Research Article

CFD Analysis of the Passive Decay Heat Removal System of an LBE-Cooled Fast Reactor

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This paper presents capacity of the passive decay heat removal system (DHRS) operated under the natural circulation conditions to remove decay heat inside the main vessel of the Lead-bismuth eutectic cooled Fast Reactor (LFR). The motivation of this research is to improve the inherent safety of the LFR based on the China Accelerator Driven System (ADS) engineering project. Usually the plant is damaged due to the failure of the main pumps and the main heat exchangers under the Station Blackout (SBO). To prevent this accident, we proposed the DHRS based on the diathermic oil cooling for the LFR. The behavior of the DHRS and the plant was simulated using the CFD code STAR CCM+ using LFR with DHRS. The purpose of this analysis is to evaluate the heat exchange capacity of the DHRS and is to provide the reference for structural improvement and experimental design. The results show that the stable natural circulations are established in both the main vessel and the DHRS. During the decay process, the heat exchange power is above the core decay heat power. In addition, in-core decay heat and heat storage inside the main vessel are efficiently removed. All the thermal-hydraulics parameters are within a safe range. Moreover, the highest temperature occurs at the upper surface of the core. A swirl occurs at the corner of the lateral core surface and some improvements should be considered. And the natural circulation driving force can be further increased by reducing the loop resistance or increasing the natural circulation height based on the present design scenario to enhance the heat exchange effect.

1. Introduction

The LFR shows great potential for industrial development due to the excellent transmutation capacity and inherent safety [1]. Motivated by the properties, a lot of research has been performed on the design and application of the LFR, such as SSTAR [2] and SUPERSTAR [3] launched by USA, SVBR-100 [4], and BREST [5] in Russia, MYRRHA [6], and ALFRED [7] designed by the EU, etc. Meanwhile, an engineering project has been launched to develop ADS in China, which consists of the neutron source, the spallation target and the subcritical LFR ($k_{eff} < 1$). Among the components of ADS, the reactivity of the LFR is controlled by the neutron flux intensity, which means the reaction of the LFR cannot be maintained without the neutron flux. The reactor uses lead-bismuth alloy (LBE) as a coolant, and LBE has a high boiling point, which can effectively prevent the problem of core exposure caused by coolant boiling, though, for further development of the ADS, with a focus on the inherent safety of the LFR,

still much work on the inherent safety of the LFR is required.

The occurrence of the Fukushima Nuclear Power Plant accident compelled the researchers to find out the reason to remove the decay heat in the main vessel under the Station Blackout (SBO) [8], though, during the accidental scenario, when the reactor shuts down in emergency, the main pumps and the main heat exchangers stop operating, so that the decay heat is generated continuously, resulting in increasing of the risk of core melting accident. Considering the challenges mentioned above, the DHRS was adopted according to the design of the LFR [9, 10]. Driven by the gravity or natural circulation, the need for power equipment such as pumps or fans can be eliminated in the DHRS; particularly the complication of the nuclear system and the risk due to the improper operation might be reduced.

Many methods have been implemented to evaluate the heat exchange capacity of the DHRS, such as Matlab-Simulink [11], Relap-5, and Relap-3D [12], etc. However,

FIGURE 1: The heat transfer process during the SBO. The main pump and the main heat exchanger stop operation under the SBO condition and the decay heat is transferred to the LBE through the core surface. And the natural circulations occur in both the main vessel and the DHRS to remove the decay heat. The ACS is fully activated after 110s.

most of the results cannot provide the details information for the structural improvement and experimental design. Based on the above conclusions, the CFD [13] commercial code STAR CCM+ was used to simulate the operation of the DHRS under the SBO condition to evaluate the heat exchange capacity. The velocity and temperature distributions of the DHRS were monitored during the simulation. Furthermore, the diathermic oil was selected as a coolant of the DHRS so that the system might operate under the atmospheric pressure and maintain higher heat transfer efficiency [14].

