Optimization of Heat-Sink Cooling Structure in EAST with Hydraulic Expansion Technique

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Abstract Considering utilization of the original chromium-bronze material, two processing techniques including hydraulic expansion and high temperature vacuum welding were proposed for the optimization of heat-sink structure in EAST. The heat transfer performance of heat-sink with or without cooling tube was calculated and different types of connection between tube and heat-sink were compared by conducting a special test. It is shown from numerical analysis that the diameter of heat-sink channel can be reduced from 12 mm to 10 mm. Compared with the original sample, the thermal contact resistance between tube and heat-sink for welding sample can reduce the heat transfer performance by 10%, while by 20% for the hydraulic expansion sample. However, the welding technique is more complicated and expensive than hydraulic expansion technique. Both the processing technique and the heat transfer performance of heat-sink prototype should be further considered for the optimization of heat-sink structure in EAST.

Keywords: EAST, heat-sink, heat transfer performance, hydraulic expansion

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1 Introduction

The EAST tokamak has already been in operation for several years [1]. Until March of 2009 EAST had completed one engineering commissioning using stainless steel plates instead of CuCrZr heat-sink and two engineering commissioning using CuCrZr heat-sink with active cooling water system [2,3]. One of the basic requirements for the cooling water system in EAST is to ensure that the water inside in-vessel components doesn’t leak into vacuum vessel. However, if a minor crack appears, an embrittlement highly sensitive to transition temperature will occur due to unstable performance of chromium-bronze material used in EAST [4,5]. Seven leakages had happened during two period of engineering commissioning. The original design was that water cooling channels were drilled along the heat sink plates with 20 mm thick, and each module of water channels was connected in series [6]. Considering utilization of the original chromium-bronze material to optimize the heat-sink structure in EAST, leakage problem can be solved by embedding copper tube in heat-sink. Stainless steel tube couldn’t be used in heat-sink because the heat flux of 1 MW/m² would give a thermal gradient of 66°C/mm through stainless steel. It is necessary to know the heat transfer performance of the heat-sink with cooling tube compared with original sample without cooling tube, and to conduct a test to compare different types of connection between tube and heat-sink. When the connection between copper tube and heat-sink is clearance fit, the heat transfer performance of tube-inside structure can be reduced by about 40% compared with the original sample in first test. The thermal contact resistance becomes even large when the temperature of heat-sink wall increased from 100°C to 200°C, that is because the diameter of heat-sink hole gets large when the heat-sink is heated, and the copper tube shrinks while it is cooled by water, the gap between heat-sink hole and tube will accordingly change with the temperature difference. The types of connection between heat-sink and copper tube have an effect on the thermal conductivity. It must be ensured that heat sink and copper tube are tightly contacted regardless of the temperature difference. Some types of connection between heat-sink and copper tube are discussed as follows: a. Heating the heat-sink and cooling the tube to assemble for interference fit. b. Using hydraulic expansion to minimize the residual stress between copper tube and heat-sink. c. High temperature vacuum welding. Samples (as shown in Fig. 1) are fabricated to compare the heat transfer performance for each connection and a test is carried out in the University of Science and Technology of China (USTC), the test facility can be seen in Fig. 2.

2 Numerical analysis of cooling channel structure

For optimizing the structure of heat-sink, the convenient method is that copper tube embeds in the heat-
sink without changing the previous channel. The thickness of tube is 1 mm, it is necessary to calculate heat transfer performance when the diameter of hole changed from original 12 mm to 10 mm without considering the thermal contact resistance between copper tube and heat-sink. The toroidal limiter in EAST was selected for calculation. Fig. 3 shows the temperature distribution of the toroidal limiter with channel diameter of 10 mm and heat flux of 1 MW/m², under this condition the water temperature is nearly close to the boiling point. The comparison results of overall calculation are shown in Figs. 4 and 5, in which \( d \) means diameter of channel in heat-sink, \( v \) means velocity, and \( h \) means heat flux.

After reducing the diameter of channel in heat-sink, according to the calculation, it can be found the velocity of high flux target increases up to 5.8 m/s from the original 4.1 m/s to meet the pump load available. If heat flux is 1 MW/m², it can operate in steady state; if heat flux is 3.6 MW/m², it can operate from 24 s to 28 s considering the water boiling. The velocity can be turned down by controlling pump load, while increasing the velocity, the pipe will be eroded and water hammer phenomenon will be appeared, therefore, it is not proposed the flow rate increases much higher. After reducing the diameter of cooling water channel in heat-sink, according to the calculation, the velocity of low flux target is nearly the same as the pump load available. With the same velocity of 3.2 m/s, it can operate from 65 s to 60 s with heat flux of 1 MW/m² and can operate 24 s with heat flux of 3.6 MW/m².

