Thermal Fluid Modeling of BEPCII IR Quadrupole Magnet Cryostat

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A pair of superconducting interaction region quadrupole magnets for BEPCII was designed and fabricated at Brookhaven National Laboratory, USA. The cryogenic system for the IR magnets was designed at Harbin Institute of Technology, China. This paper provides the results of thermal fluid modeling for the magnet cryostat. The numerical analyses were carried out for two types of cooling methods, the subcooled liquid helium and the supercritical helium flow. The pressure and temperature changes in the cooling circuits are given.

INTRODUCTION

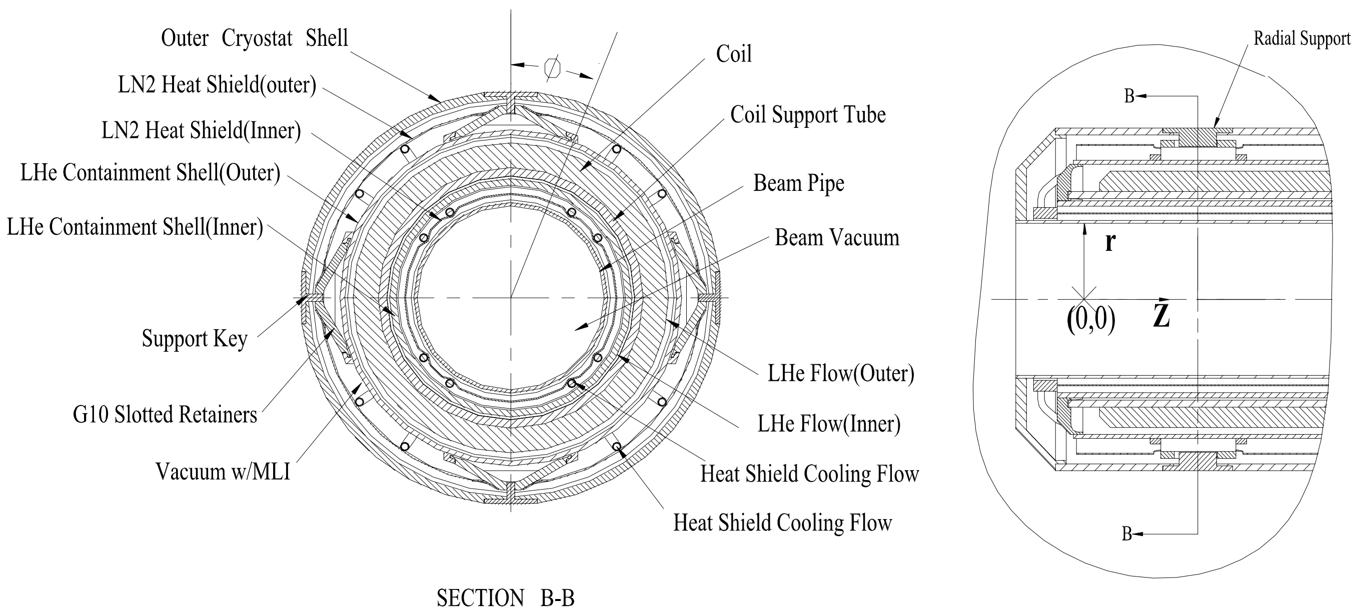

Figure 1 Cryostat of SCQ magnet in BEPCII

Two identical iron-free and non-collared magnets with active shielding are proposed for the BEPCII interaction region upgrade. Each magnet consists of seven coils wound in a common stainless steel cylinder [1, 2]. Due to the requirement of small size and low field leakage as well as the limitation of available space, the magnet cryostat was designed compactly. Figure 1 shows the cross section of the cryostat. The main components include, from inner to outer, the cryostat inner vacuum vessel, the inner heat shield with a series of liquid nitrogen cooling tubes, the inner helium vessel, coil support tube, outer helium vessel, outer heat shield, and outer vacuum vessel (see Figure 1). Each magnet is fixed by eight radial supports and one axial support. The heat loads at 4K for the SCQ magnet are mainly due to the thermal conductions of the radial key supports and the axial support, the thermal conduction and radiation through multi-layer insulation (MLI). The stainless steel support keys, aligned with and welded to the outer vacuum vessel, engage slots in G-10 retainers, arranged in a 90° pattern around the circumference of the outer helium channel, in two axial locations. The G-10 retainers are also mechanically and thermally stationed to the 80K heat shield. The inner diameter of the outer cryostat wall is 290mm and the outer diameter of the inner cryostat wall is 138mm. The gaps of outer and inner helium cooling passages are respectively 6.0mm and 2.0mm. The cooling tubes of heat shields are 5.0mm in diameter. In order to avoid the flow instabilities in the constrained cooling channels, the single-phase helium fluid including the subcooled liquid or supercritical flow will be adopted to cool the magnets and were studied in this paper by numerical simulation.

