Fusion Engineering and Design 89 (2014) 2685–2690

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Preliminary design and performance study of EAST liquid lithium limiter based on CPS

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HIGHLIGHTS

- Liquid lithium limiter will be applied in EAST tokamak to improve the plasma performance.
- CPS is used to prevent the liquid lithium from splashing under high EM forces.
- Active cooling water system is designed for high heat flux resistance.
- Good heating efficiency of the heat sink to the CPS is verified under bench test.

ARTICLE INFO

Article history:
Received 22 February 2014
Received in revised form 28 May 2014
Accepted 9 July 2014
Available online 24 August 2014

Keywords:
EAST
Liquid lithium limiter
CPS
Analysis
Bench test

ABSTRACT

Lithium has the ability of H recycling suppression and impurities absorption and it can be used as plasma facing material (PFM) in tokamaks. Lithium conditioning experiments were launched on EAST, HT-7 and some other tokamaks for many years by using the methods of GDC, IRCF and evaporation. Liquid lithium has better performances in effective lifetime and heat removal aspects compared to non-liquid lithium. While, applying liquid lithium in the tokamak would cause the safety problem as the lithium can react with many substances violently and the magnetohydrodynamic behavior is difficult to be handled. EAST liquid lithium limiter (LLL) system is under developing and will be applied in EAST to study the main technologies of the liquid lithium application. The normal operation temperature of the limiter is expected as 230–550 °C under the active cooling of water. Capillary porous system (CPS) is used to prevent the lithium from splashing under large electromagnetic force by increasing the surface tension of the lithium. In order to investigate the cooling performance of the cooling design, the thermal-hydraulic analysis was done which shows that with 3 m/s flowing velocity, the water can keep the limiter under 550 °C all the time if the heat flux is lower than 0.7 MW/m^2. Under heat flux of 1 MW/m^2, the limiter should be retreated within 7 s to avoid erosion. The pressure drop of the coolant under 3 m/s is less than 40 kPa with temperature difference nearly 34 °C which meet the design requirements very well. The key manufacture process and technologies like vacuum bonding between the CuCrZr heat sink and 316L guide plate were well studied in the R&D process. The heating test on the test bench showed that the CPS can be heated efficiently by the heaters attached into the heat sink.

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1. Introduction

EAST is an important fusion experimental device aims to the plasma physics study especially in the fields of long pulse and H-mode operation. With the development of plasma discharging research, the plasma wall conditioning and the interaction between the plasma and the plasma facing material (PFM) have presented a significant challenge nowadays. Hydrogen isotopes retention and collection of dust can cause PFM erosion, and finally interrupt the plasma existence, which restrains the steady state of tokamak operation [1]. Lithium, severed as PFM, has a large potential to suppress H recycling and reduce the impurities like H, O that are captured by the PFM and released during plasma operation [2]. As an element with low atomic number, the lithium has the properties such as a low melting point (180 °C), high boiling temperature (1343 °C under 1 atm pressure), low z and low activation which allows the lithium become the best candidate of the PFM [1,3]. Lithium conditioning experiments were used by the ICRF to coat the graphite

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http://dx.doi.org/10.1016/j.fusengdes.2014.07.006
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Table 1
Main parameters of the EAST LLL.

Parameter	Value
Total weight of the limiter	~7 kg
Dimensions	340 mm (L) × 174 mm (H) × 28 mm (D)
Capillary pressure	5×10^4 Pa
Amount of lithium	~70 g (the CPS saturated)
Area of lithium surface	0.04 m^2

first wall (FW) of the EAST with lithium from the oven and the He-GDC is used to perform the lithium coating on HT-7 [2]. Based on the results of the above experiments, the plasma performances like plasma current and density were improved easily after lithium coating. Besides, the increase of particle and energy confinement time was observed [2]. Moreover, lithium evaporation was also applied in TJ-II [4] and NSTX [5] in which the reduction of the H-mode threshold power after lithium coating was achieved.