The purpose of this paper is to evaluate the heat exchange capacity and structure design of the DHRS. The relevant information about the design scenario and operation of the DHRS and geometry domain is described in Section 2. In Section 3, the spatial discretization and validation are presented. Section 4 covers the choice of the turbulence model and the properties of the coolant adopted in the DHRS and LFR. And the boundary conditions of the heat sink and core are discussed, too. Using the transient method, the results and discussion are presented in Section 5; particularly the evaluation of the heat exchange capacity and design scenario of the DHRS and the main vessel are discussed.

2. Outline of the DHRS for LFR

The half-pool structure is adopted into the LFR with the 10 MW designed power. Driven by the accelerator, the reactivity coefficient and the temperature reactivity coefficient are negative during the operation. The primary loop of the LFR consists of the main vessel, the main pump, the main heat exchanger, and the main connection pipes. The core uses hexagonal fuel assemblies lying in the main vessel and surrounded by the LBE. About 500t LBE is kept inside the main vessel. Therefore, the main vessel has a considerable heat storage capacity, and the temperature of the LBE rises slowly even during the accidental conditions. The core inlet and outlet temperature are kept 280°C and 380°C, respectively. The core power under the normal operating condition is removed by the pump and the main heat exchanger with the forced circulation. However, the main pump and the main heat exchanger lose power supply and stop operation under the SBO condition, so the coolant flow in the core is greatly weakened. In the simulation, the decay heat is completely transferred through the core surface to the LBE, and the flow heat transfer inside the core is not considered.

The DHRS consists of the auxiliary heat exchanger, the heat sink, and pipelines. The heat transfer process is illustrated in Figure 1. During the operation of the DHRS,

TABLE 1: The specifications of the DHRS fluid domain.

Geometrical parameters	Unit	Diameter	Length
Inlet pipe	m	0.145	3.209
Central pipe	m	0.135	3.010
Bottom(head)	m	0.356	
Heat exchange tubes	m	0.014	2.998
Header	m	0.356	3.102
Outlet pipe	m	0.170	0.050
Heat sink	m	0.170	0.100
Natural circulation height	m		8.000

FIGURE 2: The geometry domain of the main vessel and DHRS. 96 heat exchange tubes are arranged in a triangular distribution.

the reactor core continuously generates decay heat and the LBE in the main vessel is heated. Driven by buoyancy, the LBE floats to the upper main vessel and contacts with the heat exchange tubes of the auxiliary heat exchanger. Thus, the heat is transferred to the auxiliary heat exchanger. And the LBE is cooled and sinks to the bottom of the main vessel. So, a natural circulation is formed in the main vessel. The diathermic oil is selected as the coolant of the DHRS. Meanwhile, the coolant of the DHRS is heated in the heat exchange tubes and a driven force upward is generated in the loop. After floating out of the auxiliary heat exchanger, the diathermic oil enters the pipelines and the heat sink. Then the diathermic oil is cooled and flows back to the auxiliary heat exchanger. Due to the heat transferring occurring in the heat exchange tubes and heat sink, a natural circulation of diathermic oil is formed in the loop of the DHRS, too. Therefore, the decay heat is removed by the natural circulations formed in the main vessel and the DHRS to prevent the temperature of the core from being excessively high.

In this paper, the behavior of the DHRS under the SBO condition is simulated to evaluate the heat exchange capacity. According to the design scenario, four sets of the DHRS are equipped with the LFR and only two sets are used each time. Besides, it is planned to be put into use after the LFR shutdown for 3600s. The design heat exchange power of single auxiliary heat exchanger is defined as $Q_{exchange} = 0.1\text{MW}$. With the constant heat exchange power, a natural

circulation occurs in the loop of the DHRS and the auxiliary heat exchanger inlet temperature is 225°C .

Among the components, the height of the auxiliary heat exchanger is 6.338m. Single auxiliary heat exchanger consists of 96 heat exchange tubes arranged in a triangular distribution with diameter of 0.014m and length of 2.98m. Table 1 shows the specifications of the auxiliary heat exchanger geometry fluid domain. Besides, the height difference between the heat source (heat exchange tubes) and the heat sink (natural circulation height) is also listed in Table 1. For the radial symmetry of the main vessel, only 1/8 of the fluid domain is modeled with two symmetry planes. And the corresponding 1/2 sector of the DHRS is used in the simulation, too. Thus, 1/4th decay heat power is loaded on the core surface in the simulation according to the design scenario. The geometry is illustrated in Figure 2. A simplified model is used instead of the heat sink and the pipelines between the heat sink and the auxiliary heat exchanger in the fluid domain. To match the real pressure loss, the porous medium method was adopted in the heat sink and the settings will be discussed in Section 4.3.2.

