SEVERE ACCIDENT ANALYSIS OF THE DUAL-FUNCTIONAL LITHIUM-LEAD TEST BLANKET MODULE USING ISAA-DFLL CODE

by

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The international thermonuclear experimental reactor (ITER) project aims to build a tokamak fusion test reactor to verify the feasibility of fusion reactors. The test blanket module (TBM) is the key component of the international thermonuclear experimental reactor. The fusion design study team proposed the concept of the dual-functional lithium-lead test blanket module (DFLL-TBM). The integral severe accident analysis (ISAA) is a self-developed ISAA code that models the progression of severe accidents in nuclear power plants. A broad spectrum of severe accident phenomena including fission product release and transport behavior is modeled in ISAA. In this paper, a new version of ISAA, referred to as ISAA-DFLL is introduced for the application of DFLL-TBM test blanket module into the treatment of multi fluids and the modules of the new physical property and heat transfer. The modification is verified by comparing the steady-state temperature distribution of the DFLL-TBM first wall with the design parameters. Then accident analysis of In-vessel loss of helium coolant in first wall and TBM pipe is conducted by using the ISAA-DFLL code. By comparing the calculation results with the general safety requirements for TBM, it is concluded that the design of the DFLL-TBM system and the modifications of the current version are reasonable and accurate.

Key words: *ISAA-DFLL, DFLL-TBM, multi-fluid, loss of coolant accident, accident analysis*

Introduction

Research background

In 1985, the USA and the Soviet Union put forward the ITER project with the support of the International Atomic Energy Agency (IAEA), which aimed to establish a tokamak fusion experimental reactor in engineering in order to verify the feasibility of the nuclear fusion reactor [1]. In the fusion reactor, as a very critical carrier, a blanket is mainly used for radiation shielding, tritium breeding (neutron+lithium→tritium), and energy (nuclear power→

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heat) proliferation. Blanket research is of great significance, for it is the functionality carrier to achieve the goal of engineering application of fusion reactor. In March 2004, China officially proposed to independently develop the test blanket producing tritium using a liquid lithium lead breeder [2]. The TBM technology is a crucial key technology in the development of fusion energy, and its tritium production technology is also sensitive. Large scale tritium proliferation experiments can be carried out by using the tritium production experiment module [2]. Its application will have a stormy impact on the development of fission energy and fusion energy, as well as the application of nuclear science and technology. Due to the material and engineering limitations of the fusion reactor, it is very necessary to use numerical simulation to conduct a preliminary feasibility analysis of the experimental scheme. On the one hand, it can be used to verify the feasibility and rationality of the scheme. It can also provide strategy and guiding significance for subsequent design and development.

