla \cdot \rho\vec{v} = 0 \qquad (1)$$

Momentum equation of total fluid;

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \eta\nabla^2\vec{v} + \vec{G} \qquad (2)$$

Momentum equation of superfluid;

$$\frac{\partial}{\partial t}(\rho_s\vec{v}_s) + \nabla \cdot (\rho_s\vec{v}_s\vec{v}_s) = -\frac{\rho_s}{\rho}\nabla p + \rho_s s\nabla T - A_{GM}\rho_n\rho_s(\vec{v}_n - \vec{v}_s)^3 + \vec{G} \qquad (3)$$

Energy equation;

$$\rho c\frac{\partial T}{\partial t} + \rho c\vec{v} \cdot \nabla T = f^{-1}(T)^{\frac{1}{3}}\nabla \cdot (\nabla T)^{\frac{1}{3}} \qquad (4)$$

where,

$$f^{-1}(T) = \frac{\rho^2 s_\lambda^4 T_\lambda^3}{A_{GM}}\left[\left(\frac{T}{T_\lambda}\right)^{5.7}\left(1-\left(\frac{T}{T_\lambda}\right)^{5.7}\right)\right]^3 \qquad (5)$$

$$A_{GM} = \frac{\rho}{(11.3)^3\rho_s\eta_n} \qquad (6)$$

$$\vec{G} = [0 \quad g(\rho_0 - \rho)]^T \qquad (7)$$

These equations were solved by the finite element method in terms of the He II in the channels. At the initial simulations, several of a simple and a small channel were used in consideration of convenience of comparison between the results of experiments and simulations, where many studies on those channels have been made. 2)

The results of the simulations follows; the temperature distributions in the channels were in good agreement with the experimental facts, and the motions of total fluid, normal fluid component, and superfluid component ware obtained simultaneously. From now on, it is necessary to apply the present simulations to complicated channels like those of the helical coils. So we must test conductors, model coils, and model channels of helical coils in the He II and improve these simulations through obtained results. To design He II cooling systems of helical coils for the phase II operations of the LHD in details, we must evaluate cryogenic stability of helical coils in He II, developing the present studies.

Reference
1)S.W. Van Sciver : Helium Cryogenics (1986)
2)Hamaguchi, S. : doctoral thesis (1998)