As mentioned above, for heat flux of 1 MW/m², the variation of heat-sink channel diameter from 12 mm to 10 mm affects the temperature distribution. However, for higher heat flux of 3.6 MW/m², the variation of heat-sink channel diameter has little effect on the temperature distribution.
3 Comparison of each connection

3.1 Heating and cooling [7]

Supposing the largest temperature difference between tube and heat-sink is $200^\circ C$, about $\Delta l = \alpha l \Delta T = 18 \times 10^{-6} \times 12 \times 200 = 0.043$ mm is required for interference fit. Heating the heat-sink to 573 K, the diameter of heat sink channel increased by about 0.075 mm; cooling the copper tube with the liquid $N_2$ to 80 K, the diameter of tube decreased by about 0.045 mm. If the assemble tolerance is no more than 0.05 mm, at least 0.05 mm interference fit can be ensured.

3.2 Hydraulic expansion [8]

Before fabricating the sample, numerical calculation has been done. The boundary conditions are as follows: in the first step, the pressure in channel is set to be 20 MPa, then in the second step, the pressure is set to be 0 MPa, the copper tube appears plastic deformation at 33 MPa. The residual stress between copper tube and heat-sink, which is about 13 MPa, is given by the numerical calculation, as can be seen in Fig. 6. During fabricating the sample, the pressure is set to be 24 MPa, which is shown in Fig. 7. In principle, at least 0.05 mm the interference fit should be ensured. However, it may be difficult to find the proper pressure from numerical calculation, the proper pressure should be validated by test.

3.3 High temperature vacuum welding

In fact, high temperature thermal cycle can degrade the strength and thermal conductivity of chrome-bronze by up to 60% and 50%, respectively. The approach using a rapid heat cycle or a fast quench is to minimize the time the component spends in the temperature range where over-precipitation becomes an issue. The steps of the approach are as follows. Firstly, the chrome-bronze should be heated to 980$^\circ$C and remain for half an hour. The second step is high-pressure gas quenching $[9-11]$, which is the most critical step, the cooling rate with no less than 1$^\circ$C/s can make Cr elements have no time to precipitate and retain in the copper and thus a supersaturated solid solution is formed. The third step is aging, the proper aging temperature is 470$^\circ$C, preserving 4 hours. The last step is cooling in the furnace to 200$^\circ$C, then air-cooling to room temperature. The device for welding is shown in Fig. 8 and the real temperature curve is presented in Fig. 9.

4 Test result and discussion

In the first sample, the heat-sink was heated to 573 K and the copper tube was cooled down to 80 K to ensure 0.05 mm interface fit. However, it was hard to ensure the tube in straight line with hole and would not be able to assemble when cold copper tube contacted with the hot wall. So this method is not feasible in view of processing technique. In the second sample, which using hydraulic expansion method to ensure residual stress,
it is hard to determine the amount of interface fit, the result should be evaluated by heat transfer performance test. In the third sample, which using high temperature vacuum welding, the welding should ensure the temperature is higher than 1200 K and meet the requirement of fast cooling down with furnace in heat-sink.

Heat transfer performance of each sample is shown in Fig. 10, in which the temperature of 473 K or 573 K means the temperature of heat-sink side wall. The heat transfer performance is evaluated according to the heat removed by water. It can be computed by the equation \[ \Delta Q = cm\Delta T, \]
where \( c \) is the specific heat, the mass \( m \) can be got from water flow \( Q \), \( \Delta T \) is shown in \( Y \) direction of Fig. 10. Conclusion is given as follows. The original sample without cooling tube in heat-sink is always the best one. The heat transfer performance of welding sample is closest to that of the original sample. Compared with the original sample, the thermal contact resistance can reduce the heat transfer performance of welding sample by 10\%, while by 20\% for the hydraulic expansion sample.

![Fig.10](image)

**Fig.10** Heat transfer performance for each test model

5 Summary and conclusions

It is feasible to reduce the channel diameter of heat-sink from 12 mm to 10 mm according to numerical analysis, and using hydraulic expansion and high temperature vacuum welding can ensure residual stress in copper tube in view of the processing technique. On the whole, the heat transfer performance of welding sample is closest to that of the original sample. Compared with the original sample, the heat transfer performance of the welding sample is reduced by 10\%, while for the hydraulic expansion sample, it is reduced by 20\%. The welding technique had already been used in SST-1 tokamak\,[12]. But the welding technique is more complicated and expensive than high-pressure processing technique. Comparison of the prototype of heat-sink with the mentioned-above two techniques will be conducted in the future.

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