The status and progress

There are many ways of classifying claddings by tritium enrichment agent, coolant, construction material, and exit temperature. However, they can be broadly classified into two categories: solid enrichment claddings and liquid enrichment claddings. In current cladding designs, there are three main types of coolant: helium, water, and liquid metals (including molten salts). The solid enrichment cladding has only one coolant and therefore only a single cooling mode is available. The liquid cladding, on the other hand, can be cooled in single, dual, or liquid metal self-cooling mode. In the case of the liquid enrichment cladding, liquid LiPb enrichment is the most attractive option due to its good compatibility with silicon carbide, SiC, low chemical reactivity with water and air, low electrical conductivity compared to lithium, Li, relatively weak MHD effect and relatively mature technology. The liquid LiPb cladding has therefore received a lot of attention internationally and is considered to be one of the most promising cladding concepts. After extensive research and in-depth analysis of the current status of international fusion reactor cladding design and technology development, the fusion design study (FDS) group at the Institute of Plasma Physics, Chinese Academy of Sciences, combined with the FDS group's long-term experience in lithium-lead cladding concept research, proposed a LiPb experimental cladding solution with Chinese characteristics that balances technical development feasibility and advancement, called DFLL [1]. For China, research in related technologies is in its infancy, but substantial developments have been made in liquid metal circuits as well as in structural materials. The study of the liquid metal LiPb bifunctional experimental cladding module includes neutronic analysis, thermo-hydraulics analysis, structural mechanics analysis, material activation analysis, and severe accident analysis. Due to physical and engineering constraints, the design of the thermo-hydraulics must be carried out based on which the rationality of the cladding's thermo-hydraulic scheme is assessed and verified through power balance modeling, structural design solutions, neutronics, and MHD calculations, where the thermo-hydraulic flow scheme includes a He flow scheme and a liquid metal LiPb flow scheme. Wang *et al.* [3] proposed a thermal-hydraulic design scheme for the FDS-2S double-cooled LiPb DLL of the fusion power reactor based on structural design and neutronics calculations. The liquid LiPb flow field and first wall structure were also simulated using numerical simulations. Liu *et al.* [4] designed the preliminary design scheme and equipment arrangement of the He cooling system based on the thermal-hydraulic conditions as well as safety and space requirements for the operation of the DFLL-TBM in ITER. Among them, the thermal-hydraulic design focuses on the design of a cooling system with a simple and reliable structure, reasonable temperature and stress distribution, high coolant outlet temperature, and high thermal conversion efficiency for the research object, and also involves the structural design and neutronic design of the fusion reactor, so it is the key element in the cladding design. At the stage when the experimental scheme is not yet mature, it is necessary to conduct a numerical analysis of the DFLL-TBM for thermal hydraulics. The main purpose is to obtain the temperature change and pressure change of coolant flow, *etc.* by numerical simulation, so as to evaluate the rationality of the thermal hydraulics scheme design. Safety analysis is an essential part of the design process, and the placement of TBM devices in ITER requires that they meet certain safety requirements, and therefore must be subjected to accident analysis. For the dual-function liquid LiPb experimental cladding module scenario, Li *et al.* [5] conducted steady-state and accident analysis using the system program RELAP5/MOD3 embedded with a liquid LiPb thermal-hydraulic submodule. In addition, Merrill *et al.* [6] modeled the DCLL-TBM using the modified severe accident analysis program MELCOR, which to perform accident analysis calculations such as los of coolant accident (LOCA) outside the vacuum chamber and LOCA inside the vacuum chamber. Marshall *et al.* [7] used other programs such as ATHENA-INTRA to perform safety analysis of TBM. Sun *et al.* [8] addressed the problem that RELAP/SCDAPS/MOD4.0 could not handle the contact between liquid metal and non-condensable gas by modifying the calculation flow of the source code and adding the gas phase properties of LiPb eutectic alloy so that the modified code overcomes its shortcomings in simulating the coexistence of LiPb and non-condensable gas. By using the modified RELAP/SCDAPS/MOD4.0 code, FLUENT, and theoretical correlation to analyze several cases, the comparison results show a good agreement between them, which verifies the accuracy and feasibility of the modified code. Finally, the modified RELAP/SCDAPS/MOD4.0 was applied to the safety analysis of coolant leakage from the TBM internal enrichment tank of the Chinese DFLL-TBM. Chen *et al.* [9] used the 3-D CFD code FLUENT coupled with the system code RELAP5/MOD4.0 to simulate the pressure propagation behavior in a DFLL cladding LiPb loop system triggered by an in-vessel LOCA accident. The reflection and superposition of pressure waves in the complex channels of the DFLL cladding components were accurately simulated using FLUENT, and the propagation of pressure waves in the LiPb loop system was simulated using the RELAP5 program. The coupling code connecting FLUENT and RELAP5 transfers the pressure at the inlet/outlet interface of the blanket module to the LiPb loop. The simulation results show that the transient peak pressure at each monitoring point within the cladding module reaches 14.454 MPa in the initial stage, and 9.612 MPa and 14.454 MPa at the inlet and outlet of the cladding module, respectively. Zhang *et al.* [10] developed a fluid-solid coupled bi-directional model based on ANSYS WORKBENCH and validated the model by injecting high-pressure helium into liquid lithium lead with experimental data. The validated model was then applied to the transient pressure wave propagation analysis and structural stress analysis of a DFLL blanket to explore the structural integrity of the blanket under LOCA in the box. In addition, the effects of fracture location on pressure and structural stresses were investigated in six cases. It was found that in any case, the instantaneous pressure of the DFLL blanket goes through three stages: step-up, oscillation, and leveling off. The peak pressure occurs during the oscillation and its value depends to a large extent on the fracture location. The closer to the inlet/outlet, the higher the pressure peak. The maximum pressure reaches more than twice the inlet pressure (up to about 16 MPa). Although these codes have made considerable improvements for ITER TBM, when a hypothetical accident is more severe, such as the occurrence of a rupture and melting of the (FW), the chemical reaction between the structural material coating and water vapor, and then aerosol or even hydrogen generation are phenomena beyond its consideration, a more complete program is needed to simulate the subsequent phenomena, and severe accident analysis code is a good choice, it can provide strong support for further optimization of design solutions.

More in-depth analysis and research are required on the design of the DFLL-TBM circuit and the numerical simulation of the thermal-hydraulic properties to ensure the feasibility and accuracy of the design. However, due to the special needs of the DFLL-TBM, such as multiple workings, the release of radioactive source terms, hydrogen generation, *etc.*, the existing program is no longer adequate to fully meet its special characteristics, and the original ISAA cannot be directly used for accident analysis of the DFLL-TBM, which is missing many modules, such as the flow of dual coolant helium and liquid LiPb in the DFLL-TBM, the corresponding workings heat exchange models, and oxidation models for the new materials beryllium and tungsten. Therefore, this paper first develops the model for the existing ISAA program, using equations for He and water in the physical properties module for the single phase, and linear interpolation of the physical properties table for the mixed phase to obtain the required physical properties for the corresponding working materials, while the soft sphere model is used to calculate the physical properties for liquid metals. After the addition of the new physical model, the physical properties of the He and liquid metal LiPb required in the DFLL-TBM were initially verified at single and multiple points, respectively. Then, for the heat transfer module, the heat transfer equation for the corresponding workpiece is added and the first wall helium loop and the liquid LiPb loop in the proliferation zone of the DFLL-TBM are selected for steady-state calculations, which are initially validated by comparing the results with those of other authors. Finally, the DFLL-TBM is modeled using a modified ISAA for the liquid LiPb experimental cladding module, and safety analyses are carried out for selected in-vessel and ex-vessel LOCA accidents.

Introduction of the liquid LiPb test blanket module

A DFLL-TBM is the device installed in the window frame of ITER. The DFLL-TBM is a sturdy rectangular box-like structure consisting of a FW, radial-poloidal stiffening plates (rpSP), "˥"-shape toroidal stiffening plates (tpSP), covers, and helium manifold constituted by the back plate.

The goal of TBM thermal-hydraulic design is to discharge nuclear heat from the internal structure and cool the whole breeding zone structure. The DFLL-TBM incorporates the thermal-hydraulic design of dual cooling, including helium gas flow scheme and liquid LiPb flow scheme. The He gas flow loop and the flow distribution scheme are shown in fig. 1. The liquid LiPb flow diagram in DFLL-TBM is shown in fig. 2.

According to the thermal-hydraulic design, the thermal-hydraulic parameters of DFLL-TBM are listed in tabs. 1 and 2. The coolant pressure of the FW He loop is 8 MPa and liquid LiPb pressure in the breeding zone is 1 MPa. The total heat absorbed by He gas and Li is 0.66 MW, among which 0.4819 MW is absorbed by He gas and 0.1791 MW is absorbed by liquid Li. The heat absorbed by He gas contains the nuclear heat produced by the neutron irradiation and the plasma heating to FW, which is 0.24 MW. This heat is taken away by the He gas of FW.