The most defect of non-liquid lithium wall conditioning on tokamak is because of its short effective lifetime. While, liquid lithium has the ability of removing high heat flux resulted from the bombardment for high-energy particles and realize the regeneration of the damaged surface. Besides, lithium has low melting point property which can simplify the design of the liquid metal circuit when it is applied to fusion devices, is an important reason to be chosen as PFM. Liquid lithium experiments were carried out on the CDX-U, FTU, T-11M and HT-7 tokamak and obtained many good results [2,6,7]. However, the key issue for the feasibility of flowing liquid metal surfaces contacted with plasma is their magnetohydrodynamic (MHD) behavior [8]. As a kind of metal, lithium is a good conductor of electric current that self-generate from the liquid motion in the magnetic field which can strongly influence the dynamics and surface shape of the liquid metal flow. In order to analyze the heat removal ability of the liquid lithium served as the PFM and its stability under high heat loads and high intensity of magnetic field, the EAST LLL will be installed in the EAST tokamak to take part in the next physical experiment campaign. By contrast with the experiment results of the HT-7 LLL without CPS, the function of liquid lithium confinement of the CPS can be tested. Besides, the physical mechanism of lithium erosion and the improvement of plasma confinement after the lithium application are aimed to be studied. In this paper, the engineering design and basic engineering tests of one kind of EAST LLL is introduced.

2. Mechanical design of the EAST LLL

2.1. Main parameters of EAST LLL

The LLL will be installed in the H port of EAST tokamak, and in order to enhance the maintainability of the limiter, a maintenance box is designed which is arranged in the outside of the EAST vacuum vessel (VV) and connected with the H port flange by a gate valve (CCQ-500). During the maintenance phase, the limiter can be assembled or disassembled and mended in the box. After that, the box would be sealed and pumped to the vacuum about 10^{-5} Pa, the LLL would be heated to nearly 300 °C to outgas and at last the limiter can be transported by its drive system into the VV to its working position. As confined by the nominal diameter of the valve, the size of the limiter should be special designed and optimized. In order to avoid collision, 25 mm clearances between the EAST LLL parts and the port are necessary. Once the outline dimensions of the limiter were decided, the weight of the limiter, the size of the CPS and the weight of lithium contained in the CPS were calculated after. The main parameters are shown in Table 1.

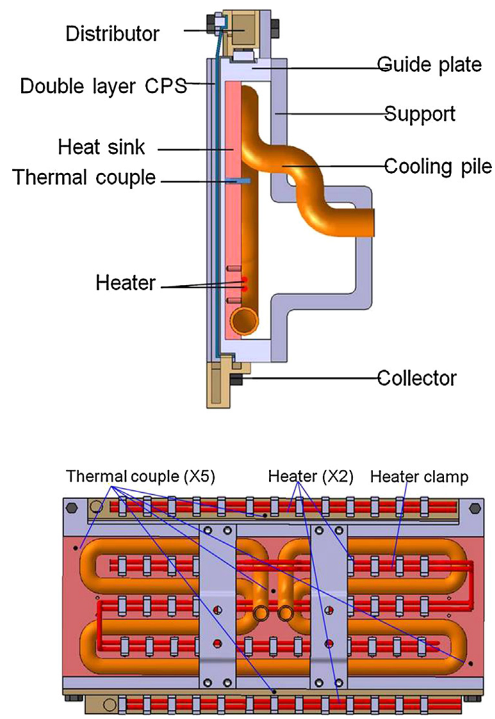

Fig. 1. General view of the EAST LLL.

2.2. Main structure design

Fig. 1 shows the structure of the limiter which includes six main parts: the distributor, the guide plate, the cooling pipe, the heat sink, the collector and its support. On the distributor, there are 168 little overflow holes with the diameter of 1 mm arranged in the length direction, the liquid lithium is injected from the inlet pipe which connects the distributor and the lithium supply system of the EAST LLL. As all the holes have the same diameter and are arranged in the same height level, the liquid lithium can cover the guide plate's surface uniformly when overflowing from the above holes. The distributor is connected with the guide plate with bolts that can be disassembled conveniently and replaced with other ones (with different overflow hole design) easily which improves the utilization ratio of the device. During the discharge phase, the limiter's surface would be working under large thermal load of heat flux caused by the particle bombardment and plasma radiation. To keep the liquid lithium in the distributor and collector especially on the surface of the guide plate in 230–550 °C, the active cooling system is designed. The thickness of the guide plate is 2 mm which is connected with a 7 mm thickness heat sink by welding. A cooling pipe is vacuum brazed to the heat sink to cool the liquid lithium layer indirectly. To avoid point discharge, all the edges of the guide plate are replaced with transition filets.