PHYSICAL MODEL AND BOUNDARY CONDITIONS

The single-phase helium flow goes through the outer and the inner cooling channel of the magnet in turn. The numerical simulation for the cooling channel was performed by a commercial computational code of FLUENT. The simplified physical model is given in Figure 2. Without considering the axial heat load, one quarter of the channel is modeled due to symmetry of structure and radial thermal loads. The helium fluid adsorbs the heat along the passage induced by the heat conduction through the radial supports and radiation from 80K heat shields. In the model, for the outer shell of the outer cooling channel, the heat conduction fluxes are added to the contact surfaces with the support keys, and the radiation heat is evenly guided into the whole area of the outer shell. For the inner cooling passage, only the radiation heat is taken into consideration. The lengths of the outer and inner channel are about 900mm and 1000mm, respectively. The material of the channel is stainless steel, and the properties are used as the function of the temperature.

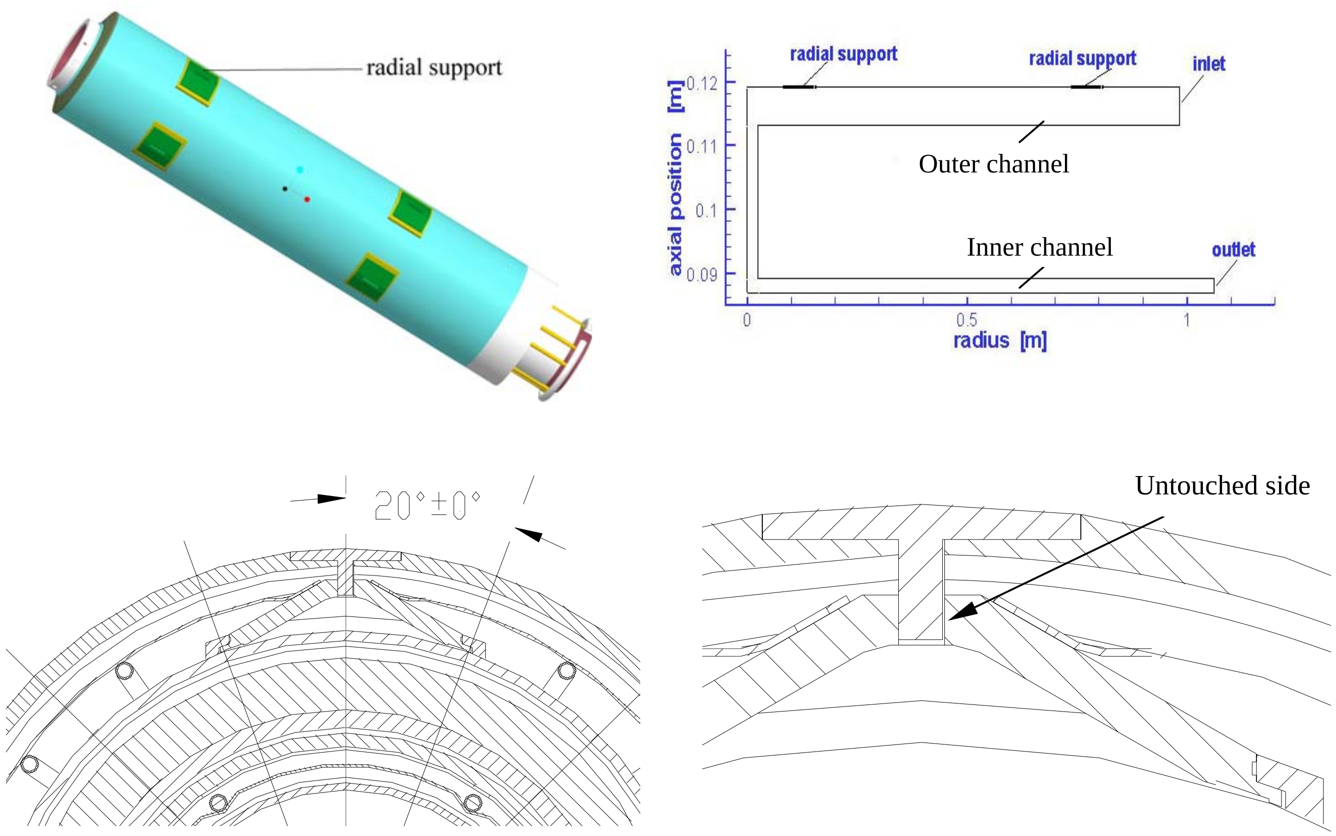

Figure 2   Physical model

SUPERCRITICAL HELIUM COOLING MODELING

The supercritical helium used to cool the magnet is produced by the subcooler. The helium at 2.7bar and 5.2K from the J-T circuit of the refrigerator flows through the heat exchanger immersed in the LHe control dewar and cooled to 4.46K by the saturated liquid helium at 1.2bar in the dewar. And then the helium goes into the magnet cryostat. The steady state, three-dimensional turbulent flow was