TRACE Analysis for
Transient Thermal-hydraulics of
A Heavy Liquid Metal Cooled System

Master Thesis
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Abstract

Heavy liquid metal (HLM - lead or lead bismuth eutectic) is considered as a candidate coolant for next-generation fast reactor and accelerate-driven systems (ADS), due to its favorable chemical, thermo-physical and neutronic properties in comparison with sodium which has been used as coolant in fast breeder reactors (FBRs). To perform design-base-accident analysis for the HLM-cooled reactors, the well-known transient thermal-hydraulic analysis codes (e.g., RELAP5 and TRACE) are being applied to the reactors with the new coolant. Since these codes were originally developed for light water reactors (LWRs), validations are necessary to ensure the codes to count all influences of the thermo-physical properties of HLM.

In this thesis, the TRACE code is employed to simulate the transients performed on the TALL test facility which is a medium-size loop for thermal-hydraulic study of lead bismuth eutectic (LBE). The objectives of the present work are two-fold: i) to interpret the transients performed on the test facility; ii) to qualify the capabilities of the TRACE code for HLM-cooled system by using the experimental data and then perform separate-effect study beyond the experimental conditions. The transients related to safety issues such as loss of heat sink, loss of primary pump, loss of both primary/secondary pumps, overpower and accelerator trip are chosen in the simulations. In addition, the operational transients, the startup and the shut-down of the system are also simulated, respectively. Two configurations of the facility are considered: Configuration-A with a core tank, and Configuration-B with a fuel rod simulator. The separate-effect study is conducted to investigate the effects of coolant inventory, LBE flow resistance and mass flowrate in the secondary loop on natural circulation in the primary loop.

Generally speaking, for all the cases analyzed in the present study, the calculation results have a good agreement with the experimental data for the primary side (LBE) parameters (e.g., variations in temperature and mass flowrate). Specifically, the simulation for the transient loss of heat sink indicates the same tendency as in the experiment in term of temperature: it is rising at the inlet and outlet of the core simulator, as well as at those of the intermediate heat exchanger. The temperature keeps going up till the resumption of the heat sink as a protective measure, and then it decreases sharply at the very beginning and gradually returns to steady-state conditions. For the transient loss of primary pump, the temperature level is elevated and a significant natural circulation in the primary loop obtained. The simulation well reproduces the establishing process of natural circulation and final flowrate, but it overestimates the peak temperature. Such simulation outcome
applies to the transient “loss of both primary and secondary pumps”, except for a further elevated temperature. The calculation results of the transients startup and overpower are perfectly matching the experimental data, especially when approaching the final steady state, while the transients of shutdown and heater trip are underestimated in their final temperatures but the trends are well captured in both the transients.

In general, the transient time to a steady state or the maximum temperature level of Configuration-B is much shorter than that of Configuration-A, mainly because of the larger inventory of LBE in Configuration-A. The separate-effect study also shows that the LBE inventory in the primary loop plays a mitigative role in the transients. For the loss of primary pump transient, decrease in primary flow resistance and increase in secondary flowrate all contributes to passive safety.

**Keywords:** Heavy metal liquid, transient thermal-hydraulics, safety analysis, TRACE
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1 Introduction

1.1 Background of nuclear power plant development

With fast expansion of world’s population and great improvement of living quality, more and more energy is required, which also leads to adverse environmental impacts and potential long-term consequences from global climate change, especially the global warming caused by too much CO2 emission mainly produced by fossil fuel. In order to achieve a sustainable development of human society, we have to increase the use of clean, safe and cost-effective energy supplies. Nuclear energy is one of most important choices to reach such goal.

From June 26, 1954, when world’s first commercial nuclear power plant generated electricity, till now, 442 nuclear power plant units (Figure 1.1) with an installed electric net capacity of about 375 GW are operating in 30 countries and 65 plants (Figure 1.2) with an installed capacity of 63 GW are under construction in 16 countries [1].

Figure 1.3 gives an overview of the development of nuclear power systems [2]. The first generation was designed as the prototype reactors in the 1950s and 1960s. The second generation is the start of large commercial power plants in the 1970s. However, some severe accidents happened during long term commercial operations, typically the Chernobyl accident and Three Miles Island accident, which raise the requirements of developing safer and more advanced nuclear power systems and Generation III began to construct in the 1990s with a number of evolutionary designs that offer significant advances in safety and economics. The further development of Generation III are still underway (named Generation III+), and new plants built between now and 2030 will likely be these plants. At the same time, the conceptual prototype of Generation IV is proposed to achieve higher goals: sustainability, economics, safety and reliability, proliferation resistance and physical protection (Table 1.1) based on renewed R&D. And its commercial applications are expected to be available and prosperous beyond 2030s.
Figure 1.1 Number of reactors in operation, Jan 19, 2011 (IAEA 2011) [1].

Figure 1.2 Nuclear power plants under construction, Jan 19, 2011 (IAEA 2011) [1].
Figure 1.3 An overview of nuclear power systems developing map [2].

Table 1.1 Goals for Generation IV Nuclear Energy System [2]

<table>
<thead>
<tr>
<th>Goals</th>
<th>Goals</th>
</tr>
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</table>
| **Sustainability**     | 1. Provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy Production.  
                           2. Minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment. |
| **Economics**          | 1. Have a clear life-cycle cost advantage over other energy sources.  
                           2. Have a level of financial risk comparable to other energy projects. |
| **Safety and Reliability** | 1. Excel in safety and reliability                                   
                           2. Have a very low likelihood and degree of reactor core damage.  
                           3. Eliminate the need for offsite emergency response. |
| **Proliferation Resistance** | 1. Increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism. |
1.2 Generation IV nuclear energy system

The most promising types of nuclear power systems, which can meet the goals of Generation IV, are nominally three thermal reactors and three fast reactors. The thermal reactors include Very-high-temperature reactor (VHTR), Supercritical-water-cooled reactor (SCWR) and Molten-salt reactor (MSR). The fast reactors include Gas-cooled fast reactor (GFR), Sodium-cooled fast reactor (SFR) and Lead-cooled fast reactor (LFR). The LFR system was considered in the Generation IV Technology Roadmap as a most promising technology, especially in the mission of sustainability, actinide management and economics for electricity production.

Japan Atomic Energy Research Institute (JAERI) has carried out R&D on transmutation of long-lived nuclides with a special emphasis placed on the fast reactors with accelerator-driven systems (ADS). Innovations in heat transport are a central feature of the LFR options afforded by natural circulation, lift pumps, in-vessel steam generators, and other features. The heat removal from the fuel pin lattice uses natural or low-speed forced circulation through an open lattice of ductless assemblies. Heat transfer correlations, pressure drop correlations, pressure drop form factors for plenum flows and transitions, and flow redistribution patterns need to be developed as a function of geometry and pin linear heat rate both in the lattice and in the overall reactor flow circuit. The effects of grid spacers, deposits, and clad aging will have to be understood to support the long-term viability of natural circulation. This requires the availability of loops with a height useful for natural circulation and large-scale plenum flow facilities. Also the assurance of reliable and effective thermo-structural reactivity feedback is the key to the passive safety/passive load following design strategy and will require coordinated neutronics/thermal-hydraulics/structural design of the core. Early ADS concepts employed solid tungsten target and sodium coolant due to sodium has excellent thermal performance, good compatibility with stainless steel and technology maturity [3][4]. A chloride molten-salt system and a molten-alloy system were investigated as advanced options because of the improved safety and possible reduction of construction cost of the system [5][6]. Currently, the lead-bismuth cooled option becomes the main candidate for the ADS design and lead-bismuth eutectic can plays roles of both coolant and spallation target material. Based on the technologies of liquid-metal cooled FBRs and ex-USSR lead-bismuth cooled submarine reactors, a conceptual drawing of a lead-bismuth cooled 800-MWt ADTS was designed with a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium as shown in Figure 1.4 [7][8][9].
Europe has historically a large experience in the field of sodium-cooled fast reactors and recently has made a big effort in the development of the Lead-Bismuth Eutectic (LBE) technology for use in the sub-critical reactors due to its great advantages as listed in Table 1.2 to meet the four Goals of Generation IV. The project of “European Lead Cooled System” (ELSY) has been arranged to aim to demonstrate the possibility of designing a competitive and safe fast critical reactor using simple engineered technical features [10]. The activity consists of management and technical activity subdivided into six Work-Packages as following:

WP1: Design objectives, cost estimate, future R&D needs and compliance with the GEN IV goals.
WP2: Core design and performance assessment.
WP3: Main components and systems.
WP4: System integration.
WP5: Safety and transient analysis.
WP6: Lead technology.