The whole structure is heated by the armored heaters, and based on the experience got on HT-7 LLL experiments, the heaters were easily damaged. Although it's possible to repair the LLL during plasma operation by withdrawing the limiter into the maintenance box and closing the gate valve, however, the safety of the heating system is well considered during its design. To prevent the EM force from tearing the heaters, clamps are used to fix two sets of heaters on the sink parallel. During the operation phase of the LLL, only one set of the heaters is used and the other is the spare one. To improve the security of the heating system, the guide plate, distributor and collector are heated separately. Five thermal couples are installed on the limiter to measure the liquid lithium's temperature and three of them are located on the diagonal line of the guide plate. Except for the heat sink and cooling pipe that are made by CuCrZr which has good performance of thermal conductivity, all of the other parts of the LLL are made by stainless steel (SS) 316L.

2.3. CPS design

There are many issues that can occur with the application of liquid lithium in tokamak which are the liquid lithium splashing caused by J × B force during MHD instabilities and disruptions as well as temperature monitoring and controlling of the limiter to prevent the lithium evaporation under heat load [1]. The most progressive method to solve the above problems is using the CPS. In recent years, the CPS has been applied on many tokamaks (T-11M, FTU, T-10, HT-7 and et al.) successfully and the advantages of liquid lithium to be the PFM were realized and the problems of their application were overcome [9,10]. The surface tension force of the liquid lithium being in the capillary channels is the main reason that can make it resist the EM force during the plasma disruption event.

Based on the Young–Laplace equation, the capillary pressure P_c is expressed as:

$$P_C = \frac{2\gamma(T)\cos\theta}{R}$$

where θ: the edge-wetting angle; γ: the surface tension of lithium; R: the radius of the capillary channel. Compared with other alkalis, lithium has the highest surface tension value which reaches to 406 mN/m at melting temperature, and the high surface tension of lithium really play an important role in its high capillary pressure [9]. When the liquid lithium upward flowing in the channel, P_c is the driving force of the flowing, while, the gravity and the viscosity resistance impede it. As lightweight metal, lithium has a low density which benefits for its flowing in capillary channels.

The condition that the liquid lithium is supplied continuously and steadily on the CPS surface can be expressed as: $P_c \geq \Delta P_L + \Delta P_G + \Delta P_F + \Delta P_{MHD}$, where P_c is CPS capillary pressure; ΔP_L is the hydraulic pressure drop in CPS, ΔP_G is the hydrostatic pressure drop; ΔP_F is the pressure drop on evaporating surface due to liquid–vapor phase transition; ΔP_{MHD} is the pressure due MHD effect [10]. In addition to lithium restraining, the other key issue of the CPS is thermal removal which is realized by the flowing of lithium in it. Minimizing the pore size of the CPS can increase its capillary pressure; however, little pore size decreases the flow ability of lithium at the same time. Available minimum pore size on the surface of the CPS and sufficiently large pores in the body is the major principle for the CPS application. In this design, two layers of CPS mesh are used which covered the surface of the guide plate. The outer layer is a 1 mm thick CPS made by SS fiber with the effective pore radius of 50 um, which has the capillary pressure of 1.5×10^4 Pa. The capillary pressure of the CPS with effective pore radius of 50 μm is significant higher than the sum of the forces that splash the lithium from the CPS which satisfies the demand for the EAST LLL design. The inner layer is a 1 mm CPS mesh with effective pore radius of 100 μm, which provides the sufficient low hydraulic resistance (Fig. 2).