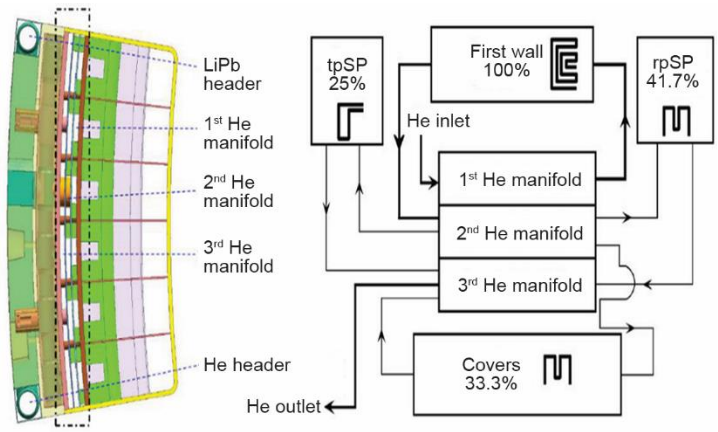

Figure 1. The DFLL-TBM helium gas flow loop and the flow distribution scheme [1]

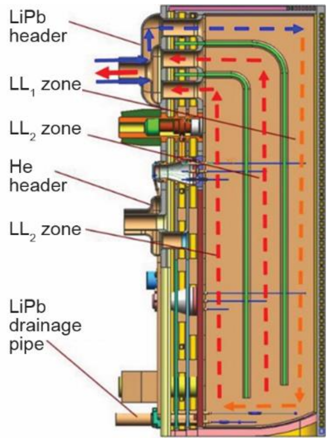

Figure 2. Liquid LiPb flow diagram in DFLL-TBM [11]

Table 1. Thermodynamic parameters of He gas of the DFLL-TBM main structure

Working fluid	Name	The thermodynamic parameters			Deposited, Q [MW]
		Inlet, T [°C]	Outlet, T [°C]	v [ms^{-1}]	
He	FW	340	395	50	0.04231
	rpSP	395	402	60	0.0156
	tpSP	395	402	64	0.0204
	Covers	395	412	59	0.0153
	He manifold	1st/2nd/3rd: 402/395/340			0.009

Table 2. Thermodynamic parameters of liquid LiPb of the DFLL-TBM main structure

Working fluid	The thermodynamic parameters				Deposited, Q [MW]
	Inlet, T [°C]	Outlet, T [°C]	v [ms^{-1}]	G [kgs^{-1}]	
LiPb (l)	480	700	14/5.5/5.5	4.33	1.0

The modules in ISAA-DFLL code

Description of ISAA-DFLL code

The ISSA code is an integrated systems-level computer code developed at Xi'an Jiaotong University, which is mainly used to describe the severe accident process in nuclear reactors [12]. A wide range of severe accident phenomena can be modeled by some advanced verified physical models [13, 14]. The ISAA follows a modular approach that which several different modules are utilized to model the different physical phenomena during a severe accident [15]. For instance, the basic thermal hydraulics phenomena in different components are modeled in thermal hydraulics module. The main modules are shown in fig. 3. In addition, ISAA is not only developed for light water reactors (BWR and PWR) but also can be expanded as an improved version to model the accident behavior in some specific advanced plant applications. Here in order to accurately simulate typical design basis accidents, over-design basis accidents or severe accidents of DFLL-TBM, an improved version of ISAA, referred to as ISAA-DFLL, is developed, with the specified physical properties of coolant the relevant physical models updated in the corresponding modules.

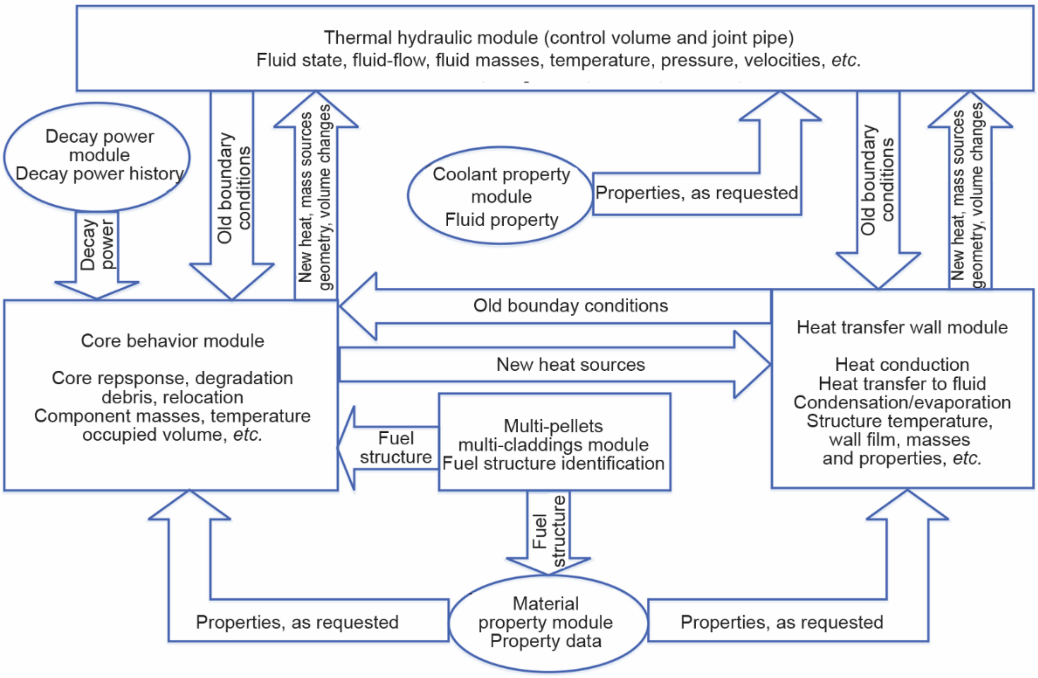

Figure 3. Main modules in ISAA

Modification of coolant property module

The default coolant in basic ISAA is water without considering multi-fluid. It is necessary to modify the coolant property module of ISAA-DFLL in order to calculate the physical properties of the coolant of DFLL-TBM, such as the density, heat conductivity, specific heat, and viscosity to update the ISAA to ISAA-DFLL. The coolant property module mainly calculates physical parameters for thermal hydraulics module. In the calculation process, the coolant property module will be called by different subroutines of different modules to fulfill different functions.