Figure 1.4 Conceptual drawing of LBE cooled ADTS [7].
Table 1.2 Main solutions proposed for ELSY in order to comply with the four Goals for Generation IV.

<table>
<thead>
<tr>
<th>Goals Areas</th>
<th>Goals for Generation IV Nuclear Energy Systems</th>
<th>Goals achievable via</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainability</td>
<td>Lead inherent features</td>
<td>Specific engineered solutions</td>
</tr>
<tr>
<td>Resource utilization.</td>
<td>Lead is a low moderating medium. Lead has low absorption cross-section.</td>
<td>Breeding Ratio close to 1</td>
</tr>
<tr>
<td>Waste minimization and management.</td>
<td>Core with fast neutron spectrum even with important coolant fraction.</td>
<td>Presence of Minor Actinides</td>
</tr>
<tr>
<td>Life cycle cost.</td>
<td>Lead does not react with Water. Lead does not burn in air. Lead has a very low vapour pressure. Lead is cheap.</td>
<td>Reactor pool configuration. No intermediate loops (necessary condition for economics). Compact Primary System. Simple design of the reactor internals. Supercritical steam (high efficiency).</td>
</tr>
<tr>
<td>Risk to capital. (Investment protection)</td>
<td></td>
<td>Potential for all removable in-vessel components (to be evaluated and confirmed, as one of the challenge of the design activity).</td>
</tr>
<tr>
<td>Safety and Reliability</td>
<td>Operation will excel in safety and reliability.</td>
<td>Primary system at atmospheric pressure. Low coolant AT between core inlet and outlet.</td>
</tr>
<tr>
<td>Low likelihood and degree of core damage.</td>
<td>Lead does not react with water. Lead does not burn in air. Lead has: - a very high boiling point; - a very low vapour pressure; - a high shielding capability for radiation.</td>
<td>Primary Pumps in the hot collector. DHR Coolers in the cold collector.</td>
</tr>
<tr>
<td>No need for off site emergency response.</td>
<td>Lead density is close to that of fuel. (Considerably reduced risk of re-criticality in case of core melt).</td>
<td>Large fuel pin pitch. Decay Heat Removal (DHR) in natural circulation.</td>
</tr>
<tr>
<td>Proliferation Resistance and Physical Protection</td>
<td>Unattractive route for diversion of weaponizable material.</td>
<td>Use of a MOX fuel containing MA increases Proliferation Resistance. No blanket.</td>
</tr>
<tr>
<td>Increased physical protection against acts of terrorism.</td>
<td>Primary coolant chemically compatible with air and water operating at ambient pressure.</td>
<td>Independent redundant DHR loops operating in natural circulation.</td>
</tr>
</tbody>
</table>

1.3 Lead-Bismuth eutectic cooled system

As mentioned above, LFR with ADS is the primary choice of Generation IV nuclear power plant. While the heat transportation by LBE cooling system is the key during the
whole design and application. However, many technical issues still need to be investigated and resolved, especially its thermal hydraulic performance in the reactors, before its application as the coolant of LFR. Chen et al. [11] analyzed the dynamic behaviors of the ADTF facility [12], which aimed to demonstrate the feasibility of the accelerator-based transmutation of nuclear waste, under the transient scenarios of doubled external source, protected loss-of-flow, unprotected loss-of-flow and unprotected loss-of-heat sink to provide basic knowledge about the safety. Analyzed results shown that LBE cooled system could provide a sufficiently high cooling capability of the reactor core and avoid an overheating of the coolant, the cladding and the fuel due to its good buoyancy-driven convection. Cinotti et al. [13] described the 80MW Pb-Bi cooled eXperimental Accelerator Driven System (XADS) in detail and simulated the thermal-hydraulic behavior of its primary and secondary systems through a modified version of RELAP5/MOD 3. In addition, Schikorr et al. [14] performed a comprehensive safety analysis for XADS firstly, and then various codes (RELAP5, RELAP5/PARCS, TRAC-AAA, EAC, SAS4/SASSYS, and SIMMER) were applied to compare the simulated results with each other to achieve a consistency. However this approach could not substitute the experiments for the code validation while the experimental tests are needed to supply a pertinent data base and validate the code analysis. Towards this objective, a Thermal-hydraulic ADS Lead-bismuth Loop (TALL) test facility was designed and constructed at KTH [15][16]. TALL was a medium-size experimental facility, which used the XADS as a reference design. Some transient experiments were performed in TALL including: loss of heat sink, loss of primary pump, loss of both primary and secondary pumps, overpower, overcooling, heater trip and start-up/shut-down operational transients and the TRAC/AAA code was used to perform the corresponding calculations to compare with the experimental results [17].

1.4 Research objectives

In this study the TRACE code is employed to calculate the transient thermal hydraulic performance of the TALL test facility [17], comparing the simulation results with the experimental results obtained from the LBE-cooled system. The objectives of the present work are two-fold: i) to interpret the transients performed on the facility; ii) to qualify the capabilities of the TRACE code for HLM-cooled system by using the experimental data and then perform separate-effect study beyond the experimental conditions.
2 Simulation Tools

In this thesis, the TRACE code is selected as the simulation tool with the version 5.0 Patch 2.

2.1 TRACE code

TRACE means “The TRAC/RELAP Advanced Computational Engine”, with the former name of TRAC-M, developed by the U.S. Nuclear Regulatory Commission (U.S. NRC). It is the combination of four main NRC’s system codes: TRAC-P, TRAC-B, RELAP5 and RAMONA. As a modernized computational tool, TRACE becomes a popular reactor system code for the light water reactors gradually. It can be used to analyze a lot of questions such as transient, steady-state neutronic and thermal-hydraulic phenomena.

Some models, such as non-equilibrium thermo-dynamics, generalized heat transfer, reflood, level tracking, and reactor kinetics, etc., are implemented in the TRACE code. Thus, not only accident scenarios like loss-of-coolant accidents (LOCA) and operational transients can be simulated, but also the phenomena may occur in experimental facilities can be modeled to perform best-estimate analyses.

TRACE is a component-based code. That means every physical structure will be modeled as a component. Moreover, nodalization of these components will be carried out subsequently. In this procedure, components will be nodalized into cells in which the equations are averaged. Main equations used in the code are the partial differential equations and the fluid-dynamic equations which are used in describing two-phase flow and heat transfer in finite numerical methods and in the multi-step time-differencing process respectively. Besides, the coupled and non-linear equations series that formed by hydrodynamic phenomena finite difference equations are solved by the Newton-Raphson iteration method while the linearized equations are solved by matrix inversion. As a user-friendly approached code, the model is easy to be modified. The number of components is not limited and the size limitation only depends on the computer memory. For the type of components, TRACE code can model pipes, plenums, separators, valves, pressurizers, fuel channels, power, heat-structures (HTSTR) etc. Specified components’ model of TALL facility will be introduced in the following chapter.
2.2 Characteristics of TRACE

**Variable-Dimensional Fluid Dynamics**

A general phenomenon, such as Emergency Core Cooling (ECC) occurring in the reactor vessel, can be simulated due to 3D \((r, \theta, z)\) flow calculation which carries out the more explicit calculation of multidimensional flow is used. The flow in the components will be dealt as one-dimensional flow.

