ASSESSMENT STUDY OF RELAP5/SCDAP CAPABILITY TO REPRODUCE LIQUID METAL TALL FACILITY THERMAL HYDRAULIC BEHAVIOUR

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ABSTRACT

The paper presents the assessment of RELAP5/SCDAP code capabilities to simulate the thermal-hydraulic behavior of liquid metal. The code has been recently modified to work with liquid metal; new heat transfer correlations have been implemented. As the code is widely used in our institute during the design process of the Chinese ADS reactor the assessment of the newly modified RELAP5/SCDAP is seen as a necessary step to ensure the quality of the code results. The present paper focuses on the simulation of the transients performed on the TALL facility. TALL has been constructed and operated at KTH Royal Institute of Technology of Stockholm. The full height facility was designed and operated to investigate the heat transfer performance of different heat exchangers and the thermal-hydraulic characteristics of natural and forced circulation flow under steady and transient conditions. Two different configurations are available for the TALL facility however only one is simulated for the present study with six transient analyzed. A consistent and systematic approach for the nodalization development and assessment procedures that respond to the IAEA guidelines is discussed and thoroughly applied. The procedures and the database developed constitute the base in our institute for further study when more experimental data is made available.

KEYWORDS
TALL, RELAP5/SCDAP assessment, LBE simulation

1. INTRODUCTION

The RELAP5 code is widely used in the nuclear industry to perform safety analysis of water cooled reactors, for both light water and heavy water reactors [1]. The code is verified and qualified to perform calculations of normal and abnormal operation, accident scenario and Anticipated Transient Without Scram (ATWS). Any modification of the source code and the application of the code outside the spectrum of the performed V&V require a new qualification process of the code. The experimental database for the LWR nuclear technology is well established and is mainly constituted of the experiments available through the OECD/CSNI Integral Test Facility (ITF) [2] and Separate Test Facility Effect (STF) matrix [3, 4]. These databases collect over thirty years of experiments: separate effects tests for individual phenomena, integral tests for large break Loss Of Coolant Accident (LOCA), small break LOCA,

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transients, Beyond Design Basis Accidents (BDBA) and accident management in PWRs, BWRs and WWERs types of reactor. The vast amount of information has been used for code assessment in the framework of V&V activities for the state-of-the-art system thermal-hydraulic (SYS-TH).

The PRC is committed to the closure of the nuclear fuel cycle [5] and the Institute of Nuclear and New Energy Technology of Tsinghua University (INET) is the key institute for the Nuclear Energy development in China. One of the options currently investigated is the development of an ADS commercial reactor to be commercially available in 2030 [6]. RELAP5/SCDAP is among the codes used to support the design and to perform preliminary safety analysis of the proposed reactor. The code has been modified to work with LBE as a working fluid and new heat transfer correlations have been implemented (see section 2.1). Section 2.2 will describe the glycerol properties introduced in the code to simulate the set of experiments performed on the TALL facility. The facility, the experimental test matrix and the computational model developed for the present study are discussed in section 3.

The procedure used to develop the TALL (Thermal-hydraulic ADS Lead–bismuth Loop) model follows the steps and techniques developed at the Nuclear Research Group of San Piero a Grado (GRNPSG) of the University of Pisa, which have been discussed in a previous paper [9]. The methodology is based on a multiple independent feedback process to assure the quality of the experimental database. The facility source data and model input data are respectively described in two separate documents, namely Reference Data Set (RDS) and the Engineering Handbook (EH). The code results are quantitatively and qualitatively qualified in a systematic way and the results of this phase are documented in a Qualification Report (QR). Such methodology is envisaged by IAEA [10, 11] to set up a qualified experimental database.

2. RELAP5/SCDAP CODE MODIFICATIONS

2.1. Liquid Metal Heat Transfer Correlation

The liquid metal Heat Transfer (HT) mechanism differs from the HT in the other fluids used as a coolant in nuclear reactors due to the higher influence of the convective conduction on the total energy exchange. In other words, the ratio between the convective conduction to the advection of fluid particle is larger in liquid metal coolants. The heat transfer correlations are thereof consistently different than the one used for water implemented in SYS-TH codes. Any application of SYS-TH code developed and qualified for LWR analysis requires a modification of the source codes and therefore the code needs to be re-validated.

A State of the Art (SoA) review of the available correlations in the open literature has been performed. Two correlations have been implemented in RELAP5/SCDAP available at INET. The new correlations inserted in the code have been selected, taking into account the recommended applicability range of the particular HT correlation and the geometry of the experimental data from which the correlation has been developed.