3. Analysis of the coolant's thermal and hydraulic performance

The EAST LLL works under two different working conditions: the preparation phase and the operation phase. Temperature is the key parameter that should be paid attention to. The main characters of the limiter are shown in Table 2. In the preparation phase, the limiter is heated by the heaters and the coolant is not working. Using thermal couples to monitor the temperature on the guide plate's surface, and maintaining it at 230 °C to make the lithium melted and flowed on the limiter. In the operation phase the temperature of the limiter is maintained in the range of 230–550 °C by using the coolant to remove the thermal load of heat flux from the plasma radiation and particle bombardment.

Table 2
EAST LLL working condition.

Characteristic	Value
Power of heater	~700 W
Heat flux	0.1–1 MW/m^2
Plasma duration	≥5 s
Initial temperature	230 °C
Operation temperature	230–550 °C

In large fusion (experimental) device whose PFM is lithium, water is prohibited to be used in its cooling system which can react with lithium violently and has the possibility to cause explosion. The liquid lithium experiment on EAST is a small scale lithium application and the cooling water with inlet temperature of 25 °C can be chosen as the coolant. The cooling pipe applied on the limiter has 1.35 mm wall thickness with the inner diameter of 10 mm. To ensure the temperature uniformity on the surface of the guide plate, the pipe is arranged on the heat sink uniformly. The hydraulic performance of the limiter should be satisfied with the following design requirements: the pressure drop of the coolant is less than 0.05 MPa to decrease the power consumption of the pump; the temperature difference of the coolant between the inlet and outlet area is less than 40 °C to ensure the uniformity of the temperature on the guide plate so that the thermal stress of the LLL can be controlled. Compared with laminar flow, the turbulent flow which is planned to be used in this design has better performance in terms of cooling for its larger convective heat transfer coefficient. With the flow rate of the cooling water increasing, the flow state of cooling water in the pipe turns from laminar flow to turbulent flow. However, increasing the rate flow can aggravate the corrosion of the pipe's inner surface caused by the flowing fluid accordingly. Besides, high flow rate causes large flow resistance of the pipe which increases the power consumption of the cooling pump. In engineering, the velocity of water between 1 m/s and 7 m/s is commonly used.

3.1. Analysis of the peak temperature of the limiter

By using ANSYS software the peak temperature of the limiter under different values of heat flux with a serious of current velocities were simulated. In the hydraulic-thermal coupled analysis, the heat flux was applied on the surface of the guide plate to simulate the heat load on the limiter caused by the plasma operation. During the operation phase of EAST tokamak, the plasma discharge is excited intermittently; the maximum values of temperature gotten from the steady thermal-hydraulic analysis have large safety margin. The steady analysis results are shown in Fig. 3.

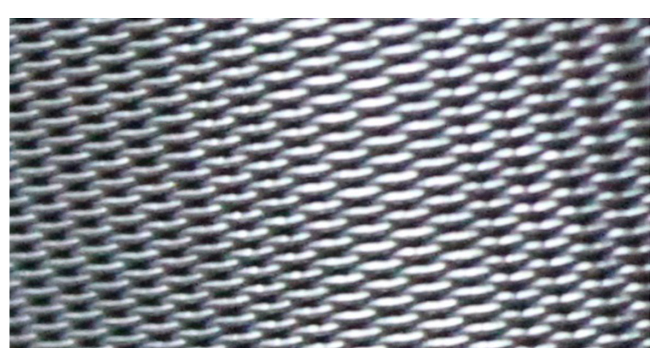

Fig. 2. Microstructure of the CPS used in EAST LLL design.

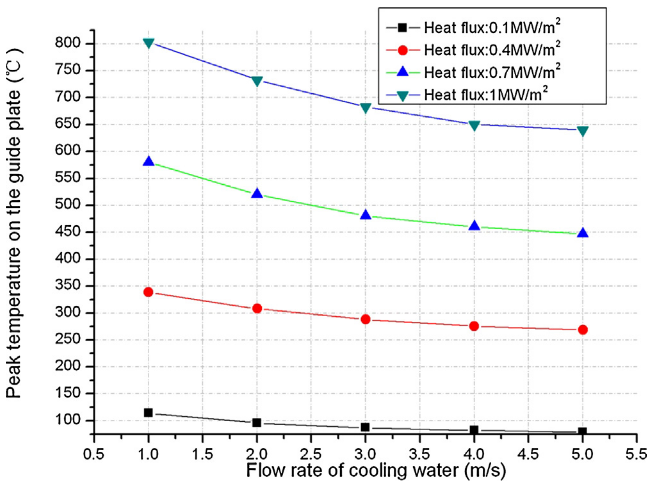

Fig. 3. Maximum temperature of EAST LLL under different flow rates.