**Non-homogeneous, Non-equilibrium Modeling**

The steam-water flow is described by the full two-fluid hydrodynamics model that contains 6-equations, as a result, some vital phenomena such as counter-current flow limit (CCFL) will be treated more accurately. Mass balance (7\(^{th}\) equation) describes a non-condensable gas field while eighth field equation describes the solutes in the liquid.

**Flow-Regime-Dependent Constitutive Equation Package**

Mass, energy and momentum transferring between steam-water phases and the interactions of the 2 phases, both of them are described by the thermal-hydraulic equations. Because of the dependency on flow topology of these interactions, the flow-regime-dependent constitutive equation package is integrated in the code.

**Consistent Analysis of Entire Accident Sequences**

As an important feature of TRACE, including initial conditions and the continuous calculation, the whole accident sequences can be addressed and modeled. In another word, the modeling will have no need to use different codes to analyze the accidents. In addition, both calculation of steady-state and the transient can be operated in the same run.

**Comprehensive Heat Transfer Capability**

Conduction of heat in metal structures uses the 2D \((r,z)\) in TRACE. The quench front heat transfer is simulated by the dynamic fine-mesh rezoning during reflood, meanwhile, the fuel rod heat transfer will be calculated by using flow-regime-dependent HTC.

**Physical Phenomena Considered in TRACE**

Most physical phenomena occurred in nuclear power plants can be modeled in TRACE listed as following [20]:

---

9
- Large break LOCA, small break LOCA, non-LOCA;
- ECC down-comer penetration and bypass, including counter-current flow and hot walls effect;
- Lower-plenum refill and phase separation effects;
- Falling-film quench fronts and bottom-reflood;
- Multidimensional flow patterns in down-comer, plenum regions and core;
- Pool formation and counter current flow at the region UCSP (the upper-core-support-plate);
- Pool formation in the upper plenum;
- Steaming binding;
- Average and hot rod cladding temperature histories;
- Alternate Emergency Core Coolant injection system, Hot-leg and upper-head injection included;
- Sub cooled ECC water direct injection;
- Liquid carryover when reflood;
- Water/metal reaction;
- Water-hammer effects;
- Wall friction losses;
- Natural circulation;
- Horizontally stratified flows;
- Non-condensable-gas tracking and interfacial condensation effect of non-condensable gas;
- Liquid-solute tracking;
- Balance-of-plant modeling capability;
- 1D calculation or 1D and 3D mixed calculation;
- Trip, control-system and general component action modeling.

2.3 User Limitation

Generally, codes should be applicable among their assessment range. For TRACE, it has got the qualification to analyze both large and small break LOCA in ESBWR, PWR and BWR. Recently, an assessment of BWR stability analysis has also been carried out. But it is not suitable for simulating the situation that the momentum transfer plays a significant role. Moreover, TRACE is not appropriate to perform the transient with large changing asymmetries in core power. Undoubtedly, more shortages will be found by users, because TRACE is a relatively new code compared to other traditional nuclear industrial codes. However the code will be improved through the continuous validation and upgrade.
2.4 SNAP

Symbolic Nuclear Analysis Package (SNAP) is an editor sponsored by US government which can simplify both the process of performing the thermal-hydraulic analysis and the complicated work of compiling the input file in ASCII code formatting. It is developed in the Java environment with the functions like creating and editing the input of engineering analysis codes, submitting, error check, monitoring and so on. Currently, SNAP can support the RELAP5, TRACE, CONTAIN and FRAPCON-3 codes while the supporter of MELCOR and FRAPTRAN plug-in is under development [21].

The user interface of SNAP Model Editor includes Main Toolbars, View Toolbars, Navigator, Main Property View, 2D/3D Views and Message Window as illustrated in Figure 2.1.

![Figure 2.1 The SNAP model editor user interface.](image)

All the components used in TRACE code can be modeled in SNAP model editor. The main TRACE components with representation logo in SNAP are showed as the following Table 2.1:
In this work, model creating and editing as well as submitting are all accomplished in SNAP. The specific TRACE model description of TALL facility will be introduced in the following chapter.
3 Model description

The TRACE simulation runs executed in this study are corresponding to the transient test scenarios carried out on the TALL facility at KTH. In this chapter, a TRACE simulation model is created through choosing appropriate components to match the corresponding parts of the facility.

3.1 TALL facility and transient tests

The TALL facility contains two loops: the primary loop and the secondary as shown in Figure 3.1[15]. The primary loop is LBE loop, with the lead-bismuth eutectic inside, mainly containing an EM pump, EM flowmeter, controllable heater, heat exchanger, pipes, core tank, sump tank and expansion tank. The secondary loop with Glycerol as working fluid is composed of a pump, oil tank, flowmeter, heat exchanger and piping. The whole height is 6.8 m and the major parameters including LBE volume, pressure drops, flow velocity are scaled by the prototypic ratio (power/volume) of a conceptual ADS design. The technical parameters are listed as follows:

- All parts contacting with LBE fluid are made of 316 or 316L stainless steel and the internal surface are dealt by the oxidizing process
- The height is 6.8m
- Maximum electric power is 55kW
- Maximum flow velocity of LBE can reach 3 m/s in the heat exchanger.
- Maximum LBE volume flow rate can reach 2.5 m$^3$/h.
- Maximum LBE temperature maintains at 500°C.
- Maximum temperature difference of the heat exchanger is 150°C.
- The top pressure is ~1bar and the bottom pressure is ~8bar.
- Maximum natural convection velocity is ~0.5m/s.
- LBE is consisted by 45% Pb and 55% Bi in weight. The melting point is 123.5°C.
- The purity of LBE is higher than 99.5%.
- Oxygen level in LBE could be measured.
- Glycerol ($C_3H_8(OH)_3$) is used as the coolant of the secondary loop with the boiling point of 290°C.
- Configuration provides flexibility for employing different intermediate heat exchanger, core tanks, etc.
- Data acquisition and controlling are provided.
The TALL facility as shown in Figure 3.1 is called Configuration-A, where the core tank holds four immersion heaters that have 28kW electric power supply. The 1 meter long core tank (item 2 in Figure 3.1) of ~8 liters in volume was scaled so that it can represent the reactor core of a conceptual ADS design corresponding to one tube of the
intermediate heat exchanger, especially from the aspects of flow resistance and coolant inventory. Multi-hole plates are placed in the tank in order to increase the flow resistance. The IHX (item 14 in Figure 3.1) is composed of an inner tube and an outer pipe, with the LBE flowing in the inner tube and glycerol flowing in the annulus. A 10-mm-I.D. and 1.5-mm-thick-wall tube is used as the inner tube. The inside diameter of the outer pipe is 22 mm. Some transient experiments performed on this configuration include [17]:

- Loss of heat sink.
- Loss of primary pump.
- Loss of both primary and secondary pumps.
- Over power.
- Overcooling.
- Heater trip (to simulate accelerator trip in an ADS rector).
- Startup/shutdown operation.

In order to investigate the LBE flow and heat transfer performances around a single fuel rod, the TALL facility is modified by replacing the core tank by a core simulator which is composed of a single fuel rod simulator inserted in a pipe, as illustrated in Figure 3.2, called Configuration-B. Besides, the geometry of the IHX is changed in the modification (cf. Figure 3.2c) to scale the ratio of pressure drops in the core simulator and the new IHX. Except these two components, other components in Configuration-B remain the same as Configuration-A. The details of the core simulator, the single fuel rod simulator and the new IHX can be found in Figure 3.2.
Figure 3.2 Core simulator and new heat exchanger. (a) Core simulator, (b) Fuel rod simulator, (c) New IHX.