3. Spatial Discretization of the Studied Domain

The polyhedral method is adopted to generate the mesh. For the main vessel, the mesh size is set as 0.01~0.02m. The

FIGURE 3: The resistance coefficient and heat transfer coefficient test results for a single heat exchange tube.

surface mesh size of the interface between the main vessel and the auxiliary heat exchanger is the same as that of the auxiliary heat exchanger to ensure the convergence of the simulation and the growth rate is 1.2. Due to the difference of the mesh size between the main vessel and the interface, the main vessel cells increase to 4345227.

As for the mesh scheme of the DHRS, the auxiliary heat exchanger is mainly analyzed. The result calculated with empirical correlation shows that the pressure drop along the heat exchange tubes takes up a great proportion. And the heat inside the main vessel is transferred to the DHRS through the heat exchange tubes; the mesh scheme of the heat exchange tubes has a greater influence on the simulation accuracy. The mesh size of the heat exchange tubes with 0.0015~0.0025m and the $y^+ \geq 30$ is selected. The cells of the single heat exchange tube are 141084, which occupies most of the total cells. The validation results of the mesh scheme for single heat exchange tube are illustrated in Figure 3, the relative error of Nu (heat transfer coefficient) is about 4~10%, and the relative error of f (resistance coefficient) is 2~4%. The mesh size of the rest part is 0.006~0.008m and the pressure drop result of the auxiliary heat exchanger is illustrated in Figure 4. Finally, the cells number of the auxiliary heat exchanger is 7779669. The mesh test results of the DHRS are shown in Figure 5.

The interface between the main vessel and auxiliary heat exchanger is created by imprint method and set as baffle interface to improve the mesh quality [15] ('STAR CCM+ User Guide').

4. Calculation Model

4.1. Turbulence Model. In this study, the Realizable $k-\varepsilon$ model is applied to the main vessel domain and the

FIGURE 4: Pressure drop in channel 1 for various numbers of cells.

FIGURE 5: The mesh test results of the DHRS.

transport equation is illustrated below [15] ('STAR CCM+ User Guide').

$$\frac{d}{dt} \int_V \rho k dV + \int_A \rho k (v - v_\varepsilon) \cdot d\alpha = \int_A \left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \cdot d\alpha + \int_V [f_c G_k + G_b - \rho ((\varepsilon - \varepsilon_0) + Y_M) + S_k] dV \quad (1)$$

$$\frac{d}{dt} \int_V \rho \varepsilon dV + \int_A \rho \varepsilon (v - v_g) \cdot d\alpha = \int_A \left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \cdot d\alpha + \int_V \left[f_c C_{\varepsilon 1} S_\varepsilon + \frac{\varepsilon}{k} (C_{\varepsilon 1} C_{\varepsilon 3} G_b) - \frac{\varepsilon}{k + \sqrt{\nu \varepsilon}} C_{\varepsilon 2} \rho (\varepsilon - \varepsilon_0) + S_\varepsilon \right] dV \quad (2)$$

where S_k and S_ε are user-defined source term and ε_0 is the ambient turbulence value in the source term that counteracts turbulence decay. And f_c is the curvature correction factor. G_k is the turbulent production and G_b is the buoyancy

TABLE 2: The physical model selection.