modeled. The standard $k-\varepsilon$ momentum equation and standard wall function were adopted for the simulation. The coordinates of the circumferential ϕ, radial r and axial z are defined as shown in Figure 1. The origins are set at the end of the outer channel. The mass flow rate is 12g/s.

The temperature change at different radius at the same circumferential ϕ is show in Figure 3. At ϕ=20^{o} and ϕ=-20^{o}, along the radial direction, the conduction heat goes into the cold mass at liquid helium temperature region through the local small contact surface between the G-10 retainers and the outer wall of the outer cooling channel. For the worse case, the stainless steel key only touches the left surface and the surface along the positive Z direction of the G-10 retainers (Figure 2). It will cause the different heat flux to the cooling flow at different spots along the passage. Based on the above structure and the calculated curves, the temperature changes are different for the spots at ϕ=20^{o} (Figure 3a) and ϕ=-20^{o} (Figure 3b). The highest temperature of the supercritical helium channel is about 6.0K at ϕ=-20^{o}, but 5.5K at ϕ=20^{o}, which happens nearby the outer wall of the channel. The closer to the cold mass, the lower is the temperature of the fluid. The helium fluid close to the magnet keeps lower than 4.8K even at the hot spots. The pressure drop is about 10Pa to be neglected. In the inner helium channel, due to only radiation heat flux, the temperature is almost uniform. In order to lower down the highest temperature, the mass flow rate should be increased.