3.2 Simulation model

Based on the test facility described above, the corresponding simulation model is created as shown in Figure 3.3.
3.2.1 The primary loop model

For the primary loop, core tank is modeled by a pipe component-pipe 100. The pipe 100 is divided into 10 cells. The inlet and outlet of core tank are defined as cell-1 and cell-10 respectively. Cells are divided by the geometry scale according to the facility, thus, it is not an averaged dividing. From cell-2 to cell-5, power-51 which links to heat structure-31 is located to simulate the heaters of core tank in TALL facility. Heat structure-31 is represented by 6 mesh intervals: 3 of them represent the NiCr, 1 is put for modeling filler of MgO, and another 2 are stainless steel 316 cladding. There are no options for material properties of NiCr and MgO, thus, the material properties of NiCr and MgO are defined as material-50 and material-51, respectively, showed in Table A.1 and Table A.2 in Appendix 1. The multi-hole plates in the upper part of core tank are simulated by decreased flow areas and pressure drop coefficients between cell-6 and cell-10 of pipe-100. The pressure loss coefficient can be calculated by the following correlations [19].

For sudden flow area changing:

1) Expansion: \[ K_{\text{exp}} = \left( 1 - \frac{F_0}{F_1} \right)^2 \] (3.1)
2) Contraction:  
\[ K_{con} = 0.5 \cdot \left(1 - \frac{F_0}{F_1}\right) \]  
(3.2)

Where \( F_0 \) and \( F_1 \) are the flow areas upstream and downstream, respectively.

For pipe bending:

1) Small curvatures \( \left(\frac{R_o}{D_h} < 1.0\right)\):  
\[ K_{fr} = 0.0175 \cdot \lambda \cdot \frac{R_0}{D_h} \cdot \alpha + \frac{0.21}{\left(\frac{R_0}{D_h}\right)^{2.5}} \cdot C \]  
(3.3)

2) Large curvatures \( \left(\frac{R_o}{D_h} \geq 1.0\right)\):  
\[ K_{fr} = 0.0175 \cdot \lambda \cdot \frac{R_0}{D_h} \cdot \alpha + \frac{0.21}{\left(\frac{R_0}{D_h}\right)^{0.5}} \cdot C \]  
(3.4)

\[ C = \begin{cases} 
0.9 \cdot \sin \alpha & \text{for } \alpha \leq 70^\circ \\
1.0 & \text{for } \alpha = 90^\circ \\
0.7 + 0.35 \cdot \frac{\alpha}{90} & \text{for } \alpha \geq 90^\circ 
\end{cases} \]  
(3.5)

Where \( R_0 \) and \( D_h \) are the band radius and the hydraulic diameter of the pipe, respectively; \( \alpha \) is the bend deflection angle \( (^\circ) \); \( \lambda \) is the friction pressure loss coefficient as Equation 3.6.

\[ \lambda = \max \left[ \frac{64}{Re} \left( \frac{0.316}{(Re^{0.25})} \right) \left( 2 \log \left( \frac{D_h}{2 \cdot ROUGH} \right) + 1.74 \right) \right]^{-2} \]  
(3.6)

The LBE–glycerol heat exchanger is simulated in two parts, the side of LBE loop is modeled as pipe-400 whereas the secondary side is simulated by pipe-900. Heat structure-41 is used to simulate the inner pipe wall of heat exchanger which represents the heat transfer between two sides of heat exchanger.

EM pump is simulated by 3 components. The volume of pump is modeled by pipe-600. The mass flow controller is simulated as pump-650 linking to function -1 which can carry out the mass flow variation with time. During the transient loss of primary pump, the single junction-6 will work as the pump bypass due to the pump-650 will shut down. To avoid the reverse flow, an extreme large coefficient of \( K_{rev} = 10^{10} \) has been defined for the junction. The symbol picture of EM pump in SNAP is as shown in Appendix B Table B 1.
The expansion tank is modeled by a BREAK component-BREAK-81 with a constant pressure equal to 1.2 bar. The symbol picture of EM pump in SNAP is as shown in Appendix B Table B 1.

Heat structures (91, 101, 121, 131, 141, 151, 161, 171,181,191, 201, and 211) are used to model the heat losses through the insulation of the primary loop. Because the asbestos is the insulation material for the TALL facility, its properties including density, conductivity and heat capacity in different temperatures are input as materials-54 shown in Appendix A Table A.4.

Due to the melting tank and the sump tank will not influence the thermal-hydraulic properties much, these two components will be ignored during the simulation.

3.2.2 The second loop model

The main function of the secondary loop is to provide the steady coolant for the LBE-Glycerol heat exchanger. In that case, it needs not to simulate the whole loop. Thus, the secondary loop is modeled as Figure 3.4 showing:

![Figure 3.4 TRACE model of secondary loop.](image)

Pipe-900 is the secondary side of heat exchanger, the hydraulic diameter and the flow area are 0.012 m and 3.58E-4 m², respectively. The break-90 is to maintain the outlet boundary condition while the Fill-61 will provide the mass flow. In addition, Fill-71 is set for reflood in the transient loss of heat sink, controlled by trip.
3.2.3 Modification of HTC

In the simulations the glycerol flow in the secondary side is replaced by LBE, since the properties of glycerol are unavailable in the TRACE code. The flowrate of the LBE flow and heat conduction resistance of the IHX inner wall is scaled up so as to maintain the temperature level in the secondary side and total heat transfer coefficient (HTC). This way the effects of the secondary side on the thermal-hydraulics in the primary loop are properly captured.

To keep the temperature difference $\Delta T$ in the secondary side of the IHX, the instead mass flow of LBE can be calculated by the following equations:

$$Q = C_{p-LBE} \cdot m_1 \cdot \Delta T$$

$$Q = C_{p-glycerol} \cdot m_2 \cdot \Delta T$$

Where $Q$ is the heat transferred in the LBE-glycerol heat exchanger; $C_{p-LBE}$ and $C_{p-glycerol}$ are the heat capacity of LBE and glycerol under temperature of 130 °C, respectively; $m_1$ and $m_2$ are the mass flow rate of instead LBE and glycerol. $m_2$ is 0.69 kg/s in the experiments, thus, corresponding $m_1$ is calculated to be 13.924 kg/s.

To calculate $v_{-LBE}$ (the velocity of instead LBE) and $v_{-glycerol}$ (the velocity of glycerol), following equations are used:

$$v_{-LBE} = \frac{m_1}{A} \cdot \frac{1}{\rho_{-LBE}}$$

$$v_{-glycerol} = \frac{m_2}{A} \cdot \frac{1}{\rho_{-glycerol}}$$

Where $A$ is the flow area of LBE which is the same with the flow area of glycerol in experiments, $\rho_{-LBE}$ and $\rho_{-glycerol}$ are the density of LBE and glycerol, respectively. Thus, $v_{-LBE}$ is 21.48487 m/s and $v_{-glycerol}$ is 9.063 m/s. The total heat transfer coefficient of the heat exchanger is defined as $H_f$, then, $H_{f-glycerol}$ (HTC of glycerol) and $H_{f-LBE}$ (HTC of LBE) can be expressed as following equations:

$$H_{f-glycerol} = K_{-glycerol} \cdot \frac{Nu_{-glycerol}}{L}$$

$$H_{f-LBE} = K_{-LBE} \cdot \frac{Nu_{-LBE}}{L}$$

Where $K$ is the thermal conductivity, $Nu$ is the Nu number and can be calculated by Equation 3.13 for LBE and Equation 3.14 for glycerol.
To calculate Nu number:

\[
\text{Nu}_{-\text{LBE}} = 7 + 0.0025(Re_{-\text{LBE}} \times Pr_{-\text{LBE}})^{0.8}
\]  \hspace{1cm} (3.13)

\[
\text{Nu}_{-\text{glycerol}} = \frac{(f/g) \cdot (Re_{-\text{glycerol}} - 1000) \cdot Pr_{-\text{glycerol}}}{1 + 12.7 \cdot (f/g)^{0.5} \cdot (Pr_{-\text{glycerol}}^{2} - 1)}
\]  \hspace{1cm} (3.14)

Where Re-glycerol and Re-LBE denote the Reynolds number of glycerol and LBE, respectively; Pr-glycerol and Pr-LBE are the Prandtl number of glycerol and LBE, respectively. The Reynolds number and Prandtl number can be calculated by Equation 3.15 and Equation 3.16.

\[
Re = \frac{(\rho \times v \times D_{h})}{\mu}
\]  \hspace{1cm} (3.15)

\[
Pr = \frac{C_{p} \times \mu}{K_{\mu}}
\]  \hspace{1cm} (3.16)

Where \(D_{h}\) is the hydraulic diameter of annular bypass of coolant in heat exchanger, \(\mu\) is the dynamic viscosity. In experiment, the inner tube of LBE-glycerol heat exchanger is made of Stainless Steel 316 (with the thermal conductivity \(K_2\)). To remain the same HTC after replacing the glycerol into LBE, a new material with thermal conductivity \(K_1\) is set to instead the Stainless Steel 316.