The working fluids of DFLL-TBM are He gas, liquid LiPb, and water.

– Physical properties model of He gas

The DFLL-TBM uses He gas as a coolant of wallboard structures. In this paper, we use the known thermodynamic property table to calculate the physical properties of He gas. The liquid phase is calculated by a single-valued function of temperature and the gas phase is treated as an ideal gas. The TPF file of He gas, which was obtained from the RELAP5 property package, was read into ISAA-DFLL by a specific subroutine to obtain a regenerated physical table, and according to the requirements and physical state, to calculate the corresponding thermodynamic parameters.

– Physical properties model of liquid metal

The TPF file for liquid metal property calculation is also obtained from the RELAP5 property package. The soft-sphere model [16], which can calculate a variety of metal materials properties, is used in this paper's liquid metal property calculation.

– Modified method

To simulate the different physical properties of various coolants, an additional option has been introduced into thermal hydraulics module to identify the type of coolants. The coolants used include He gas, water, and liquid LiPb. The new coolant property module will use external interfaces to calculate the physical properties of the coolants in the thermal hydraulics module.

Modification and verification of heat transfer wall module in ISAA-DFLL

Modification of heat transfer wall module

Liquid metals have high thermal conductivity and low Prandtl number, usually within the range of 0.01 and 0.001, which means that for liquid metals, the heat conduction mechanism is more dominant than the momentum mechanism. The heat transfer equations used in the heat transfer wall module of the original ISAA code are limited to water. Therefore, when the working fluid is He gas or liquid LiPb, it is necessary to reconsider the calculation logic and heat exchange equation of flow and heat transfer.

The heat transfer calculation is mainly in the heat transfer wall module. In this module, the walls between different control volumes are modeled, and the coolants of the corresponding control volume on both sides of the wall are identified. Various subroutines are used to calculate the heat transfer coefficients of natural or forced convection and boiling heat transfer.

For natural/forced convective heat transfer, based on theoretical analysis, Kirillov and Ushakov [17] recommended using the heat transfer equation developed by Subbotin *et al.* [18] for liquid metal. Therefore, the heat transfer equation is used for single-phase liquid metal in this paper:

$$\mathrm{Nu} = 5 + 0.025\,\mathrm{Pe}^{0.8} \tag{1}$$

For boiling heat transfer, we choose the circular tube flow heat transfer equation developed by Kovalev and Zhukov [19]:

$$h = 0.33 p_{mm}^{0.25} q^{0.7} \tag{2}$$

For liquid metals, the CHF relation is also very important. Caswell and Balzhiser [20] recommended the following empirical formula:

$$\frac{q_{cr} c_{p,\mathrm{l}} \sigma}{\lambda^2 \rho_\mathrm{v} k_\mathrm{L} J} = 1.18 \times 10^{-8} \left(\frac{\rho_\mathrm{l} - \rho_\mathrm{v}}{\rho_\mathrm{v}} \right)^{0.71} \tag{3}$$

After preliminary comparison, we choose this formula for the CHF prediction in the liquid metal flow heat transfer module.

Verification of heat transfer module in ISAA-DFLL

The code-to-code approach is used to verify the above modification. For the heat transfer wall module, the FW He loop of DFLL-TBM and the liquid LiPb loop of the breeding zone are used as the calculation object.

– He gas

The flow path of He is from the primary He manifolds to the FW and then to the secondary He manifold. It follows back and forth four times in the U-shaped tubes of the FW, so the flow directions between adjacent flow paths will be opposite to each other to enhance heat transfer.

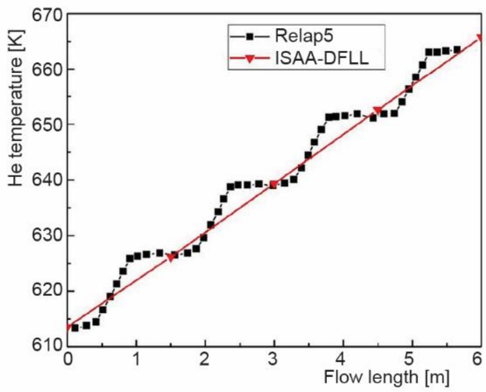

Figure 4. The FW He gas temperature curve along the flow direction

Therefore, the physical properties and heat transfer model can be verified by a simple simulation of the FW. After the calculation is stable, the temperature of the FW is output and has been compared with the calculation results of RELAP5 [5], as shown in fig. 4. It can be known from fig. 4 that the calculated outlet temperature of every section is consistent with the RELAP5 results, which demonstrates the validity of the modification of He gas physical properties and heat transfer module.

