Numerical Simulation of Heat Transfer Characteristics between Liquid Lithium Lead and Oil

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Abstract. The liquid LiPb experimental loop is an essential device for studying the compatibility of LiPb with structural materials of the fusion reactor. The heat exchanger is one of the most important devices of the LiPb loop, which is used to control the temperature distribution and study the LiPb flow characteristics in the working condition of the LiPb loop. Based on the heat transfer theory, the liquid LiPb experimental loop cooler is designed at first, which is a tube-type countercurrent heat exchanger with YD-300 heat-conducting oil as the coolant. Numerical simulation analysis was carried out to verify the feasibility of the design scheme under the design condition and the normal operation by using the FLUENT software. The results show that the theoretical design parameters are in good agreement with the numerical simulation results and the average concentration deviation is less than 2%. Furthermore, the average volume temperature and film temperature of heat conducting oil under different working conditions are lower than 310°C and 375°C respectively, which indicates that the cooling effect of the LiPb fluid can be realized and the design scheme of the cooler is reasonable.

1 Introduction

Nuclear fusion energy is one of the most ideal energy sources for humanity, and has many advantages, such as large release energy, rich resources, environment-friendly, zero carbon emission, etc [1]. As a key component to realizing energy conversion in fusion reactors, liquid LiPb cladding is one of the most promising cladding, which is highly valued by various countries in the world [2-4]. Before the commercial application of fusion energy can be realized, a series of key technical problems of liquid LiPb cladding must be solved, and the liquid LiPb experimental loop is the necessary experimental platform for studying these key technical problems [5, 6]. The FDS team of Chinese Academy of Sciences has continuously carried out the design, construction and experimental research of DRAGON series lithium lead experimental loop for many years, which has carried out a good foundation for the research of liquid lithium lead cladding in China [7-9].

The cooler is the key device to control the temperature distribution of liquid LiPb experimental loop, which has a great influence on the flow velocity and flow rate distribution of LiPb [10]. In the design process of the cooler, many factors should be considered, such as high-temperature corrosion resistance of structural materials, pressure drop of fluid and heat exchange area [11, 12]. According to the classification of coolant, there are three types of coolers for liquid metal loop. The first type is the water cooler. In order to avoid LiPb solidification, a high-pressure water loop or intermediate layer is needed to separate LiPb from water. The second type is the gas cooler. The cooling medium is usually air, helium or carbon dioxide gas, which requires a large heat exchange area. The third type is the oil cooler. As a cooling medium, the heat conducting oil can be well adapted to the higher operating temperature, and the structure of the cooler is simplified, making its design simpler [13].

Based on the design experience of liquid metal loop cooler, a casing type countercurrent cooler suitable for liquid LiPb experimental loop is designed in this paper. The coolant is the heat conducting oil. FLUENT was used to conduct numerical simulation analysis of the cooler's design and different operating conditions. The results show that the theoretical design parameters are in good agreement with the simulation results, the average volume temperature of heat conducting oil and the average temperature of oil film were both within the acceptable range, and the cooler design scheme is feasible.

2 Loop Cooler Design

2.1 Design parameters

The mass flow rate of LiPb in the cooler is 4.33 kg/s. During normal operation, the LiPb inlet temperature and outlet temperature are 700°C and 480°C respectively, and the temperature decreases by 220°C. Heat transfer

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margin should be considered in the design. The design inlet temperature and outlet temperature of LiPb are 700℃ and 420℃ respectively, and the design of temperature drop is 280℃. The thermal power of the cooler is 227.22 kw under the design condition and 178.53 kw under the operating condition.

2.2 Coolant selection

Heat transfer oil YD-300 is selected as the coolant. This type of thermal oil can withstand high temperature and the maximum allowable film temperature is 375℃. It can work for decades at 300℃ or so [14]. To prevent lead - bismuth solidification, the lowest temperature of heat conduction oil in the cooler is 240 ℃ [15]. To meet the design requirements of the cooler, it is assumed that the inlet temperature, outlet temperature and flow rate of the heat conducting oil are 240℃, 280℃ and 3m/s respectively.