In experiment,

\[
\frac{1}{H_{f}} = \frac{1}{H_{f-\text{LBE}}} + \frac{L}{K_{2}} + \frac{1}{H_{f-\text{glycerol}}}
\]  \hspace{1cm} (3.17)

After material replacing,

\[
\frac{1}{H_{f}} = \frac{2}{H_{f-\text{LBE}}} + \frac{L}{K_{1}}
\]  \hspace{1cm} (3.18)

Where \(L\) is the effect length of secondary side of heat exchanger. So, \(K_1\) can be calculated by resolving Equation 3.17 and Equation 3.18. Other properties should be the same as Stainless Steel 316.

According to the modification mentioned above, the modified thermal conductivities for the defined new material (material-53 properties under different temperatures are listed as in Appendix A Table A.3. The whole model of TALL facility in SNAP editor is shown as in Appendix B Figure B. 1.
4 Results and discussions

The simulation results by using TRACE code are reported in this chapter, together with the comparison between the simulation results and the experimental data from the tests on the TALL facility with Configuration-A [15][16][17] and Configuration-B[18]. The transients simulated for Configuration-A include loss of heat sink, loss of primary pump, loss of both primary and secondary pumps, overpower, heater trip, start-up and shut-down transient, as listed in Table 4.1. Due to space limitation and time constraint, only the transients of start-up and loss-of-heat-sink of Configuration-B are presented in the thesis. Furthermore, as a separate-effect study, some additional loop features which are not implemented in the experiments are also simulated and reported here, so as to give an idea how the LBE inventory and flow resistance in the primary side and mass flowrate in the secondary side will affect the transient thermal-hydraulic performance of the LBE-cooled system.

4.1 Transients of Configuration-A

All the cases simulated are listed in Table 4.1 below:

<table>
<thead>
<tr>
<th>Cases</th>
<th>LBE initial conditions</th>
<th>Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up</td>
<td>LBE: T=200 °C, v=0 m/s</td>
<td>Pumps and heater power are switched on at the same time</td>
</tr>
<tr>
<td>Loss of heat sink</td>
<td>$T_{\text{IHX, inlet}}=400$ °C, $\Delta T_{\text{IHX}}=100$ °C, v=1 m/s</td>
<td>Switch off the glycerol pump</td>
</tr>
<tr>
<td>Loss of primary pump</td>
<td>$T_{\text{IHX, inlet}}=350$ °C, $\Delta T_{\text{IHX}}=80$ °C, v=1 m/s</td>
<td>Switch off the EM pump</td>
</tr>
<tr>
<td>Loss of both primary and secondary pumps</td>
<td>$T_{\text{IHX, inlet}}=350$ °C, $\Delta T_{\text{IHX}}=80$ °C, v=1 m/s</td>
<td>Reduce the LBE and glycerol flow rates simultaneously</td>
</tr>
<tr>
<td>Overpower</td>
<td>Steady-state forced convection</td>
<td>Increase the power by 100%</td>
</tr>
<tr>
<td>Heater trip</td>
<td>$T_{\text{IHX, inlet}}=400$ °C, $\Delta T_{\text{IHX}}=100$ °C, v=1 m/s</td>
<td>Switch the heater for 15 s and 25 s</td>
</tr>
<tr>
<td>Shut-down</td>
<td>Steady-state forced convection</td>
<td>Switch off the heater, keeping forced flow and glycerol pump</td>
</tr>
</tbody>
</table>
4.1.1 Start-up of forced circulation

The start-up of TALL facility is an operational transient. The initial/steady conditions are: LBE temperature of the primary loop is about 200 °C initially; power of core tank initially is 0 kW, while the final power is 8.5kW; initial LBE flow is 0 kg/s and final LBE flowrate is 0.91 kg/s; initial and final Glycerol (oil) flow are 0 kg/s and 0.69 kg/s, respectively.

After the beginning of transient, at about 140th second, power of core tank started to be provided whereas both of the primary and secondary loop pumps were switched on to work. As you can see in Figure 4.1, the velocity of LBE in IHX (intermediate heat exchanger) under steady-state is 1m/s and its temperature drop would reach about 50 °C.

Figure 4.1 illustrates the simulation results at the condition of start-up forced circulation. Figure 4.1 (a) - (b) show the temperature variation during the start-up case of TALL facility; Figure 4.1 (c) presents the temperature difference both in the core tank and IHX; and Figure 4.1 (d) - (e) show the mass flow and velocity of LBE in IHX respectively. The experimental data are also plotted in corresponding figures for comparisons.

At the beginning of this transient, due to the coolant in the secondary loop, the outlet temperature of heat exchanger would decrease to a low value (appears at about 200 s) which close to the inlet temperature of core tank. As the colder LBE flowing from the outlet of IHX to the inlet of core tank, the minimum inlet temperature of core tank appears at around 350 s. Then, the outlet temperature of core tank increases with the power input. Due to the LBE fluid moves from core tank to IHX, the inlet temperature of IHX would increase too. The stable balance will be established, the steady state is obtained at about 3000 s.

It can be seen from Figure 4.1 that the simulation results with TRACE code have a good agreement with the experimental data. It is noteworthy that the computational results reach the stable state earlier than the experimental data due to the lower value of insulation leading heat loss decrease.

Generally, according to comparison between computational results and experimental results, the validation shows the TRACE code is suitable for simulating the performance of LBE fluid.
(a) Temperature variation of core tank.

(b) Temperature variation of heat exchanger.
(c) Temperature difference of Heat exchanger and core tank.

(d) LBE velocity in IHX.
4.1.2 Loss of heat sink

A loss of heat sink event is usually considered in the safety analysis for all types of reactors. Its consequences are often quite severe and most safety analyses have to assure good predictions. Thus, it is very important to study the progression phenomena of loss of heat sink.

The initial conditions of performance of this transient are as following: inlet temperature of LBE-Glycerol heat exchanger is around 300 °C; the temperature drop in LBE side of heat exchanger is about 50 °C; the core tank power input is 8.5 kW and the velocity of LBE flow in IHX is around 1 m/s.

Secondary pump was switched off at the 650th seconds after steady-state. Therefore the glycerol flow would reduce to 0 kg/s immediately. The reflooding pump will provide the coolant as before when the temperature of inlet of core tank reached 460 °C, since the tests will be stopped to avoid overheating. The reflood process is controlled by the trip in the TRACE model.
Figure 4.2 shows the performances of loss of heat sink transient. In Figure 4.2 (a) and (b), we can see that the temperatures of both inlet and outlet of core tank and IHX increase rapidly after the beginning of the transient. Moreover, the outlet temperature is very close to the inlet temperature in heat exchanger. When loss of heat sink occurs, heat exchanger will stop working. Thus, the temperature drop of IHX will be close to 0 °C.

At around 4000 s, the secondary pump is restarted when the outlet temperature of core tank has reached to 460 °C. As a result, the heat exchanger gets the coolant again and the IHX will restart to work. Its temperature drop will reach over 100 °C as illustrated in Figure 4.2 (d). Figure 4.2 (c) shows the similar consequence. That owes to the propagation of cooled LBE. Finally, the steady state is re-established.

Comparing with the experimental results, it takes a relatively longer time to the stable state after reflooding and the temperatures of both core tank and heat exchanger reduce relatively slow. The possible reason is the insulation modeled in TRACE model is higher than that in reality tests.