– Liquid LiPb

The liquid LiPb flow zone of DFLL-TBM is also known as the breeding zone. The breeding zone is separated into two parts circumferentially by the rpSP and divided into zones LL_1, LL_2, and LL_3, fig. 2, by tpSP radially, forming six liquid LiPb flow paths. To simulate the LiPb flow, the node diagram is shown in fig. 5. The liquid LiPb flows into the LL_1 zone of the supply/feed box from the outer ring, *i.e.*, CV102, of the concentric tube, then passes the three breeding zones. The LL_1 zone is divided into four control volumes in the simulation. The CV100 and CV101 are used to represent the zones in the horizontal direction, while CV105 and CV106 are for zones in the vertical direction. The LL_2 zone is simulated by four control volumes (CV200 to CV203), while two control volumes are used to simulate the LL_3 zone (CV300 and CV301). Finally, they are converged together to leave the supply/feed box through the inner ring, *i.e.*, CV102, of the concentric tube. The inlet and outlet control volumes are set as time-independent control volumes, and the flow rate of the inlet flow path is given as constant to simplify the calculation of the flow and heat transfer of the liquid LiPb in the breeding zone. All control volumes are connected by flow paths according to the flow direction of the liquid LiPb. The heat structures, red zones in fig. 5, are added and attached to control volume to simulate the irradiation heating effect from neutron.

The calculated inlet temperature and outlet temperature as well as the temperature distribution in the three breeding zones shown in fig. 6 are in good agreement with the CFX [21] simulation results, which can prove the correctness of the modification of liquid LiPb physical properties and the heat transfer module.

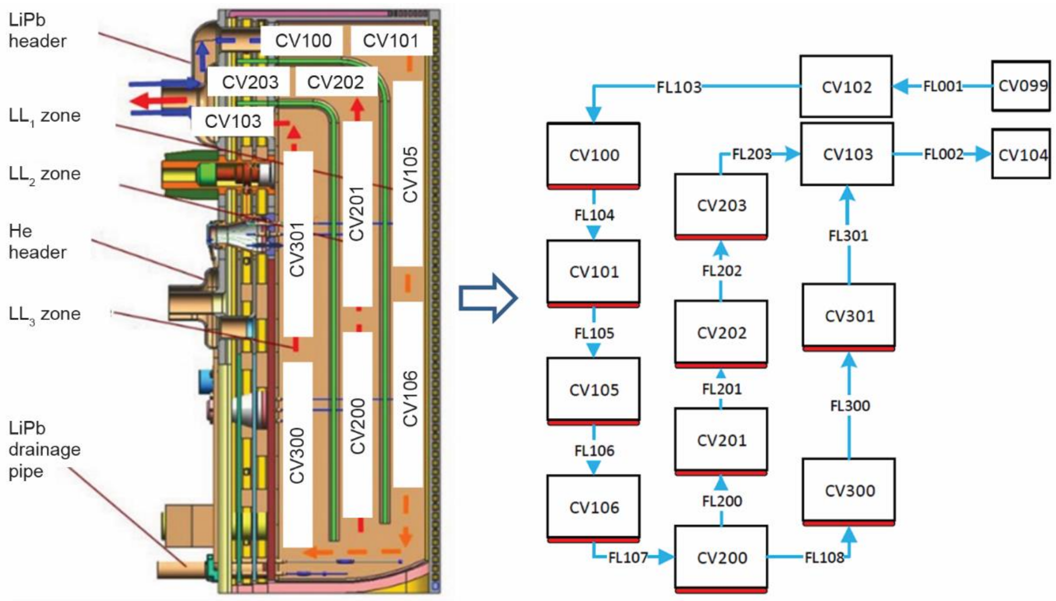

Figure 5. Simplified modeling node diagram of the breeding zones

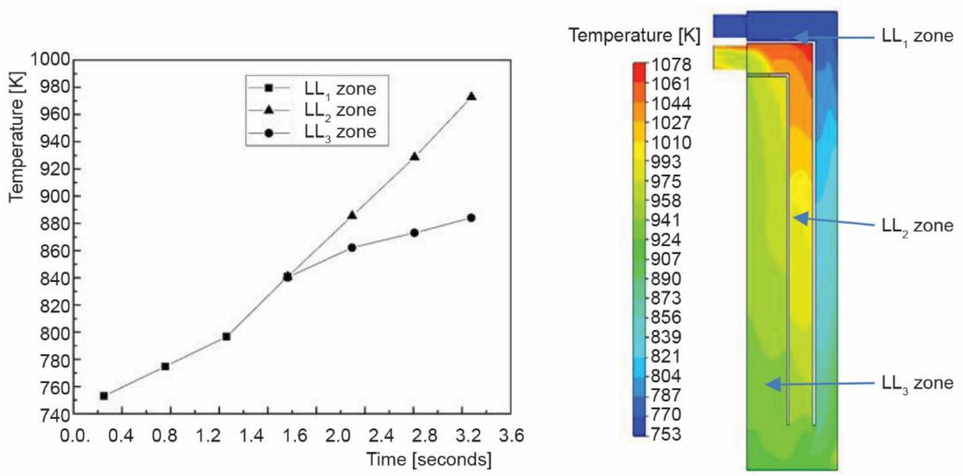

Figure 6. Comparison of temperature curve of the liquid LiPb in the breeding area along the flow direction

The DFLL-TBM modeling and accident analysis

The DFLL-TBM modeling

In view of the actual situation of ITER, a severe accident of the TBM module is defined as [22]:

– The TBM module ruptures. The vacuum vessel is contaminated when He gas or the gas containing tritium of the TBM module flows into the vacuum chamber.

– The melting of the TBM module will not only cause damage to itself but also structural damage to its surrounding vacuum vessel.
– The tritium leakage will damage the environment and cause the reactor to shut down.

In addition, the safety requirements for the TBM system are as follows [23].