Models	Passive decay heat removal system	Main vessel
k- ϵ Turbulence models	Standard k- ϵ Low-Reynolds	Realizable k- ϵ
Time	Implicit unsteady	Implicit unsteady
Time step	0.005	0.005
iteration	10	10
Flow	Segerated flow	Segerated flow
Wall treatment	All y+ treatment	All y+ treatment

production. Y_M refers to the compressibility modification. The model coefficient $C_{\epsilon 1}$ is defined as follows.

$$C_{\epsilon 1} = \max\left(0.43, \frac{\eta}{\eta + 5}\right) \quad (3)$$

where $\eta = Sk/\epsilon$, and the rest of the coefficients defining the model have the following values:

$$\begin{aligned} C_{\epsilon 2} &= 1.9 \\ \sigma_k &= 1.0 \\ \sigma_\epsilon &= 1.2 \end{aligned} \quad (4)$$

Compared with the main vessel, the Standard k- ϵ Low-Reynolds model is selected for the DHRS. Standard k- ϵ Low-Reynolds model combines the Standard k- ϵ model with the Low-Reynolds number approach. It provides more damping functions based on the Standard k- ϵ model, which enable the model to be used in the viscous-affected region near the wall. The model is recommended for the natural circulation problem particularly if the Yap correction is invoked.

All y+ treatment is a hybrid treatment that emulates the low y+ wall treatment for the fine meshes and the high y+ wall treatment for coarse meshes. It is also formulated with the desirable characteristic of producing reasonable answers for meshes of intermediate resolution, i.e., when the wall-cell centroid falls within the buffer region of the boundary layer.

Both the Realizable k- ϵ model and the Standard k- ϵ Low-Reynolds model adopt the first-order for the stability of the simulation. For a transient simulation with the physical time of 110s, the time-step is initially set to 1E-4s and the final time-step is stabilized at 0.005s as the iterations increase. And the maximum inner iterations are set to 10. The physical model is illustrated in Table 2. The initial temperature inside the main vessel and the DHRS is set to 401°C.

4.2. The Coolant Properties. The LBE is used as the primary coolant and the properties are referenced to the LBE Handbook [16]. The diathermic oil is selected as the coolant of the DHRS, which makes the DHRS operates under the approximately normal pressure; particularly the system temperature might be controlled accurately. With wide uses and good heat transfer characteristics, the SCHULTZ S750 synthetic diathermic oil is adopted. The diathermic oil properties settings are as follows.

Density [kg/m^3 , K] is

$$\rho = -5 * 10^{-7} * T^3 - 2 * 10^{-5} * T^2 - 0.6706 * T + 1021.8 \quad (5)$$

Thermal conductivity [$\text{W}/(\text{m} * \text{K})$, K] is

$$\lambda = -8E * 10^{-12} * T^3 + 5 * 10^{-9} * T^2 - 9 * 10^{-5} * T + 0.123 \quad (6)$$

Viscosity [$\text{Pa} * \text{s}$, K] is

$$\mu = 9 * 10^{-13} * T^4 - 1 * 10^{-9} * T^3 + 5 * 10^{-7} * T^2 - 1 * 10^{-4} * T + 0.0096 \quad (7)$$

Specific heat [$\text{J}/(\text{kg} * \text{K})$, K] is

$$C_p = 1 * 10^{-8} * T^3 + 0.0013 * T^2 + 3.2548 * T + 1497.4 \quad (8)$$

4.3. Boundary Conditions. The LFR is also equipped with an Air Cooling System (ACS), as shown in Figure 1. The external ACS during the process is started at 0~110s. Due to low thermal conductivity of the gas in the interspace of the double-layer vessel, the boundary condition of the inner wall of the main vessel is regarded as adiabatic in the simulation of 110s. Considering conservation, it is assumed that the heat inside the main vessel is only derived from DHRS during 0~110s. After 110s, the ACS is fully activated and the design heat transfer power is higher than decay heat power. Under the operation of DHRS and ACS, the LFR is considered to be in a safe state. Therefore, the heat transferring after 110s is not simulated. Besides, the analysis domain only contains the fluid region. The conjugate heat transfer between solid and fluid region is not considered in the simulation. The boundary conditions, except the heat exchange tubes and the heat sink, are set to be adiabatic in the DHRS. The heat transfers between the DHRS and the main vessel through the interface.

4.3.1. Decay Heat Power. The decay heat is mainly transmitted through the core surface to the LBE because of the great resistance of the primary loop under the SBO. It is assumed that the decay heat distributes on the core surface uniformly, which is loaded using the surface energy method in the

TABLE 3: The porous media parameter correction results.