2.3 Thermophysical properties of materials

The cooler contains 316Ti stainless steel for the pipe wall, LiPb and heat conduction oil for the fluid inside and outside the pipe. Because the temperature gradient of the three materials is small, the thermal property change caused by the temperature change can be ignored, so the materials all adopt the physical properties at the average temperature. The thermophysical properties of the materials used in this paper are shown in Table 1.

Table 1. Thermal physical properties of materials

Material	LiPb	Oil	316Ti
Density(kg/m^3)	9050.14	730.4	7995
Specific heat(J/(kg·℃))	187.41	2754.6	514.9
Thermal conductivity(W/(m·℃))	18.28	0.1154	18.03
Viscosity (Pa·s)	0.001004	0.00055544	-

2.4 Cooler structure design

The cooler is a serpentine tube heat exchanger. It is advantageous to rely on dead weight to empty internal LiPb fluid. The heat transfer is countercurrent heat transfer, thus improving the heat transfer efficiency [16]. The design process is as follows:

2.4.1 Determination of the pipe section size

In order to reduce the pressure drop of the cooler, the section size of the heat exchange tube is the same as the size of the loop pipe, that is, the outer diameter is 42 mm and the wall thickness is 5 mm. The LiPb flow rate on the side of the pipe is 0.595 m/s. According to the heat balance Equation (1), the mass flow rate of the heat conducting oil is 2.06 kg/s. Since the designed flow rate of heat conduction oil is about 3 m/s, please refer to GB/ T17395-2008 seamless steel tube size, shape, weight and allowable deviation. The outer diameter of the outer pipe should be 65 mm in standard size and 5 mm in wall thickness. The actual flow rate of heat conduction oil should be 2.85m/s.

$$Q = M_1 C_1 \Delta T_1 = M_2 C_2 \Delta T_2 \tag{1}$$

Where, Q is the heat power of the cooler, M is mass flow rate, C is specific heat capacity, ΔT is the temperature difference between import and export, and subscripts 1 and 2 represent LiPb and heat transfer oil respectively.

2.4.2 Calculation of nussel number

Reynolds number and prandtl number of LiPb and heat conduction oil are obtained through Equations (2) and (3). LiPb's nussel number is obtained according to Equation (4), and the nussel number of heat conduction oil is calculated according to Equation (5).

$$Re = \frac{\rho v d}{\mu} \tag{2}$$

$$Pr = \frac{\mu C}{\lambda} \tag{3}$$

$$Nu = 7 + 0.025 \times \left(RePr\right)^{0.8} \tag{4}$$

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \tag{5}$$

Where Re is Reynolds number, ρ is density, ν is velocity, μ is kinetic viscosity, Pr is prandtl number, λ is thermal conductivity coefficient, Nu is nussel number.

2.4.3 Calculation of total heat transfer coefficient

According to Equation (6), the convective heat transfer coefficient of the tube side and shell side is calculated. According to Equation (7), the total heat transfer coefficient of the heat exchange tube is 1721.88kw /(m^2 • ℃).

$$h = \frac{Nu\lambda}{d} \tag{6}$$

$$\frac{1}{K} = \frac{1}{h_1} + \frac{\delta_w}{\lambda_w}\left(\frac{d_i}{\left(d_o - d_i\right)/\ln\left(d_o/d_i\right)}\right) + \frac{1}{h_2}\left(\frac{d_i}{d_o}\right) \tag{7}$$

Where h_1 and h_2 are convection heat transfer coefficients on the side of the tube and the shell, K is the total heat transfer coefficient, δ_w is the wall thickness, λ_w is the wall thermal conductivity, d_i and d_o are the inner diameter and outer diameter of the heat exchange tube.

2.4.4 Calculate the heat transfer area

According to Equation (8), the logarithmic average temperature difference is 283.25℃. According to Equation (9), the heat exchange area is 0.466m^2 and the pipe length is 4.64m.

$$\Delta T_{\mathrm{p}}=\frac{\Delta T_{\max}-\Delta T_{\min}}{\ln\left(\Delta T_{\max}/\Delta T_{\min}\right)} \tag{8}$$

$$Q=KA\Delta T_{\mathrm{p}} \tag{9}$$

Where ΔT_p is the logarithmic average temperature difference, ΔT_{max} and ΔT_{min} are the maximum and minimum values of the temperature difference between LiPb temperature and heat conduction oil at both ends of the cooler, and A is the heat exchange area.