Figure 1 shows the results of the comparison of the analyzed HT correlation available in case of a triangular bundle with p/D ratio equal to 1.8, that is the reference value for the core of the future Chinese ADS reactor [6]. The Seban/Shimazaki [12] (Eq. (1)) correlation is developed for a circular pipe and has been implemented in the code; the correlation can be used for fully developed turbulent flow and a pipe with constant wall temperature. The HT correlation introduced in the code to be used in case of a bundle heat transfer has been developed by V. I. Subbotin and P. A. Ushakov [13]. There are two versions of this correlation, a complete and a simplified, only the latter one is used in the present study. The full correlation depends on a parameter called “approximate criterion of thermal similarity”, a parameter that is a function of: the pin geometry and number of pins, the thermal conductivity of the fuel pellet, the cladding and the coolant. The influence of this parameter decreases with the increase of the pitch to diameter ratio. With $p/D>1.2$ the simplified version of the correlation can be used (Eq. (2)) with deviations of the Nusselt number not higher than ±5%. Figure 2 represents the results of the correlation used in the present study for bundle with $p/D=1.8$.

$$Nu = 5.0 + 0.025 \cdot Pe^{0.8} \quad (1)$$

$$Nu = 7.55 \cdot \frac{p}{D} - 20 \cdot \left(\frac{p}{D}\right)^{-13} + 0.041 \cdot \left(\frac{p}{D}\right)^{-2} \cdot (Pe)^{0.5} \quad (2)$$

The above correlation can be applied with a Peclet number such as $10 \leq Pe \leq 5000$ and for a bundle with $1.2 \leq p/D \leq 2.0$. Figure 2 shows the Nusselt number as a function of Peclet number for a triangular array bundle. The correlation gives an increased Nusselt number, hence a higher heat transfer value with the increase of the pitch ratio.

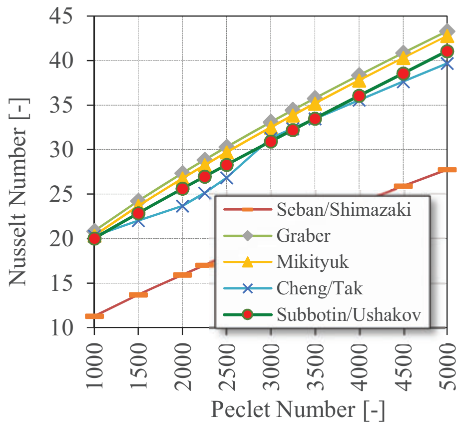


Figure 1: Nusselt number as a function of Peclet number for triangular bundle with p/D = 1.8

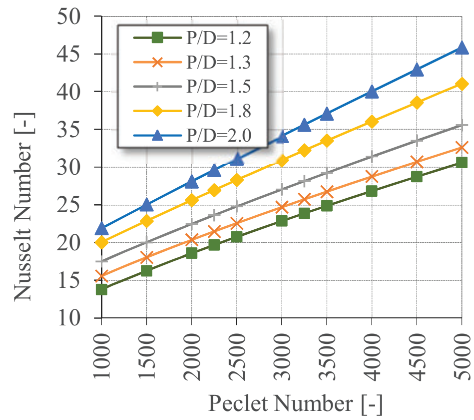


Figure 2: Nusselt number as a function of Peclet number for different p/D ratio with the Subbotin/Ushakov correlation.