The natural circulation height	8m
porosity	1.0
porous inertial resistance (x)	2286620.0kg/m ⁴
porous viscous resistance (x)	41198.29202 kg/m ² * s
volumetric energy source	$\left(\frac{T_{in}}{225}\right) * \left(\frac{-Q_{porous}}{V_{porous}}\right), (Q_{porous} = 44870.693W)$

TABLE 4: The natural circulation results of passive decay heat removal system under the designed heat transfer power.

parameters	CFD results	Design value	Relative error
$T_{in}(^{\circ}C)$	225.079	225.000	0.035%
$T_{out}(^{\circ}C)$	254.517	253.663	0.337%
$M(kg/s)$	1.436	1.484	3.235%

simulation. The decay heat power variation with reference to the following correlation [17] (unit: MW).

$$P = 0.75768 * \left((t + 381.44576)^{-0.2} - (t + 216225000)^{-0.2} + (t + 1.56838)^{-0.2} - (t + 20444.6774)^{-0.2} \right) \quad (9)$$

4.3.2. Heat Sink. A simplified model is used to simulate the heat sink and pipelines. Diathermic oil is cooled by the heat sink. Meanwhile, the porous medium method is applied for the heat sink to match the pressure drop of the actual model. Therefore, the heat sink has a great effect on the stable natural circulation of the DHRS.

The pressure drop of the pipelines and the heat sink under different mass flow conditions was calculated by empirical correlation. To compare the results, the pressure drop between the simplified model and the actual structure is equivalent by the porous media method. The porosity is set as $P_{porosity} = 1$ and the fitting result is as follows.

$$\frac{\Delta P}{\Delta L} = 2286620v^2 + 41198.29202v \quad (10)$$

where $\Delta P/\Delta L$ is the pressure drop per unit length of the porous medium. 2286620 and 41198.29202 correspond to the porous inertial resistance tensor and the porous viscous resistance, respectively. And v is superficial velocity through the porous medium.

According to the design scenario of the DHRS, the heat exchange power loaded on the surface of heat exchange tubes is 0.1 MW and the inlet temperature of the diathermic oil is 225°C. While the flow resistance is equal to the natural circulation driving force, a stable natural circulation is formed inside the loop, which is illustrated as follows.

$$\Delta P_e = \Delta P_d \quad (11)$$

where ΔP_d refers to the friction loss. ΔP_e refers to the natural circulation driving force calculated with the following correlation.

$$\Delta P_e = \Delta \rho g \Delta h \quad (12)$$

where $\Delta \rho$ is the diathermic oil density difference between the inlet and outlet of the auxiliary heat exchanger and Δh refers to the natural circulation height.

Natural circulation driving force is affected by the heat sink power and heat exchange tubes. The heat sink power needs to be adjusted to form the stable natural circulation with the design heat exchange power. However, the heat transfer efficiency is greatly affected by the velocity of the diathermic oil. In the simulation, the volumetric energy source is adopted to the heat sink compared with the surface energy source loaded on the heat exchange tubes, which has a stronger heat transfer effect. Meanwhile, the volumetric energy source is more affected by the velocity. In addition to this, in the process of establishing the natural circulation in the passive decay heat removal system, the velocity of the diathermic oil gradually increases. Besides, the length of heat exchange tubes in the geometric model is much larger than the heat sink. Therefore, compared with the heat exchange tubes, the heat transfer results in the heat sink being greatly different in the numerical simulation. Based on the above considerations, in the natural circulation, the settings of the power for the heat sink should be adjusted to match the design heat transfer power in the heat exchange tubes.

In the simulation, 1/2 sector of the DHRS is used during the simulation. Thus, the surface power of the heat exchange tubes is loaded with the design value $Q_{pipe} = 50000W$. Due to the long length of the heat exchange tubes, it is concluded that the diathermic oil is sufficiently heated while flowing through the tube and flowing out of the heat exchanger at a design temperature and enters the connected pipes. The adjustment results are corresponding to the design heat transfer power under the stable natural circulation. The numerical simulation results are illustrated in Tables 3 and 4. Under the natural circulation condition, the heat sink power is lower than the design heat transfer power, $Q_{porous} = 44870.693W$. The relative error between inlet and outlet temperatures and the design values of the auxiliary heat exchanger is within 1%. The secondary loop of passive decay heat removal system formed a stable natural circulation with a mass flow of $M = 1.436kg/s$ and a relative error of 3.235% from the design value.