According to the above design parameters and considering the rationality of cooler structure, the 4640mm long cooler pipe is designed as a coiled pipe with three straight sections and two curved sections interconnecting with each other. In order to facilitate fluid drainage, 4° inclination angle is set for the straight section. The final design structure is shown in Figure 1. Single straight pipe length is 1026.67mm and elbow radius is 260mm.

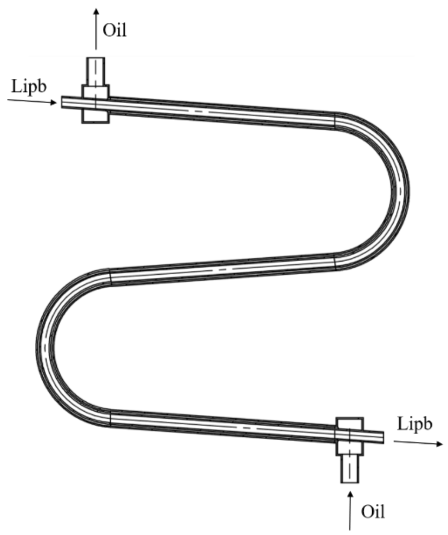

Fig. 1. Structural design of cooler

3 Results and Discussion

3.1 Calculation model and grid generation

In order to optimize simulation results and save calculation time, the cooler model is simplified. The simplified calculation model is shown in Figure 2. Cooler grid division includes LiPb region, solid region and heat conduction oil region. The calculation model has 2629874 calculation units, including 612241 LiPb region, 1182585 solid region and 835048 heat conduction oil region.

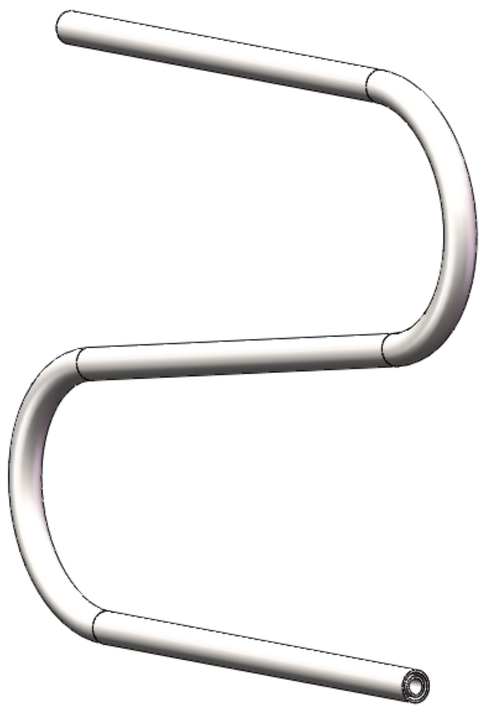

Fig. 2. Geometric model for numerical simulation

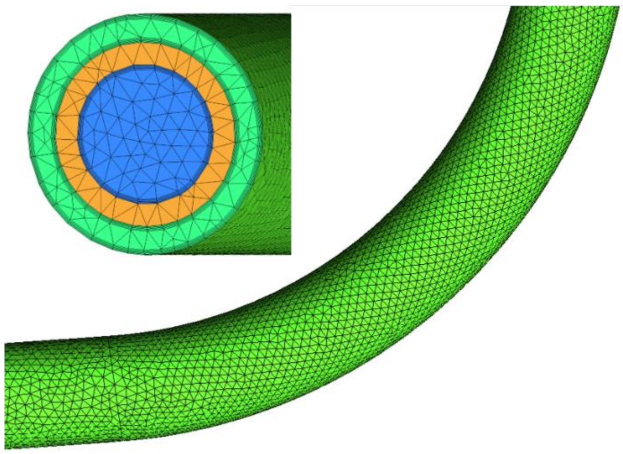

Fig. 3. Mesh generation of model

3.2 Boundary conditions

According to the heat balance Equation (1), the inlet and outlet temperatures of LiPb fluid are different in design and operation conditions, so the flow rate and temperature of heat conduction oil are different in different working conditions. In this paper, the flow rate of heat conduction oil is 2.06kg/s and 1.45kg/s respectively. Theoretical calculation values of cooler temperature and mass flow under different working conditions are shown in Table 2.