– Overpressure in the primary and secondary sides of the barriers cannot exceed the limit of the ITER design of 2 atm. ITER vacuum vessel, pressure suppression system, all cooling pipes external to the container and another auxiliary system of TBM are the primary side of the barrier, while TBM fixed module and TCWS vault are the secondary sides of the barrier.
– Decay heat needs to be removed by thermal radiation. The maximum temperature of TBM FW must be less than 350 °C within a few minutes after the reactor is shut down.
– The He leakage limit is 40 kg in order to avoid the pollution of the VV suppression system.

The DFLL-TBM and the auxiliary system are mainly divided into three loops, *i.e.*, the DFLL-TBM loop, the structure/He loop, and the LiPb/helium loop.

In the system, the He gas at 340 °C in FW and rpSP/tpSP is heated to 395 °C by the plasma and then enters the structure/He loop, subsequently, it is cooled to 340 °C through the He/water heat exchanger, and then enters the FW through He concentric tube by the fan. Liquid LiPb at 480 °C in the breeding zone is heated to 700 °C.

As the secondary LiPb loop, LiPb/He loop cools the high temperature LiPb through the low temperature He in the LiPb/He heat exchanger. Then the cooled liquid metal will be sent into the breeding zone through the concentric tube. Figure 7 shows the DFLL-TBM structure/He loop node diagram.

The simulated components in the figure include the helium coolant channel in the solid structure of the TBM, the concentric tube, and the filters. The solid structure includes FW, tpSP, rpSP, covers, and He manifold. The He enters the third stage He manifold (CV700) through the concentric tube (CV901), then flows in the internal flow path of FW, passing CV405, CV406, CV407, and CV408, sequentially. Then He leaves FW and enters the secondary He manifold (CV400). After that, He flows into primary He manifold (CV800) through three paths, *i.e.*, 25% in tpSP (CV501), 41.7% in rpSP (CV502), and 33.3% in covers (CV503). These three He flows are converged in the primary He manifold (CV800) and then flow into the structure/He loop through the inner ring of the concentric tube (CV902). The high temperature He from TBM is then cooled by a He/water heat exchanger. The He side is

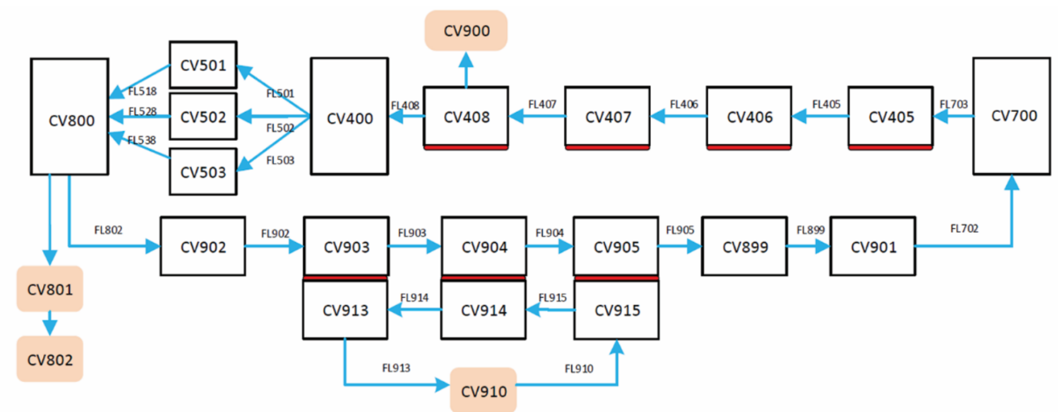

Figure 7. The DFLL-TBM structure/helium loop node diagram

simulated by CV903, CV904, and CV905, while the waterside is represented by CV913, CV914, and CV915. The cooled He then enters the filter and is pumped back into TBM to carry the heat of the fusion reactor outside. The pump is simulated by FL899. Heat transfer, including heating from plasma in FW and heating and cooling in He/water heat exchanger, is stimulated by the heat structure module, red zones in fig. 7. The nuclear heating by neutron irradiation is simulated by the internal heat source of CV in FW. The heat distribution in the DFLL-TBM is shown in tab. 3.

Table 3. Heat distribution in the DFLL-TBM

Working fluid	He					Liquid LiPb
Name	FW	tpSP	rpSP	Covers	He manifold	Breeding zones
Deposited [MW]	0.4231	0.0156	0.0204	0.0153	0.009	0.1781
Total	0.66					

The calculation results and accident analysis

The steady-state calculation results and verification

The total heat absorbed by the whole system of DFLL-TBM is 0.66 MW. Inlet temperatures of He and LiPb in the concentric tube are 340 °C and 480 °C, respectively. We set the initial state of DFLL-TBM systems in the input card. The calculation starts at 0 seconds and lasts for 500 seconds. The main parameters are presented in tab. 4.

The FW rupture LOCA accident of in-vessel LOCA

The LOCA accident in vacuum vessel includes the slight pressure increase of FW barriers (ITER VV) and the passive discharge of the decay heat in TBM, *etc.* The trigger event is a double-ended rupture of He coolant pipes of TBM FW, causing the coolant to be injected into the vacuum vessel. Tt is assumed to be the heat generated by the plasma surge. The accident hypothetical sequence is shown in tab. 5.