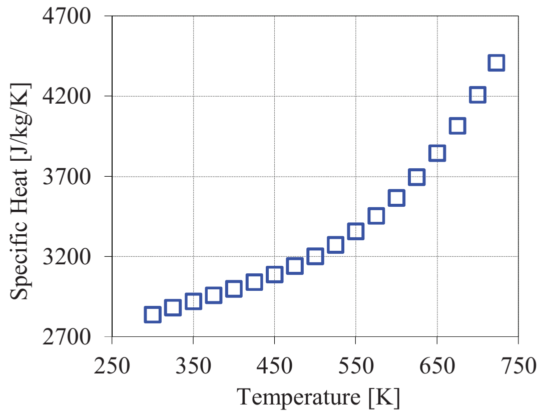
2.2. Glycerol Properties

TALL facility uses glycerol as a secondary side fluid. This section details the modification made to RELAP5/SCDAP to make it work with the organic fluid. The present status of the code allows the code to work only with single phase liquid glycerin. The specific heat, thermal conductivity and dynamic viscosity property (see equations (**3**, (**4** and (**5**) have been provided by personnel at KTH, a graph of the first two properties as a function of temperature is provided in Figure 3. The right graph in Figure 3 represents the glycerol density as a function of temperature: the red symbols represent the values provided by personnel at KTH University while the blue represent those available from literature [14]. The latter has been implemented in the code thanks to the simpler interpolating equation. The remaining properties input in the modified version of the RELAP5/SCDAP code are shown in Figure 4 and Figure 5. The first display the saturation temperature [15] and the Vapor Pressure [16], while the latter the sonic velocity [17] and the surface tension [18]. Together with the experimental data available from the indicated literature the interpolating curve input in the code is shown.

$$Cp = 10.87 \cdot (132.15 + 0.86 \cdot T - 0.001975 \cdot T^2 + 1.81 \cdot 10^{-6} \cdot T^3) \quad (3)$$

$$K = 10^n \quad with \quad n = -0.355 - 0.2097 \cdot \left(1 - \frac{T}{723}\right)^{\frac{2}{7}} \quad (4)$$

$$\mu = \frac{10^m}{1000} \quad with \quad m = -18.215 + \frac{4230.5}{T} + 0.0287 \cdot T + 1.865 \cdot 10^{-5} \cdot T^2) \quad (5)$$



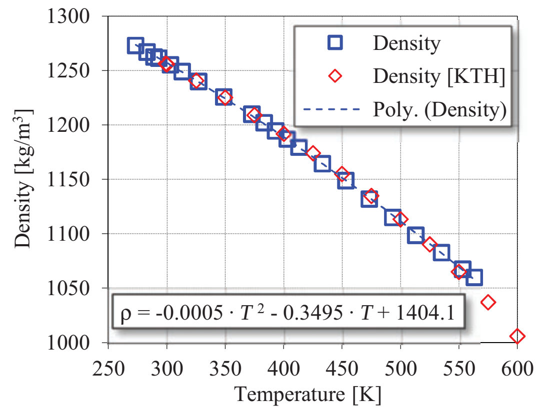
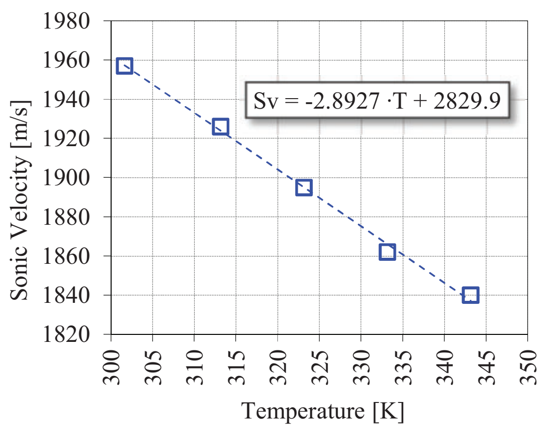


Figure 3 Glycerol Specific Heat (left) and Density (right) as a Function of Temperature.



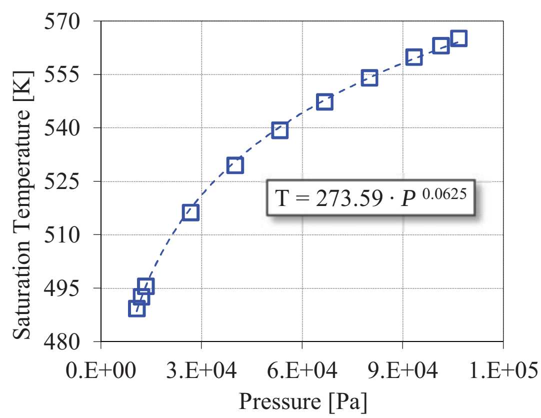
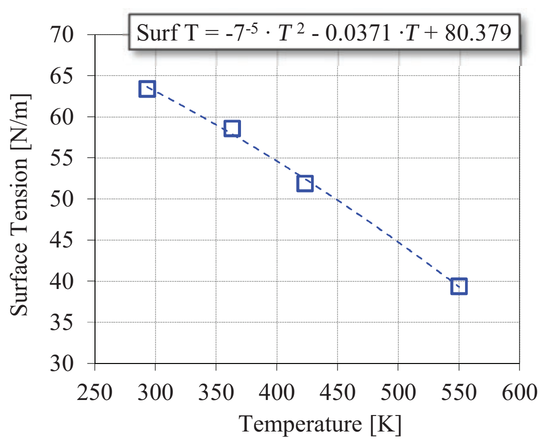


Figure 4 Sonic velocity (left) and Saturation Temperature (right).