FIGURE 6: The comparison between the natural circulation heat transfer power and the decay heat power during the simulation.

5. Results and Discussion

Transient analyses are conducted assuming the SBO after the steady-state conditions at 3600s are calculated using the above-mentioned calculation model, which is used to simulate the decay heat removal process and monitor the thermal-hydraulic characteristics inside the DHRS and the main vessel during 0~110s. The objective of the analysis is to evaluate the heat exchange capacity of the DHRS and provide reference for structural improvement and experimental design. Besides, the maximum temperature of the core surface is monitored, too. The number of DHRS and main container cells is about 13 million, and the simulation calls 48 cores with a duration of 41 days. Simulate the natural heat transfer process of the main vessel and DHRS during 0~110s.

5.1. The Natural Circulation inside the DHRS. Since 500t LBE is kept inside the main vessel, the heat storage is so large that it is difficult to change the temperature of LBE. During the operation of the DHRS from 0s to 110s, the heat transfers through the interface accounts for a small proportion of the total heat storage inside the main vessel and has a less effect on the temperature variation of the LBE. The heat exchange power is stable at about 44900W, which indicates the stability of the natural circulation inside the DHRS. The comparison between the heat exchange power and the decay heat power is illustrated in Figure 6. The decay heat power changes nearly linearly during the transient simulation, which is 43648.66W at 0s and decreasing to 43254.53W at 110s. The heat exchange power is 2.73%~3.82% higher compared with the decay heat power. Therefore, the heat storage inside the main vessel is continuously removed by the stable natural circulation even for a small proportion of the total heat storage.

The heat exchange is not considered except for the heat sink and heat exchange tubes in the DHRS. The stable temperature distributions of the DHRS under the natural circulation

FIGURE 7: The steady temperature distributions of the DHRS under the natural circulation.

are illustrated in Figure 7. The diathermic oil at the heat exchange tubes is gradually heated by the heat transferred from the interface, and the temperature rises from 186.94°C to 217.22°C. Afterwards it flows into the upper header because of the buoyance and enters the pipelines and heat sink. The diathermic oil is cooled while flowing through the heat sink, resulting in the increase of density, and then flows back to auxiliary heat exchanger again. The steady velocity distributions of the DHRS under the natural circulation are illustrated in Figure 8. The temperature difference between the inlet and outlet of the auxiliary heat exchanger is about 30°C. Since the heat exchange occurs at the heat exchange tubes and heat sink, a natural circulation is formed in the loop of the DHRS. The heat sink power is corresponding to the design power $Q_{exchange} = 0.1\text{MW}$ under the natural circulation condition, and the decay heat power continues to attenuate during the simulation. Therefore, a large safety margin is kept in the DHRS under the SBO conditions.

The natural circulation mass flow rate of the DHRS during the period of 0~110s is illustrated in Figure 9. The heat exchange power illustrated in Figure 6 is stable at 44900W, resulting in the natural circulation with a very small variation range occurring in the loop of the DHRS. The mass flow is 1.432kg/s in the loop. Considering a large heat storage remains inside the main vessel, the natural circulation driving force can be further increased by reducing the loop

FIGURE 8: The steady velocity distributions of the DHRS under the natural circulation.

FIGURE 9: The natural mass flow in the loop of the DHRS. It is stable at 1.432kg/s during the simulation.

resistance or increasing the natural circulation height based on the design scenario. Moreover, the mass flow rate in the loop can be increased to enhance the heat exchange effect.