Table 2. Thermal physical properties of materials

Case	LiPb			Oil		
	Inlet tempetature(℃)	Outlet temperature(℃)	Flow rate (kg/s)	Inlet tempetature (℃)	Outlet temperature (℃)	Flow rate (kg/s)
Design case	700	420	4.33	240	280	2.06
Operation case1	700	480	4.33	270	301.46	2.06
Operation case2	700	480	4.33	250	294.7	1.45

CFD simulation of fluid flow under different working conditions was carried out with the standard k-epsilon turbulence model. The boundary condition was the boundary outlet of mass flow inlet pressure. The values of mass flow rate and inlet temperature were shown in Table 2. All the walls were set as non-slip walls, all the walls except the heat conduction wall were adiabatic, and the heat conduction wall was set as coupled wall, so that LiPb fluid could transfer heat outward through the wall.

3.3 Analysis of simulation results

The comparison results between the simulation parameters and theoretical calculation values of the cooler are shown in Table 3. The results show that the simulation results are in good agreement with the theoretical results, the relative deviations of temperature and heat transfer coefficient are below 2%, and the cooler design scheme is reasonable.

Table 3. Comparison between simulation results and theoretical results

Parameter		Design case	Operation case1	Operation case2
LiPb	Inlet tempetature (℃)	700	700	700
	Outlet temperature (℃)	421.2	480.8	478.6
	Simulation temperature difference(℃)	278.8	219.2	221.4
	Theoretical temperature difference (℃)	280	220	220
	Relative difference	0.43%	0.36%	0.64%
Oil	Inlet tempetature (℃)	240	270	250
	Outlet temperature (℃)	279.3	300.9	294.2
	Simulation temperature difference (℃)	39.3	30.9	44.2
	Theoretical temperature difference (℃)	40	31.46	44.7
	Relative difference	1.75%	1.78%	1.12%
Overall heat transfer coefficient	Simulation result(W/m²·℃)	1724.46	1726.37	1553.15
	Theoretical result(W/m²·℃)	1721.88	1721.88	1546.42
	Relative difference	0.15%	0.26%	0.44%

The 41 observation planes were set at equal intervals along the axis of the cooler to divide the cooler into 40 sections. The distribution of the average temperature of the set plane along the axis of the cooler was observed. The temperature distribution curve of LiPb and heat conduction oil along the axis of the cooler under different working conditions is shown in Figure 4. The temperature of LiPb fluid decreases linearly from the inlet to the outlet along the axis of the cooler, while the temperature of heat conduction oil increases linearly, which conforms to the basic law of heat transfer. The distribution curve of heat exchange tube outer wall temperature along the cooler axis under different working conditions is shown in Figure 5. This temperature is also known as oil film temperature. Under the three conditions, the maximum volume temperature of the heat transfer oil is lower than 310℃, and the oil film temperature is lower than 375℃, which is the maximum allowable film temperature. Therefore, LiPb fluid in the loop pipe can be cooled.

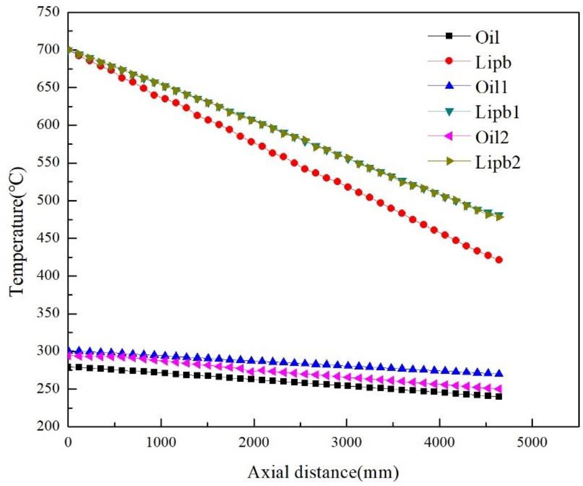

Fig. 4. Fluid temperature distribution in axial direction of cooler under different working conditions