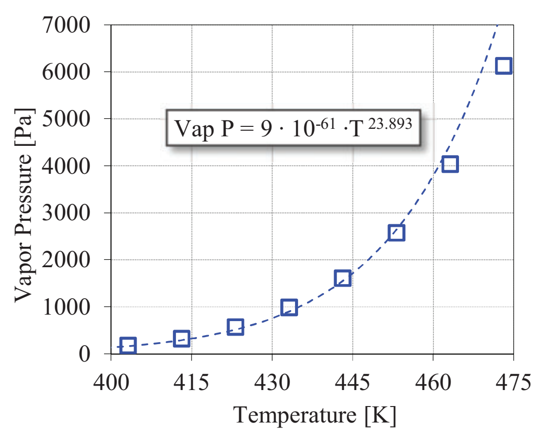


Figure 5 Surface Tension (left) and Vapor Pressure (right).

3. TALL FACILITY AND RELAP5 MODEL DESCRIPTION

Lead–bismuth eutectic (LBE) is a potential candidate for coolant for the next generation liquid metal reactors due to its favorable properties such as being chemical inert, in comparison with sodium which has been employed as a coolant in FBRs. LBE is one of the two candidates for coolant in the ADS reactor under design at INET of Tsinghua university. Thanks to its high atomic number, LBE is well suited as a spallation target for accelerator-driven systems reactors. Other interesting properties of LBE are the strong buoyancy and a high conductivity compared to other proposed coolants for ADS. The latter two characteristics should contribute to a good passive safety under postulated accident thanks to a good natural circulation and heat removal capacity. The set of experiments performed on the TALL facility "*provide a reasonably extensive data base at operating pressure, temperature and velocity towards the purpose of validation of safety analysis codes*" [19].

As RELAP5/SCDAP is extensively used at our institute as a support tool in the design process of the Chinese ADS reactor, it is necessary to assess and validate the capability of the code to accurately reproduce the liquid metal flow behavior in prototypic systems. In this respect this study represents the second of its kind following the simulation of the HELIOS facility thermal hydraulic characteristics [20] and contribute to the creation of an experimental database, a set of nodalization strategies and guidelines aimed at improving the quality of the RELAP5/SCDAP code application and results. In this context, we believe it is highly important to perform a simulation of tests on a well-scaled LBE cooled system, to provide a pertinent database that confirms both the capability of the code to reproduce the experimental behavior as well as to confirm the nodalization strategies and user choices made in the computational model development. Both these aspects are the objective of the present work.