Table 4. The DFLL-TBM steady state calculation results

System parameters	Component	Calculated value	Design value	Relative error	
Name	FW	341/393	340/395	0.3%	0.5%
	tpSP	393/400	395/402	0.5%	0.5%
	rpSP	393/411	395/412	0.5%	0.24%
Temperature [°C]	Covers	393/398	395/400	0.5%	0.5%
	Breeding zones	480/700	480/700	0.0%	0.0%
Pressure [MPa]	He loop	8.3	8	3.75%	
	Liquid LiPb loop	1	1	0.0%	
Mass flow rate [kgs^{-1}]	He loop	1.54	1.489	3.4%	
	Liquid LiPb loop	4.72	4.33	9.0%	
The velocity [ms^{-1}]	He loop	50.9	50	1.8%	
	Liquid LiPb loop	0.0123/0.0055/0.00598	0.014/0.0055/0.0055	12% 0.0% 8.7%	

Table 5. Accident hypothetical sequence of In-vessel LOCA

The accident description	Time [s]
Steady-state operation inside the DFLL-TBM	0 s ≤ t ≤ 500
Plasma annihilation as the FW coolant pipe leaks	t = 500
The FW heat flux surged to 1.8 MW/m^2 100% volume heat source	500 s < t ≤ 501
Plasma annihilation, export decay heat by radiation heat transfer	t > 501

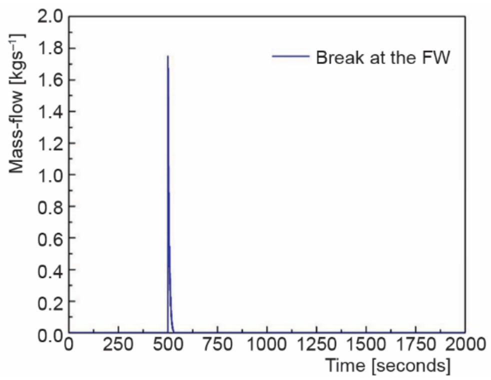

Figure 8. The He gas mass-flow at DFLL-TBM FW break

The crevasse area of the double-ended rupture of the He coolant channel in FW is 0.0006 m^2. The crevasse is triggered at 500 seconds, after which, the coolant in TBM leaks into the vacuum chamber, resulting in increased pressure in the vacuum vessel. After the accident, the differential pressure between TBM and VV causes a rapid pressure drop. Break flow is shown in fig. 8.

With helium leaking into the VV, the pressure inside the FW decreases yet the pressure within the VV rises. Shortly after the accident, the pressure of internal systems and VV reaches equilibrium, and thereafter the pressure does not change, as shown in fig 9. It can be seen from fig. 10 that 32.5 seconds after the accident, VV pressure increases to 0.017 MPa, which is far below the ITER design limit of 0.2 MPa. This demonstrates the safety of the DFLL-TBM system, and there are still a great deal of margins.

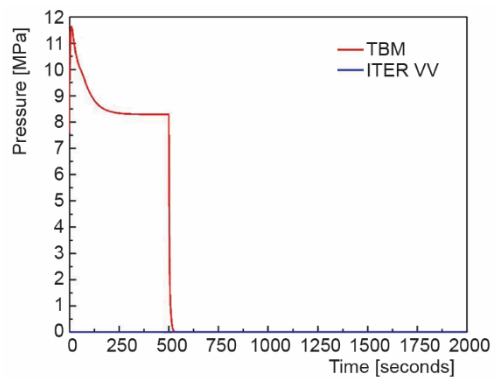

Figure 9. Pressure curves of ITER TBM and VV

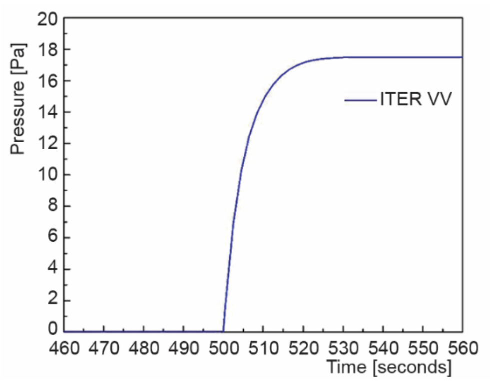

Figure 10. Pressure curve of VV

After the accident is triggered, the heat generated by the core plasma is assumed to surge. So the heat flux from the plasma to the FW soars from the original 0.32 MW/m^2 to 1.82 MW/m^2.

The FW He temperature curve is shown in fig. 11. Within 1 second after the accident, the flow rate increases because of the break, thereby causing the FW temperature to decrease. Due to the sudden increase of the heat, the temperature rises gradually. As the heat exchange between the helium and the water heat exchanger gradually achieves a balance, the temperature of the loop gradually stabilizes.

In addition, the He mass leaked into the VV has a certain limit according to the safety standard. The mass of the total He leakage is shown in fig. 12. It can be seen from the figure that the mass of helium coolant leaked into the vacuum chamber, caused by FW He coolant pipe double-ended rupture, is 10.54 kg, which is below the safety design limit of 40 kg.

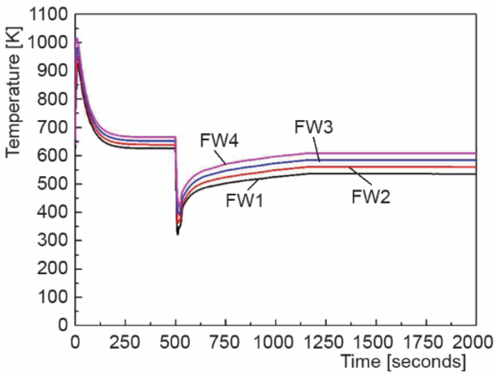

Figure 11. Temperature curve of He in ITER FW

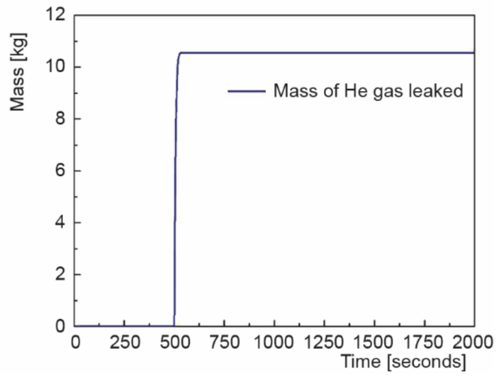

Figure 12. The mass of He leaked to VV

Ex-vessel coolant pipeline rupture LOCA accident

Ex-vessel coolant pipeline rupture LOCA accident is mainly to analyze the TBM vault pressurization and the transient behavior in TBM heated by the activated plasma.