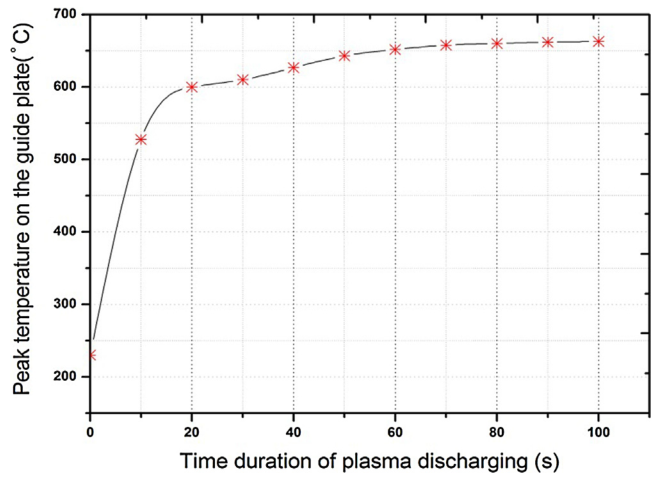

Fig. 5. Dynamic response of the temperature (heat flux = 1 MW/m^2, v = 3 m/s).

If the heat fluxes are lower than 0.7 MW/m^2, the peak temperature of the limiter is always lower than 550 °C, which means that no matter how long the plasma duration is, the liquid lithium limiter would be in safe condition. The slopes of the lines are very small which indicates that the thermal performance of the cooling water has little relationship with their flowing velocity. The velocity of the coolant was defined as 3 m/s preliminarily. As the maximum heat flux exerted on the surface of the limiter during EAST operation is 1 MW/m^2 which restrains the stability and safety of the limiter, the temperature distribution on the LLL and its dynamic response should be paid attention to.

The temperature distribution of the LLL under the cooling velocity of 3 m/s and heat flux of 1 MW/m^2 is shown in Fig. 4. Confined by its structure there is a large distance between the cooling pipe and the upper limb of the plate where the heat concentrated, and the peak temperature is 662 °C. However, except for the edge area the uniformity of the temperature is quite good on the whole guide plate which indicates that the cooling channel design is acceptable.

Realizing the changing process of the maximum temperature on the guide plate is essential for the control system design. Before the peak temperature of the guide plate reaches to 550 °C, it must be moved away from the plasma. The transient thermal analysis result of the LLL is shown in Fig. 5.

The peak temperature of the guide plate rises rapidly under the heat flux of 1 MW/m^2 and stabilizes in 80 s. Within 7 s, the peak temperature of the guide plate is lower than 550 °C, which means that the operation period of the limiter should be limited in 7 s.

3.2. Temperature rise and pressure drop of cooling water

The parameters of the cooling pump especially for its power relate to the pressure drop of the coolant after flowing through the limiter. On the cooling pipe there are 20 ninety-degree elbows and