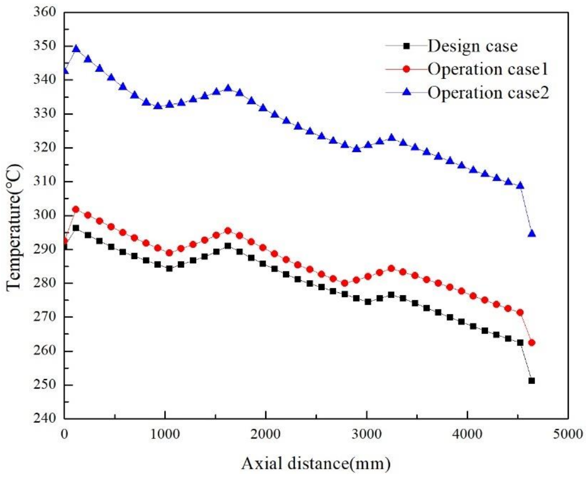

Fig. 5. The temperature distribution on the outside wall of heat exchange tube in the axial direction of the cooler under different working conditions

4 Conclusions

In this paper, the cashing oil cold heat exchanger for the LiPb experiment loop was designed. Numerical simulation and analysis are carried out under design conditions and different operation conditions to verify the reasonability of the cooler design parameters. The results show that the numerical simulation results are in good agreement with the theoretical calculation results, the relative deviation between the outlet temperature of the fluid and total heat transfer coefficient is less than 2%. The average volume temperature and oil film temperature of the heat conduction oil under different conditions are below 310 ℃ and 375 ℃ respectively, indicating that the design scheme of the cooler is reasonable.

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References

1. S. Zhou, X. Zhang, Energy, **35**, 4282-4288 (2010).
2. Y. Wu, *Neutronics of Advanced Nuclear Systems* 437-466 (2019).
3. L. Chen, M. Li, M. Ni, N. Zhang, International Communications in Heat and Mass Transfer, **84**, 110-120(2017).
4. Q. Jin, M. Li, S. Liu, W. Wang, Chinese Journal of Nuclear Science and Engineering, **31**, 345-350(2011).
5. Z. Zhu, Q. Huang, S. Gao, Y. Song, C. Li, L. Peng, Y. Chen, Fusion Engineering and Design, **86**, 2666-2669(2011).
6. C. C. Yue, L. L. Chen, K. F. Lyu, Y. Li, S. Gao, Y. J. Liu, Q. Y. Huang, Nuclear Science and Techniques, **28**, 39(2017).
7. S. Huang, Z. Zhu, W. Huang, International Journal of Energy Research, **42**, 2583-2592(2018).
8. F. R. Urgorri, S. Smolentsev, I. Fernández-Berceruelo, D. Rapisarda, I. Palermo, A. Ibarra, Nuclear Fusion, **58**, 106001 (2018).
9. W.Wang, Z. Zhu, S. Gao, J. Li, Q. Huang, FDS Team. Chinese Journal of Nuclear Science and Engineering, **30**, 166-171(2010).
10. H. Y. Wang, X. D. Zhang, Z. Q. Zhu, Journal of Hefei University of Technology (Natural Science), **12**(2011).
11. S. Q. Huang, Q. Y. Huang, S. Gao, Z. Z. Jiang, R. Y. Sa, *Advanced Materials Research*, **724**, 696-702 (2013).
12. T. Romsy, P. Zacha, Fusion Engineering and Design. (2019).
13. B.Garcinuño, D.Rapisarda, I. Fernández-Berceruelo, E. Carella, J. Sanz, Fusion Engineering and Design (2019).
14. M. Zhang, FDS Team, Annals of Nuclear Energy, **80**, 203-206(2015).
15. Q. Sun, T. Peng, Z. Zhou, Z. Chen, S. Wang, Fusion Engineering and Design, **134**, 35-42(2018).
16. B. Gao, M. G. Yang, X. K. Sun, N. Zhang, *Advanced Materials Research*, **588**, 190-193(2012).