(a) Temperature variation of core tank
(b) Temperature variation of IHX

(c) Temperature difference core tank
4.1.3 Loss of primary pump

The loss of primary pump is the totally passive-mode transient of the primary loop circulation. It is a very important transient and always be required to be analyzed for most types of nuclear reactor due to the relatively high probability. Particularly, this event is related to the natural circulation potential. With the reason that capacity of natural circulation of loop is really a key point of the LBE cooled reactor passive safety, therefore, it is essential to analyze the consequences of this transient.

The initial conditions of transient are as follows: LBE temperature at the inlet of the IHX is around 350 °C; temperature drop along the primary side of the IHX is about 80 °C; initial core tank power is 12.4 kW and the initial velocity of LBE in the IHX is around 1 m/s.

At about 550 s, the primary pump was switched off, transient was started. The rotational speed of primary pump would reduce to 0 in 2 s after pump being switched off. Therefore
the LBE flow in primary loop would loss utterly. The simulation results corresponding to the transient loss of primary pump is plotted in Figure 4.3.

As shown in Figure 4.3 (d), the forced circulation velocity of LBE in the primary flow decrease dramatically to about 0 m/s in a short time when the EM pump is switched off. After a fluctuation which lasts about 500 s, LBE velocity in IHX increases to about 0.5 m/s gradually. It is confirmed that the natural circulation is formed due to the temperature difference between core tank and heat exchanger. Because of the power input and the constant coolant provided by the secondary loop, the core tank becomes the hot leg while the primary side of IHX is turned to the cold leg, and the natural circulation is driven by the temperature difference. As a result of natural circulation, a new heat balance is established. As shown in Figure 4.3 (a), (b) and (c), the outlet temperature of core tank increases and maintains at about 430 °C while the inlet temperature of core tank decreases to about 230 °C. Due to the movement of LBE flow, similar performance occurs at the inlet and outlet of heat exchanger. Besides, the temperature drop along the heat exchanger increases from about 80 °C to over 160 °C while the temperature rise along the core tank is reaching to about 210 °C from the initial 90 °C approximately. The temperatures both in heat exchanger and core tank are increased in a big scale with the reason that the mass flowrate of LBE under natural circulation is lower than the mass flowrate under the forced circulation, the exact value are 0.47 m/s and 1.04 m/s, respectively.
(a) Temperature variation of core tank.

(b) Temperature variation of IHX.
Figure 4.3 Performances of loss primary flow transient.
Generally, it is clear that the computational results have a good agreement with experimental results.

4.1.4 Loss of both primary and secondary pumps

The transient loss of both primary and secondary pumps means the simultaneous stop of both the pumps in the primary loop and in the secondary loop. It may happen when the primary and secondary pumps shut down or the electrical supply is not working. Though the case of both pumps shut down at the same time may occur in a relatively low probability, the consequence of that would be more severe than loss of primary pump transient. Once the case occurs, the accelerator will fail to trip and reduce the core tank power.

According to the design of LBE ADS Error! Reference source not found., significant natural circulation will be formed in the primary loop by heat removal of the secondary loop where natural circulation is also ensured by design (passive safety) when its pump shuts down. It may keep enough heat removal capacity to remove the decay heat. However, in the tests on TALL facility [17], due to the height constraint of the laboratory, the natural circulation capacity of the secondary loop is not available by design. Thus, the flow rate in the secondary loop is reduced (instead of switching off the oil pump) to a certain level so as to scale the natural circulation capacity in a real transient of an ADS design. Thus, the transient becomes a partial loss of secondary flow and total loss of primary pump.

The modified initial conditions of transient are listed: (1) the temperature of LBE in inlet of the LBE–Glycerol IHX is about 350 °C; (2) temperature drop in LBE–Glycerol IHX is 80 °C; (3) initial core tank power is 12.4 kW while LBE velocity in the IHX is about 1 m/s.

In this simulation, at the 500th s after the beginning of the transient, LBE pump (the primary pump) was switched off and the whole procedure would last 2 seconds. The Glycerol flow rate in the secondary loop decreases from 1.4 kg/s to 0.4 kg/s in 5 seconds. In TRACE validation, the replacing flow rate of LBE coolant in the secondary loop would reduce from about 28 kg/s to 9.8 kg/s. This replacement is calculated and tested for many times. The simulation results are illustrated in Figure 4.4.
(a) Temperature variation of core tank.

(b) Temperature variation of IHX.
(c) Temperature difference of core tank.

(d) Temperature difference of IHX.
(e) Velocity of LBE in IHX primary side.

Figure 4.4 Performance of the transient loss of both primary and secondary pumps.

As shown in Figure 4.4 (a) and (b), the outlet temperature of core tank increase sharply accompanied by the increasing of inlet temperature of IHX when the primary pump is switched off at 500 s.

The results of transient in the first 500 s are very similar to the results of loss of primary pump transient described above. Meanwhile, the cooling capacity of secondary flow decreases with reducing of the flow rate of secondary loop, which leads to a rising of the outlet temperature in IHX primary side. This trend lasts till the end of the calculation and the new balance has not been established. The calculation stops when the outlet temperature of the core tank reaches about 470 °C since the facility may be destroyed under the higher level.

It is clear that the comparison with the experimental data shows good agreement for all the cases.
4.1.5 Overpower

Because of some possible malfunction of the accelerator in ADS system, the power of ADS-related reactor may increase sharply in a short time. For much of reactor cycle, the associate accelerator is needed to control well under the maximum level, otherwise it will lead to a large reactivity swing in the fuel cycle. Therefore the overpower transient is becoming a crucial transient for analyzing the safety of ADS system.

In this transient, the power would be doubled from 8.5 kW to 17 kW. The initial conditions were as following: (1) LBE temperature of inlet of IHX is around 300 °C; (2) Temperature drop in IHX is about 50 °C; (3) core tank power is 8.5 kW; (4) LBE velocity in IHX is about 1 m/s. The simulation results are plotted in Figure 4.5.

(a) Temperature variation of core tank.
(b) Temperature variation of IHX.

(c) Temperature difference of core tank and IHX.
As shown in Figure 4.5 (d), the power is doubled from 8.5 kW to 17 kW at 210 s, the transient starts. It can be seen from Figure 4.5 (a) - (b) that the outlet temperature abruptly increases (about 50 °C) due to the hot LBE will flow through the outlet initially. Then, the temperature of the downstream components increases gradually and sequentially with the flow of heated LBE. That is why the dramatic increase in temperature always appears at inlet and outlet of IHX and inlet of core tank. With the system temperature increasing, primary loop temperature stabilizes at a higher level. The final temperatures of both inlet of IHX and core tank rise to 150 °C while the temperature difference of core tank and IHX are enhanced to about 100 °C.

Generally, the agreement between TRACE calculation and experimental results is excellent. It is believed that TRACE code can simulate accurately under the changeable power conditions.

4.1.6 Heater trip

Beam trip occurs in a high probability and cannot be avoided in ADS. It is essential to consider the consequences of beam trip for ADS reactor safety analysis.
Heater trip transient is to simulate the beam trip event. The initial conditions are: (1) LBE temperature at inlet of IHX is around 400 °C; (2) temperature of LBE-Glycerol IHX is about 100 °C; (3) initial power is 14.7 kW and the initial LBE velocity in IHX is 1 m/s.

It should be denoted the power of core tank immersion heaters would be switched off at 160th s. While, 25 seconds later, the power is switched on again with the same value as before. Again, 15 s later, the power would shut down and after another 25 s, the power would be restarted. This switch on/off procedure would be repeated for the whole transient simulation. Figure 4.6 shows the simulation results.

(a) Temperature variation of core tank.
(b) Temperature variation of IHX.

(c) Temperature difference of core tank and IHX.
As shown in Figure 4.6 (d), after the transient starting, the power changes as a fluctuation variation. The averaged power declines to about 5.5 kW, around 37.5% of the initial power. With lower averaged power input, a new steady state will be established with lower temperature level.