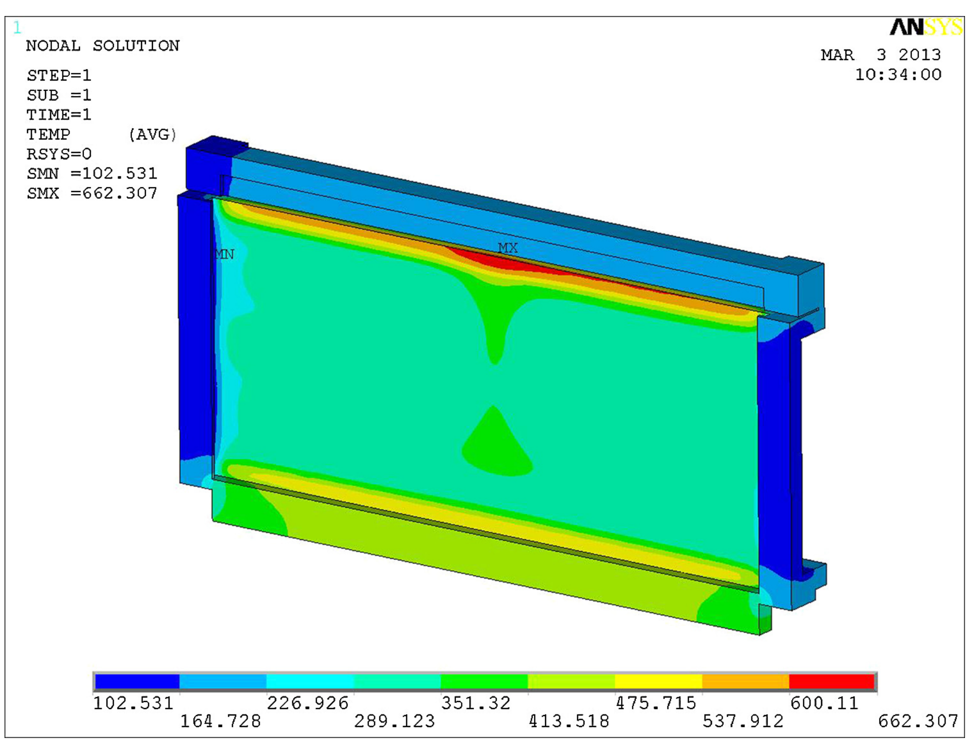

Fig. 4. Steady temperature distribution of the LLL (heat flux = 1 MW/m^2, v = 3 m/s).

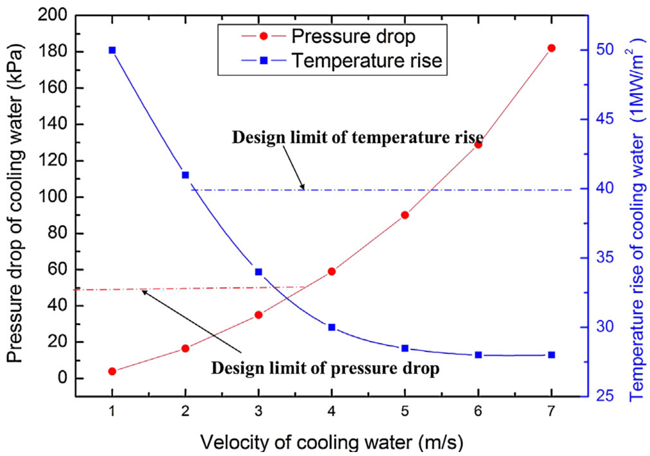

Fig. 6. Thermal and hydraulic performance of the limiter.

no change of diameter. In addition to the frictional resistance loss, the local head loss at the elbow area is another important reason for the pressure drop. The pressure drop for the coolant can be calculated as:

$$\sum h_f = \lambda \left(\frac{l + l_e}{d}\right) \frac{u^2}{2g}$$

where λ, l, l_e, d are the flow resistance coefficient, length of straight part of the pipeline, equivalent length of the elbow pipe, the inner diameter of the cooling pipe; u is the velocity of cooling water. The relationship between the coolant's pressure drop and temperature rise of the limiter is shown in Fig. 6.

By increasing the velocity of the cooling water, the temperature rise of it turns to small, and this tendency become to gentle when the velocities exceed 5 m/s, while, the fluid resistance rose sharply. With the velocity of 3 m/s, the pressure drop and temperature rise of the cooling water meet the design requirements very well. At last, the water with velocity of 3 m/s was confirmed to be used for EAST LLL cooling system.

4. Fabrication and preliminary test of the LLL prototype

4.1. Final fabrication process and main assembly techniques of the LLL

The final assembly process of the limiter was divided into three main steps: the bonding process, the clamping process and the cleaning process.