The initial event is a coolant pipeline double-end break on the TBM cooling system (the break area is 0.000064 m^2). The accident is triggered at 500 seconds, leaking into port cell. After that, the pressure of the broken coolant pipe decreases rapidly, and the flow at the break increases rapidly, as shown in fig. 13. Pressure in the loop and port cell reaches a balance quickly, as shown in fig. 14.

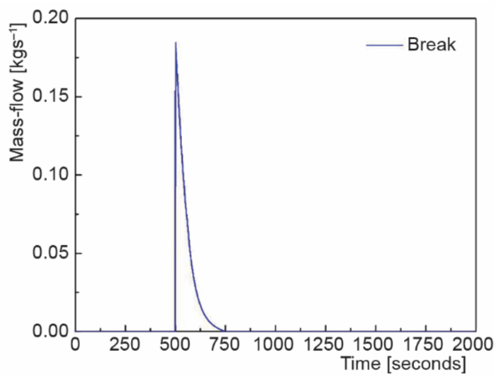

Figure 13. The He coolant mass-flow at the break outside DFLL-TBM

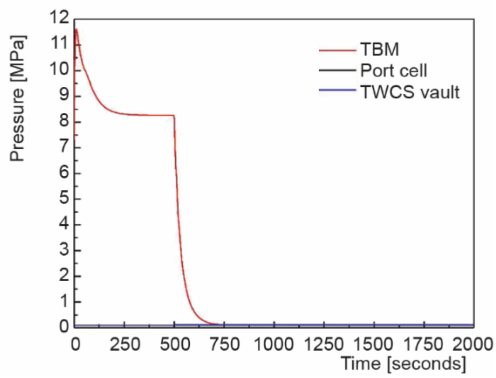

Figure 14. Pressure curves of TBM loop, port cell, and TCWS vault

As the He gas enters the port cell, the pressure of the port cell rises. There is a relief valve between the port cell and TCWS vault. Once the pressure exceeds 20 kPa, the safety valve opens and immediately closes when it is below 20 kPa.

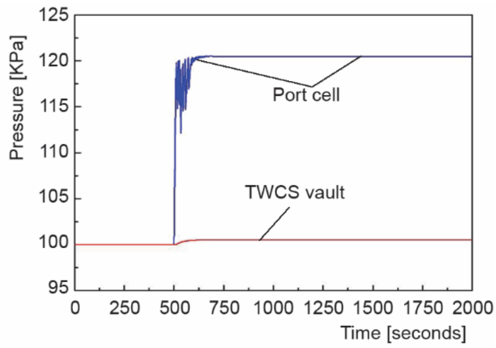

Figure 15. Pressure curve of the port cell and TCWS vault

The calculated pressure curves of the port cell and TCWS vault after the accident are shown in fig. 15. One can notice that when the differential pressure between the port cell and TCWS exceeds 20 kPa, the relief valve opens and the pressure in port cell reduces. The pressure in the loop finally reaches equilibrium. The pressure relief valve is closed, and pressure is stabilized at 1.2 atmosphere.

For ex-vessel coolant pipeline rupture LOCA accident, the port cell pressure finally stabilizes at 1.2 atmosphere, which is less than the limit of 2 atmosphere. The design meets the safety requirements and there is still a certain safety margin. However, for the LOCA accident, pressurization in the ex-vessel is greater than that in the in-vessel and the safety margin is much smaller.

Summary

The DFLL-TBM is challenging in simulation because of its multi-working fluids. In this paper, multi-physical properties, the coolant property module, and heat transfer wall module were modified to form the new version of ISAA-DFLL code which is suitable for the multi-working fluid. After verifying the accuracy and availability of the modified coolant property module and heat transfer wall module, the modified ISAA-DFLL code was applied to the steady-state, transient, and accident calculations of DFLL-TBM. Under FW rupture LOCA accident of in-vessel LOCA, VV pressure increases to 0.017 MPa, which is far below the ITER design limit of 0.2 MPa and the mass of helium coolant leaked into the vacuum chamber is 10.54 kg, which is below the safety design limit of 40 kg. Under the proposed ex-vessel coolant pipeline rupture LOCA accident, the port cell pressure finally stabilizes at 1.2 atm, which is less than the limit of 2 atm. The calculation results indicated that the current DFLL-TBM design satisfies the ITER safety requirement.

Nomenclature

$c_{p,\mathrm{l}}$ – liquid specific heat capacity at saturation temperature, [Jkg^{-1}K^{-1}]
h – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
J – coefficient, [NmJ^{-1}]
k_L – liquid phase thermal conductivity, [Wm^{-1}K^{-1}]
Nu – Nusselt number, [–]
Pe – Peclet number, [–]
p_{mm} – surface pressure of nucleate boiling heat transfer, [P]
q – average heat flux on the heated surface, [Wm^{-2}]
q_{cr} – heat flux, [Wm^{-2}]

Greek symbols

λ – latent heat of vaporization, [Jkg^{-1}]
ρ_v – vapor density, [kgm^{-3}]
ρ_l – liquid density, [kgm^{-3}]
σ – surface tension, [Nm^{-1}]

Acronyms

DFLL-TBM – dual-functional lithium-lead test blanket module
ITER – international thermonuclear experimental reactor
IAEA – International atomic energy agency
ISAA – integral severe accident analysis
FDS – fusion design study
LOCA – loss of coolant accident
FW – first wall
rpSP – radial-poloidal stiffening plates
tpSP – "˥"-shape toroidal stiffening plates
VV – vacuum vessel

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