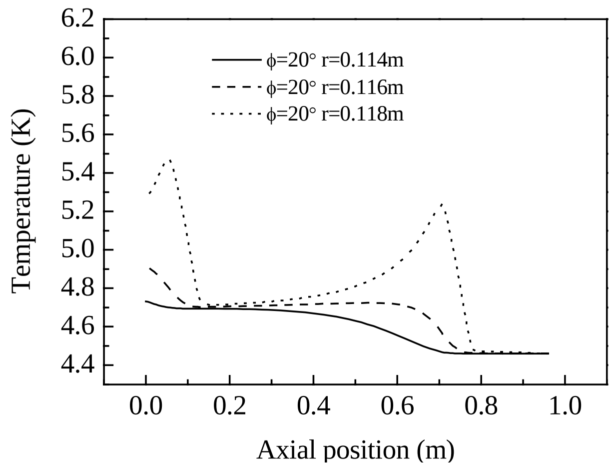

Figure 3a Temperature vs. axial position at ϕ=20^{o}

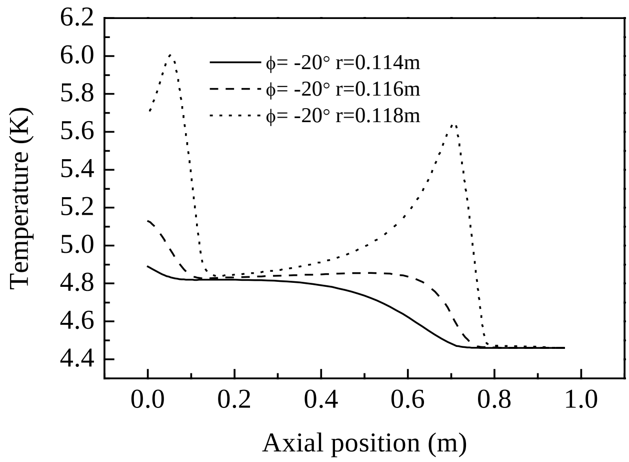

Figure 3b Temperature vs. axial position at ϕ=-20^{o}

SUBCOOLED HELIUM COOLING MODELING

For the subcooled helium cooling modeling, the standard $k-\varepsilon$ momentum equation and standard wall function were also adopted for the simulation. The inlet pressure and temperature of subcooled liquid helium are defined at 1.4bar and 4.46K, and the mass flow rate is also of 12g/s. Figure 4 presents the simulation results. By comparison, at the same spot and mass flow rate, the temperature of the subcooled helium inside the outer cooling channel is a little lower than that of the supercritical helium. The highest temperature at ϕ=20^{o} close to the outer wall is about 5.0K. The difference is due to the difference of specific heat for the subcooled liquid helium and the supercritical helium. The former is around 6000J/kg-K, and the latter is less than 5000J/kg-K. The temperature difference of the fluid close to the cold mass is less than 0.1K between the inlet and outlet along the outer passage at the ϕ=10^{o} and ϕ=30^{o}

for both cooling methods. The temperature of the magnet keeps around 4.5K.

Even though less subcooled flow can be used for the magnets cooling than the supercritical flow, one major concern for the subooled flow is when the temperature of the subcooled helium rises up to the saturated temperature of 4.6K at 1.4bar, it will turn to the two-phase and probably cause the flow instability. Therefore, the supercritical flow is preferred when the cooling capacity is plentiful.

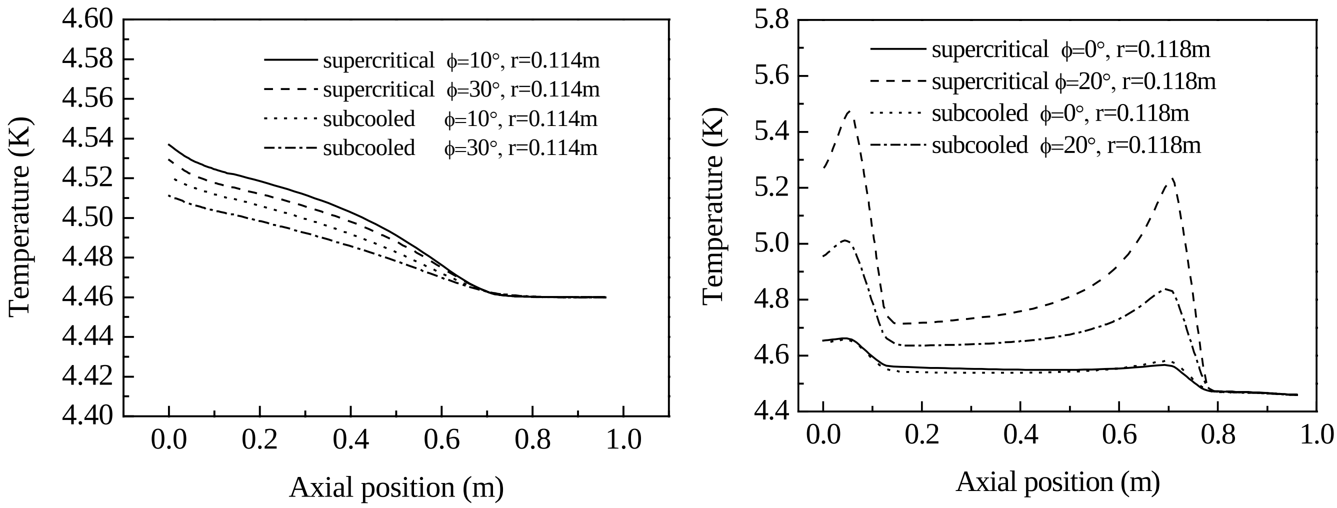

Figure 4 Comparison of the temperature vs. axial position for the supercritical and subcooled helium

CONCLUSION

The numerical simulations were performed for the magnets cooling in BEPCII upgrade. The temperature changes in the cooling circuits are analyzed in detail. By comparison, at the same spot and mass flow rate, the temperature of the subcooled helium inside the cooling channel is a little lower than that of the supercritical helium. The selection of cooling schemes is up to various factors. The supercritical flow is preferred when the cooling capacity is plentiful.

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