The welding connection between the heat sink and the guide plate was one of the most important processes during the final fabrication of the limiter. For this welding, the most difficulty is the difference of the physical properties between the two materials. As the coefficient of thermal conductivity of the copper is quite large, high temperature is necessary during the fusion welding process which could burn off the SS. Besides, the coefficient of linear expansion of copper is larger than that of SS, large deformation and crack are easy to happen when the weld joint is being cooled down. For the limiter, the quality of the weld joint affects the heating and cooling efficiency of the heat sink to the guide plate. Diffusion bonding and vacuum brazing are two methods that can be applied to the limiter. For cost consideration, the vacuum brazing was chosen at last. Before the vacuum brazing, the bonding surfaces of the guide plate and the heat sink were electroplated with nickel. Silver-base brazing filler metals were inserted into the guide plate and the heat sink, and the clearance between the two surfaces was less than 0.05 mm. The workpieces were placed into the furnace horizontally with vacuum of 6×10^{-3} Pa. The operating temperature was close to 800 °C with soaking time nearly 15 min, after that the workpieces were cooled to room temperature with the furnace.

In the clamping process, the CPS was mounted on the guide plate by using the collector and the distributor. The CPS must be close contact with the surface of the guide plate to speed up the CPS heating process. Spot welding was used as an auxiliary technical mean during the CPS installation to ensure the above requirement (Fig. 7). To prevent the CPS from loosing, the heaters were installed prior to the CPS to reduce the effect on the CPS fixing area. The oil contamination on the limiter especially on the CPS affects the infiltration of the liquid lithium significantly. When the final assembly

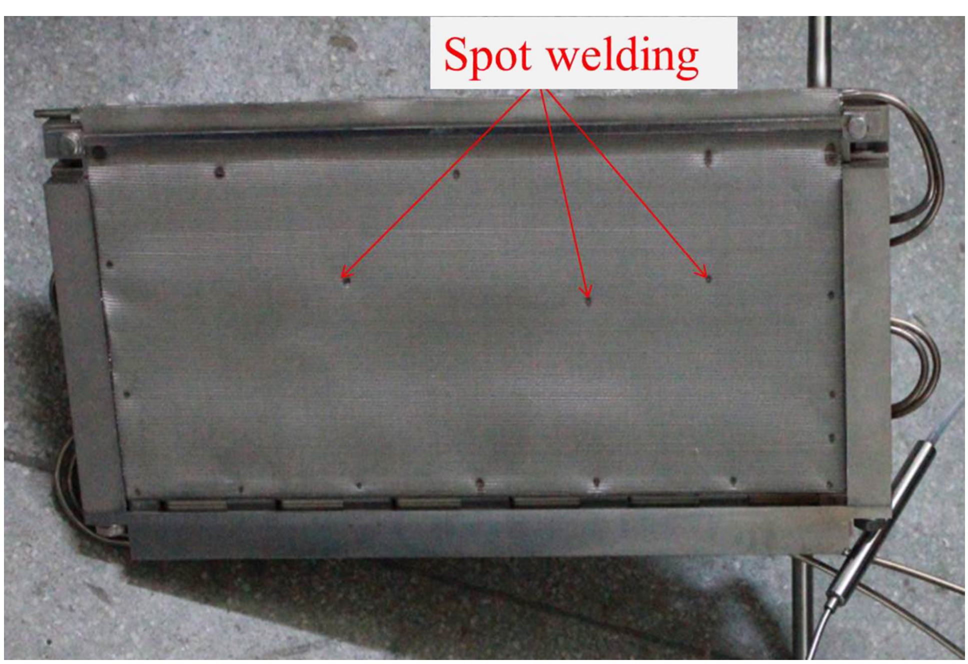

Fig. 7. Prototype of EAST LLL based on CPS.