5.2. The Main Vessel. The velocity profile of the LBE inside the main vessel is illustrated in Figure 10. The overall velocity of LBE is low and is in the range of 0.01 m/s to 0.03 m/s. Compared to the upper surface of the reactor core, the coolant near the lateral surface velocity is higher, i.e., about 0.05 m/s, due to the stronger heat transfer effect. Due to the influence of the calculation domain, the velocity near the center axis is the maximum at 0.06m/s. According to the design scheme, the coolant velocity under the natural circulation is in the safe range. As the core generates the decay heat continuously, the LBE near the surface is heated and floats to the upper

main vessel. Then the heat is transferred to the heat exchange tubes, resulting in the density increase of the LBE and sinking. A clear natural circulation occurs in the upper main vessel according to the velocity distributions, while the rest of the coolant flow direction is disordered. Besides, a swirl occurs at the corner of the lateral surface, which causes a certain loss of the natural circulation mechanical energy in the main vessel. Due to the poor natural circulation mechanical energy, some improvements such as the chamfer can be considered.

The temperature of the LBE in the main vessel varies with the height of the main vessel illustrated in Figure 11. The bottom of the main vessel is set as $y=0$, the core height is 2.345 m, and the height of the main vessel is 3.805 m. The average temperature of LBE on the bottom of the main vessel is about 220°C and the one of the upper chamber is 232°C . The temperature difference of 12°C leads to a density difference $\Delta\rho = 15.88\text{kg/m}^3$, which is also the reason for the formation of a weak natural circulation in the main vessel. Besides, the temperature range of the LBE near the lateral core surface varies from 220°C to 229°C and that near the upper core surface varies from 229 to 232°C . The temperature gradient of the coolant near the lateral surface is higher than that near the upper surface, resulting in an increase in the flow rate of the LBE near the lateral surface and the heat transfer effect is significantly enhanced. The heat can be transferred to the coolant efficiently.

The temperature distributions of the upper core surface and lateral core surface are illustrated in Figures 12 and 13. Due to the poor heat transferring, the upper core surface temperature varies from 236°C to 255°C . Comparing with the upper surface, the average temperature of the lateral surface is 238°C and the local maximum temperature near the upper surface is 249°C . The maximum temperature profile of the core surface is illustrated in Figure 14. As the sufficient heat storage capacity is kept inside the main vessel and the results are illustrated only from 0s to 110s, the heat transferred to the DHRS during the simulation is very small relative to the total heat storage inside the main vessel. The core surface temperature varies very little during the transient simulation. The maximum temperature of the core surface at 0s is 259.24°C . However, with the formation of the natural circulation, the surface temperature of the core is gradually derived through the LBE, resulting in the decrease and the maximum core surface temperature being 259.23°C at 110s. According to the trend which is shown in Figure 14, the maximum temperature of the core surface is inside the safe range and a large safety margin is left during the operation of the DHRS.

6. Conclusions

In the present study, decay heat removal capacity has been evaluated with the CFD commercial code STAR CCM+ when the DHRS is implemented with the LFR. As a result, the following conclusions are drawn.

- (1) A stable circulation occurs inside the DHRS. The heat exchange power is stable at about 44900W, which is

FIGURE 10: The LBE velocity distributions inside the main vessel. A swirl occurs at the corner of the lateral core surface.

FIGURE 11: Temperature variation of LBE at different heights in the main vessel.

2.73%~3.82% higher compared with the decay heat power. The heat storage inside the main vessel can be removed efficiently. The diathermic oil temperature varies from 186.94°C to 217.22°C and the mass flow is 1.432kg/s in the loop during the simulation.

- (2) A clear natural circulation occurs in the upper main vessel. The overall velocity of LBE is low in the range of 0.01 m/s to 0.03 m/s and that near the lateral surface

FIGURE 12: The temperature distributions of upper core surface(110s).

reaches to 0.05 m/s. The velocity under the natural circulation is within the safety range. The maximum core temperature occurs on the upper surface at 255°C. The maximum temperature of the core surface is within the safe range and a large safety margin is left during the operation of the DHRS.

- (3) Considering that a large heat storage remains inside the main vessel, the natural circulation driving force can be further increased by reducing the loop resistance or increasing the natural circulation height

FIGURE 13: The temperature distributions of the lateral core surface(110s).

FIGURE 14: The maximum temperature of the core surface during the simulation.

based on the design scenario to enhance the heat exchange effect. A swirl occurs at the corner of the lateral surface and some improvements such as the chamfer can be considered.