It can be seen from Figure 4.6 (a) and (b), the temperature of core tank outlet decrease, and then, the temperature of inlet and outlet of IHX and the temperature of core tank inlet decrease accompanied successively. The main reason has been described in the results of heater trip transient. Figure 4.6 (c) shows that the temperature difference across core tank approaches a new stable value, it decreases from 110 °C to about 50 °C. Meanwhile, the temperature difference along the heat exchanger decreases continuously.

4.1.7 Shut-down

Finally, the shut-down procedure is performed. There are two steps: (1) reducing the temperatures of all the components to about 200 °C; (2) collecting LBE in the sump tank. In present study, TRACE simulation just simulates the first step.
In this transient, initial conditions are: (1) LBE temperature at inlet of IHX is around 420 °C; (2) temperature of LBE-Glycerol IHX is about 115 °C; (3) initial power is 17 kW and, the core tank power was shut down from 17 kW to 0 kW at 280th seconds. Figure 4.7 illustrates the results.

(a) Temperature variation of core tank.
(b) Temperature variation of IHX.

(c) Temperature difference of core tank and IHX.

Figure 4.7 Performance of shut down transient.
It can be seen from Figure 4.7 that the temperature in every position decrease due to the power input becomes to be 0 kW from the beginning of transients. It takes about half an hour to reach the cold condition (about 200 °C) as shown in Figure 4.7 (a) and (b). From Figure 4.7 (c), it is noted that the temperature drop of core tank reduces to around 20 °C and keeps the stable level in about 100 s. The temperature drop in IHX primary side goes a declining trend and keeps decreasing till the transient ends. The reason is that the coolant is provided constantly.

Also, it is clear that the simulation results are comparable with the experimental data generally.

4.2 Transients of Configuration-B

4.2.1 Start-up transient

In this operational transient, the initial/steady conditions are assumed as following: LBE temperature of the primary loop is about 220 °C without forced flow and power input. At the beginning of transient (80 th s), input power would arrive at 21 kW while the velocity of LBE inside the core simulator would get 2 m/s. Figure 4.8 presents the simulation results.
(b) Temperature variation of the new IHX.

(c) Temperature differences of the core simulator and IHX.

Figure 4.8 Performance of the start-up transient of Configuration-B.
Figure 4.8 (a) - (b) show the temperature variation during the start-up case of modified TALL facility. Figure 4.8 (c) shows the temperature difference between the core simulator and IHX. The experimental data are also plotted in the corresponding figures for comparison.

At the beginning of this transient, the temperature of heat exchanger outlet reduces to a low value (appears at about 90 s) due to the coolant in the secondary loop. Because of the movement of LBE flow, the inlet temperature of the core simulator performs similarly following the temperature of HX outlet, with the peak value appearing at about 100 s. Then, as a result of inputting power, the temperature of core simulator outlet increases. The coolant in the secondary loop removes the heat in HX which causes the temperature drop along the HX. Stable balance will be set up at about 800 s. All this procedure approximates the same transient performance of the configuration-A facility. However, every process in transient last shorter time and the whole system will reach to steady state in about 700 s, while the same process of configuration-A facility needs around 2700 s. There maybe have two main reasons. Firstly, the power input in this transient is 21 kW which is much higher than the power (8.5 kW) input in the configuration-A facility test. Moreover, the volume of core simulator in this transient is much smaller than configuration-A. The volume effects will be introduced specifically in the later chapter.

Generally, the results by TRACE code predicts well comparing with the experimental data. It is interesting that the experimental curve presented in Figure 4.8 decreases earlier than the computational curve. That may be caused by the early start up of the pump in the secondary loop in the experiments.

### 4.2.2 Loss of heat sink transient

With the same reasons as the configuration-A simulations, loss of heat sink transient is operated in the single rod simulation.

The initial conditions of this transient is as following: temperature of LBE-Glycerol heat exchanger inlet is near 300 °C; temperature drop in LBE side of heat exchanger is about 50 °C; the core simulator power and the LBE flow velocity in HX are 21 kW and around 2 m/s, respectively. The results are shown in Figure 4.9.

At the 50th s, the secondary pump is switched off and therefore the glycerol flow reduces to 0 kg/s immediately. With the temperature increasing caused by the losing of heat remove capacity, the reflood process is operated when the temperature of inlet of core simulator reached 460 °C.
(a) Temperature variation of core simulator.

(b) Temperature variation of the new IHX.
Figure 4.9 Performance of the loss-of-heat-sink transient of Configuration-B.

Everything is quite similar to the former simulation of the configuration-A model. From Figure 4.9 (a) - (b), the temperature of both inlet and outlet of the core simulator and new IHX increase rapidly from the start of the transient. Moreover, the outlet temperature approaches to the inlet temperature in heat exchanger due to the loss of cooling.

At around 420 s, the outlet temperature of core simulator has reached to 460 °C that triggers the reflood. As the result, coolant in the new IHX is provided again and causes an over 40 °C temperature drop in the new IHX, as shown in Figure 4.9 (d). Besides, Figure 4.9 (c) shows the similar consequence. Owing to the propagation of cooled LBE, the steady state is re-set finally. Because of the same reason described in start-up transient analysis, the temperature rising process is obviously shorter than the transient operated in the configuration-A model.

The results are also comparable with the experimental curve. However, the computational curve decreases slowly than the experimental one. The possible reason is the parameter about insulation in the model is not very explicit.
4.3 Separate-effect analysis

In order to investigate the effects of different factors on the thermal-hydraulic performance of the TALL facility, several groups of simulation have been conducted which focuses on the effects of LBE inventory in the core simulator, flow resistance in primary side of IHX, and mass flowrate of secondary side coolant. These simulations are not tested in the TALL facility and all the models are modified from the model for the loss-of-primary-pump transient of Configuration-A.

4.3.1 Effect of LBE inventory in the primary loop

To investigate the LBE inventory in the primary loop, simulations are divided into three groups and the difference among them is the volume of the core tank. Vc1, Vc2 and Vc3 are corresponding to the volumes of the core tank in these three simulations. Vc1 is the standard volume as used in Configuration-A, while Vc2 and Vc3 are twice and half of Vc1, respectively. All other parameters and initial conditions are the same as the case in Section 4.1.3. In these groups, simulation with volume Vc1 is the base simulation, while the other two simulations are the comparison simulations. The results are illustrated in Figure 4.10.

(a) Temperature variation of core tank.
(b) Temperature variation of IHX.

(c) Temperature difference of core tank and IHX.
(d) Velocity variation of LBE in IHX primary side.

Figure 4.10 Influence of core tank volume on the loss of primary pump transient.

As shown in Figure 4.10, the whole performances of three simulations are quite similar with that of section 4.1.3 transient. From Figure 4.10 (d), new steady velocity due to natural circulation is produced in all the three simulations. Moreover, simulation-Vc2 has reached the steady velocity level first while simulation-Vc1 needs more time to get to steady level and simulation-Vc3 is the last one. According to Figure 4.10 (a), (b) and (c), all the three simulations are re-establish the steady state by natural circulation after the primary pump shut-down. However, these three simulations take different time to reach the new balance. Simulation-Vc2 is the first one to re-balance in about 1000 s after the beginning of transient. The later one is simulation-Vc1 that needs about 1500 s while the last one is simulation-Vc3 which costs about 2500 s.

The main reason is that the mass inside the primary loop is different due to the different volume of core tank in three simulations. Larger volume can hold more LBE inside with the higher heat capacity. Thus, under the same power input condition, the simulation-Vc3
with the largest volume needs the longest time to reset the steady state while the simulation-Vc2 which has the smallest volume just costs the shortest time.

By comparison, it is concluded the primary loop with bigger volume will cost more time to establish the new steady state by natural circulation. Meanwhile, the mass flow produced by natural circulation will not be changed when the balance state re-establishes.