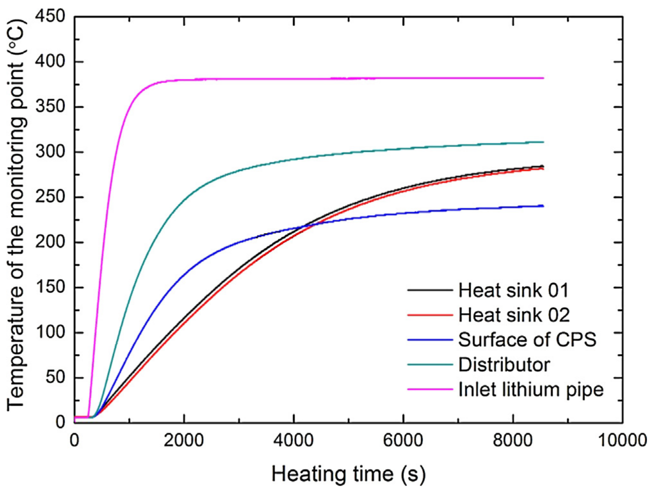

Fig. 8. Result of temperature increasing processes of different positions.

was finished, the whole limiter was performed with soak cleaning in alcohol.

4.2. Heating test on the test bench

For the LLL, the distribution uniformity of liquid lithium in the CPS during plasma discharge is the main requirement for its engineering design. Otherwise, the naked area where exposed to plasma without lithium protection would be ablated. The temperature distribution on the LLL especially on the CPS surface is one of the key factors to propel the lithium distributed uniformly on the LLL surface. As the CPS is mainly heated by the heat sink indirectly, the heating process of the CPS is slow and its maximum temperature is lower than that on the heat sink theoretically. As the temperature of the CPS should be kept higher than 230 °C, the temperature difference between the heat sink and the CPS is expected as little as possible, otherwise the heat sink must be heated to a very high temperature. If the heater is working under high heating power and temperature, the lifetime of it would be reduced evidently.

In order to reveal the heating property of the LLL, after final assembly, the EAST LLL was installed in the vacuum vessel of the test bench to do the heating test (Fig. 8). The vacuum of the vacuum vessel was kept under the level of 10^{-4} Pa to prevent the whole LLL components from oxidation. In the heating test, the spare heater on the heat sink was also used to keep each of the heaters working under low electrical parameters, and for the two heaters the currents were adjusted to 3.6 A with voltage of 100 V. As the inlet lithium pipe was heated separately (3.2 A, 100 V) and had a simple structure, the temperature of the pipe increased very fast. Two thermocouple channels on the heat sink were used in the test, whose results had a good coincidence during the whole heating period. The above two channels indicated that, the temperature had a good homogeneity on the heat sink. Contributed by the heat loads from the collector and the distributor, at the beginning of the heating process, the temperature of the CPS increased faster than the heat sink and this superiority disappeared after about 7 min. After 2.2 h, all the parts of the LLL reached their equilibrium temperatures and the results showed that the temperature difference between of the CPS and the heat sink was less than 50 °C. Good heating performance of the EAST LLL was verified through the heating test on the test bench.

5. Conclusion

EAST is an important fusion experimental device aims to the plasma physics study especially in the fields of long pulse and H-mode operation. As lithium can increase the parameters of plasma and improve the plasma confinement, lithium is planned to apply to EAST in the next physical campaign. LLL which can supply fresh liquid lithium flow to contact with plasma is being designed and will be installed in the H port of EAST tokamak in 2014.

To solve the MHD issues of the liquid lithium application, CPS is adopted to improve the lithium confinement during the LLL operation. The heating removal performance of the LLL is really important for the safety of the system, which was simulated with ANSYS software. Based on the results, the equilibrium temperature of the limiter could be lower than 550 °C under the heat flux lower than 0.7 MW/m^2, and under 1 MW/m^2 heat load, the limiter should be retreated to non-working position within 7 s to protect it from erosion. Hydraulic analysis shows that, the pressure drop and temperature raise of the coolant meet the design requirement very well. For the manufacturing and assembly, the key technologies are the weld connection between the heat sink and the guide plate with different materials and the assembly of the CPS. Vacuum brazing was adopted to do the welding and point welding was performed to assist the CPS assembly. The heating performance of the limiter is important for the lithium distribution and flowing in the CPS, and the preliminary test showed that the CPS can be heated efficiently by the heat sink. The lithium infiltration and flow test on the test bench will be started soon in 2014.

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