Data Availability

(i) Reference for the SCHULTZ S750 synthetic diathermic oil is available at <https://github.com/maojiarun/SCHULTZ-S750-synthetic-diathermic-oil.git>. (ii) The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

- [1] H. U. Wider, J. Carlsson, and E. Loewen, "Renewed interest in lead cooled fast reactors," *Progress in Nuclear Energy*, vol. 47, no. 1-4, pp. 44–52, 2005.
- [2] C. F. Smith, W. G. Halsey, N. W. Brown, J. J. Sienicki, A. Moiseyev, and D. C. Wade, "SSTAR: the US lead-cooled fast reactor (LFR)," *Journal of Nuclear Materials*, vol. 376, no. 3, pp. 255–259, 2008.
- [3] S. Bortot, A. Moiseyev, J. J. Sienicki, and C. Artioli, "Core design investigation for a SUPERSTAR small modular lead-cooled fast reactor demonstrator," *Nuclear Engineering and Design*, vol. 241, no. 8, pp. 3021–3031, 2011.
- [4] A. V. Zrodnikov, G. I. Toshinsky, O. G. Komlev et al., "Innovative nuclear technology based on modular multi-purpose lead-bismuth cooled fast reactors," *Progress in Nuclear Energy*, vol. 50, no. 2–6, pp. 170–178, 2008.
- [5] G. Yu, V. V. L. Dragunov, A. V. Moiseyev, and V. S. Smirnov, "Lead-cooled fast-neutron reactor (BREST)," in 16th LFR Prov. SSC Meeting. 2014: Heifei, China".
- [6] H. Ait Abderrahim, P. Baeten, D. De Bruyn, and R. Fernandez, "MYRRHA - A multi-purpose fast spectrum research reactor," *Energy Conversion and Management*, vol. 63, pp. 4–10, 2012.
- [7] G. Grasso, C. Petrovich, D. Mattioli et al., "The core design of ALFRED, a demonstrator for the European lead-cooled reactors," *Nuclear Engineering and Design*, vol. 278, pp. 287–301, 2014.
- [8] H. Mochizuki and T. Yano, "A passive decay-heat removal system for an ABWR based on air cooling," *Nuclear Engineering and Design*, vol. 311, pp. 35–42, 2017.
- [9] L. Cinotti, C. F. Smith, H. Sekimoto, L. Mansani, M. Reale, and J. J. Sienicki, "Lead-cooled system design and challenges in the frame of Generation IV International Forum," *Journal of Nuclear Materials*, vol. 415, no. 3, pp. 245–253, 2011.
- [10] S. C. Chetal, V. Balasubramanian, P. Chellapandi et al., "The design of the Prototype Fast Breeder Reactor," *Nuclear Engineering and Design*, vol. 236, no. 7-8, pp. 852–860, 2006.
- [11] L. Damiani, P. Giribone, R. Revetria, and A. Pini Prato, "A passive decay heat removal system for the lead cooled fast reactor demonstrator 'Alfred,'" *Progress in Nuclear Energy*, vol. 83, pp. 294–304, 2015.
- [12] F. Giannetti, D. Vitale Di Maio, A. Naviglio, and G. Caruso, "Thermal-hydraulic analysis of an innovative decay heat removal system for lead-cooled fast reactors," *Nuclear Engineering and Design*, vol. 305, pp. 168–178, 2016.
- [13] M. Vanderhaegen, J. Vierendeels, and B. Arien, "CFD analysis of the MYRRHA primary cooling system," *Nuclear Engineering and Design*, vol. 241, no. 3, pp. 775–784, 2011.
- [14] G. Colangelo, E. Favale, A. de Risi, and D. Laforgia, "Results of experimental investigations on the heat conductivity of

nanofluids based on diathermic oil for high temperature applications,” *Applied Energy*, vol. 97, pp. 828–833, 2012.

- [15] STAR CCM+ User Guide.
- [16] NEA, “Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies,” Nuclear Science Committee, 2007.
- [17] A. Rineiski, “Decay heat production in a TRU burner,” *Progress in Nuclear Energy*, vol. 50, no. 2–6, pp. 377–381, 2008.