4.3.2 Effect of flow resistance in the primary side

With the aim to investigate the effect of resistance factor in the primary loop, two groups of simulations with different hydraulic diameters (D1 and D2) of the inner tube (primary side) of the IHX are carried out. D1 is corresponding to the inner diameter of the IHX in Configuration-A, while D2 is the diameter of an assumed inner tube of the IHX whose flow area is 2 times that of the D1 tube. In both simulations, the length of the IHX is not changed, and all other parameters and initial conditions are the same with the transient in Section 4.1.3 except that the power is 18.6 kW. The results are presented in Figure 4.11.

(a) Velocity variation of LBE in the primary side of the IHX.
(b) Temperature variation of core tank.

(c) Temperature variation of IHX.
Figure 4.11 Performance of loss of primary pump transient in different inner diameters of the IHX.

It can be seen from Figure 4.11 (a) that the simulation-D2 gets the higher velocity after the transient starts reaching about 0.56 m/s while the natural circulation velocity of simulation-D1 is 0.47 m/s. It means that with the larger natural mass flowrate, the natural circulation capacity of simulation-D2 is better. This conclusion is also confirmed in Figure 4.11 (a), (b) and (c). Compared to simulation-D1, results of simulation-D2 obtains the relative lower temperature at the outlet of core tank and the temperature drop in IHX primary side is also lower due to the lower velocity in the HX. The main reason is that the resistance of the loop in simulation-D2 is lower than that in the simulation-D1 which caused by the different mass flow area parameters. There is a bigger mass flow area in Simulation-D2, as a consequence, the resistance of the loop becomes lower and enhances the velocity and mass flowrate in the loop. Therefore, the better natural circulation capacity is obtained. The effects of different volume also can be found from the figures.
By comparison, the primary loop with lower resistance can produce the larger mass flow for natural circulation in the loss of primary pump transient.

4.3.3 Effect of mass flowrate in the secondary loop

To study the effects of mass flowrate in the primary loop, two groups of simulation are performed. Simulation-Flow-1 uses the same mass flowrate with that in Section 4.1.3. While the mass flowrate used in simulation-Flow-2 is triple that of Flow-1. All other parameters and initial conditions are the same with those of the transient in Section 4.1.3. Figure 4.12 shows the calculation results.

(a) Velocity variation of LBE in IHX primary side.
(b) Temperature variation of core tank.

(c) Temperature variation of IHX.
Figure 4.12 Influence of flowrate in the secondary loop on loss of primary pump transient.

As shown in Figure 4.12 (a), the velocity caused by natural circulation in simulation-Flow-1 is around 0.52 m/s while the value in simulation-Flow-2 is about 0.47 m/s. As seen from Figure 4.12 (b), (c) and (d), the time for resetting the new balance in both simulations approximately equal with the reason that mass of LBE is same. Besides, the temperature drop along the IHX primary side of Simulation-Flow-2 is about 20 °C higher than that in simulation-Flow-1. Obviously, the natural circulation capacity in simulation-flow-2 is better. The driven head of natural circulation is caused by the temperature difference between hot leg (core tank) and cold leg (IHX) and the higher temperature drop along IHX is cause by the larger natural circulation mass flowrate. Because the coolant mass flowrate is larger in simulation-Flow-2, more heat in primary loop is removed. As a result, the average temperature of IHX primary side decreases and lead to the bigger temperature difference between hot leg and cold leg. In another word, the driven head of natural circulation enhances. Therefore, the better capacity of natural circulation is obtained.
By comparison, the mass flow produced by natural circulation will be enhanced. The loop with larger coolant mass flowrate in secondary loop will generate a better natural circulation characters in loss of primary pump transient.
5 Conclusions

Motivated by interpretation of thermal-hydraulic tests of heavy liquid metal as well as validation of the TRACE code for application to a HLM-cooled system, the TRACE code is employed in this thesis to simulate the transients performed on the TALL test facility. The transients related to safety issues such as loss of heat sink, loss of primary pump, loss of both primary/secondary pumps, overpower and accelerator trip are chosen in the simulations. In addition, the operational transients, i.e., the startup and the shut-down of the system are also simulated, respectively. Two configurations of the primary loop are considered: the one with a core tank (Configuration-A), and the other with a fuel rod simulator (Configuration-B). The separate-effect study is also conducted to investigate the effects of coolant inventory, flow resistance of the primary loop and mass flowrate of the secondary loop on the establishment of natural circulation in the LBE loop.

Generally speaking, for all the cases analyzed in the present study, the calculation results have a good agreement with the experimental data for the primary side (LBE) parameters (e.g., variations in temperature and mass flowrate), i.e., all the transients chosen can be reproduced by the simulations with acceptable deviations. Specifically in Configuration-A, the simulation for the transient loss of heat sink indicates the same tendency as in the experiment in term of temperature: it is rising at the inlet and outlet of the core simulator, as well as at those of the intermediate heat exchanger. The temperature keeps going up till the resumption of the heat sink as a protective measure, and then it decreases sharply at the very beginning and gradually returns to steady-state conditions. For the transient loss of primary pump (the external driving force), the temperature level is elevated and a significant natural circulation in the primary loop obtained. The simulation well reproduces the establishing process of natural circulation and the final flowrate, but it overestimates the peak temperature, probably due to the overshooting of the minimum flowrate. Such simulation outcome applies to the transient loss of both primary and secondary pumps, with a further elevated temperature. The calculation results of the transients startup and overpower are perfectly matching the experimental data, especially when approaching the final steady state, while the transients of shutdown and heater trip (to simulate accelerator trip) are underestimated in their final temperatures but no more than 10% and the trends are well captured in both the transients.

For Configuration-B, calculations are carried out for two transients: start-up of the system and loss of heat sink. In general, the transient time to a steady state or the maximum temperature level of Configuration-B is much shorter than that of Configuration-A, mainly because of the larger inventory of LBE in Configuration-A. This implies that the
pool-type design of reactor will mitigate the consequences of the transient, and leave more time for actions to terminate accident. For the startup transient, the simulation reproduces the temperature variation trends and final state obtained in the experiment, but within 10 minutes after the transient begins, the temperature level is underestimated. The similar is found for the loss of heat sink transient prior to resumption of heat sink; afterwards the temperature goes down back to the steady state much slower than the experiment recording. The reason for these deviations may be due to heat loss through insulation is not properly modeled (the insulation for Configuration-B is different from that of Configuration-A in reality). More analysis and scrutiny is needed for simulation of the transients performed on Configuration-B.

The separate-effect studies show that the LBE inventory in the primary loop plays a mitigative role in the transients. For the loss of primary pump transient, decrease in primary flow resistance and increase in secondary flowrate all contributes to passive safety, i.e., the primary loop with lower resistance can induce the larger natural circulation flowrate when it occurs, and the case with larger flowrate in the secondary side will have a better natural circulation capacity.

It should be noted that the possible unique characteristics of LBE flow and heat transfer [22][23] are not considered in the present work. This will be performed in the future study with close examinations of the correlations for LBE flow and heat transfer.
Reference:


## Appendix A

### Table A.1 Properties of material-50.

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<th>Temp. (K)</th>
<th>Density (kg/m$^3$)</th>
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Appendix B

Figure B.1 TRACE model in SNAP editor.
Table B.1 Specification of main components of TALL in SNAP editor.

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<th>The main components in TALL</th>
<th>Corresponding symbol in SNAP</th>
<th>Specification</th>
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<tr>
<td>Core tank</td>
<td></td>
<td>The core tank model pipe 100 is divided into 10 cells, the inlet of core tank is cell 1 while cell 10 is the outlet of core tank. Power input is located from cell 2 to cell 5. (Modification core tank for single rod model has the same design with the different geometry scale).</td>
</tr>
<tr>
<td>LBE-Glycerol heat exchanger</td>
<td></td>
<td>Heat exchanger model is as showed in picture. Pipe 400 is the primary loop inner tube model while the secondary loop annular tube is modeled as pipe 900. Both of the 2 pipes are divided into 8 cells. Heat structure 41 links the both side of cells correspondingly. (NHX is designed based on this way by changing the geometry parameters)</td>
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<td>EM pump</td>
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<td>Expansion tank</td>
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