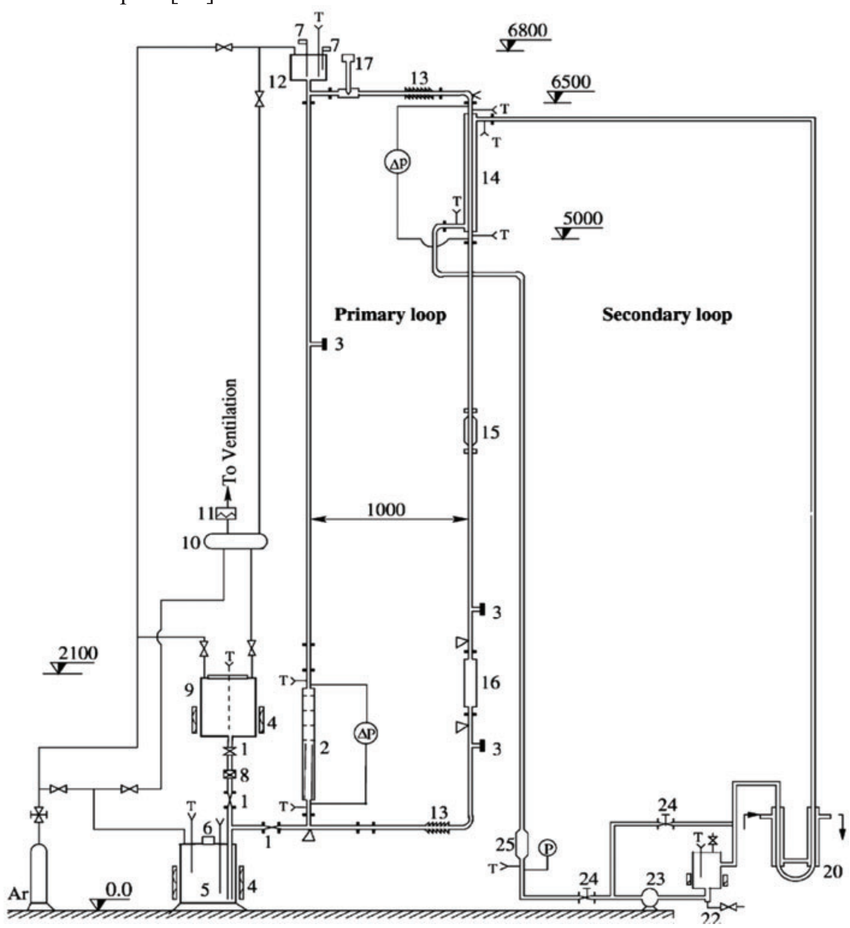
3.1. Description of TALL Facility

The TALL (Thermal-hydraulic ADS Lead–bismuth Loop) test facility [21] was designed, and erected at KTH to perform thermal-hydraulic experiments for the LBE-cooled eXperimental Accelerator-Driven System (XADS) [22]. TALL is a medium-sized full height facility, with prototypic temperature of the LBE coolant and is scaled to represent all the components with their LBE volume, the system flowrate, and heating rates corresponding to one tube of the chosen heat exchanger design. This design ensures that the loop has similar thermal-hydraulic characteristics as the prototype plant especially in terms of the natural circulation capability, which is extremely important for transients such as loss of flow. The facility has two configurations namely "A" and "B" differing mostly in the core and the HX simulators [23]. The present study and the following facility description focus on the configuration "A" of the facility.

The experimental transients performed on the TALL facility are summarized in Table I. They include the start-up and the shut-down operational transients, the loss of heat sink, the loss of primary forced flow (pump trip), the loss of both primary and secondary flows, overpower, overcooling and the heater trip.

TALL experimental facility with its primary and secondary side is schematically shown in Figure 6. The detailed description of the facility can be found in [19]. In the present paper, only a limited description is given in accordance to the objectives of the present study.
The facility is scaled to full height relative to the XADS; (ii) the temperature changes through the core tank and the heat exchanger completely cover those of the reference reactor; (iii) the facility is designed in such a way that 2.0 m/s LBE velocity is available in a single-tube HX under prototypical temperature (400 °C). More detailed scaling considerations can be found in [19 and 23].

The primary side is a closed LBE loop consisting of a pump, a flowmeter, various heaters, piping, a heat exchanger, a melting tank and an expansion tank. The secondary system uses glycerol as a coolant, taking advantage of the high boiling point of 290 °C of this fluid, which allows an operational minimum temperature in the loop much greater than 125 °C (melting point of the LBE) so that the solidification of LBE in the heat exchanger is avoided. The Glycerol is cooled in an open loop by water in a heat exchanger. As detailed information regarding the secondary loop was not available, only the HX is modeled in the present study. In addition to the above components, the facility has the systems for data acquisition, oxygen measurement, cover-gas, vacuum and exhaust. The facility components are described in detail in a technical report [21].



Primary Loop
Piping 33.4 mm O.D and 27.8 mm ID
Material: AISI 316 stainless steel
Working Fluid: LBE
Max Flowrate: 15 l/m
Piping Preheating: Rope Heater

Secondary Loop
Piping 26.7 mm O.D and 23.3 mm ID
Material: Carbon steel
Working Fluid: Glycerol
Max Flowrate: 260 l/m
Piping Preheating: Band Heater

1 – Valve for LBE	6 – Observing window	12 – Expansion tank	20 – Oil – water HX
2 – Core tank & heater (28 kW)	7 – Level Sensor	13 – Expansion tube	21 – Heater (3kW)
3 – Blind flange	8 – Filter	14 – LBE – oil HX	22 – Sump tank for oi
4 – Melting heater (6kW)	9 – Melting tank	15 – EM flowmeter	23 – Oil pump
5 – Sump Tank for LBE	10 –Exhaust gas tank	16 – EM pump	24 – Valve for oil
	11 – HEPA filter	17 – Oxygen meter	25 – Flowmeter for oil

Figure 6. TALL Test Facility Scheme.

The electro-magnetic (EM) pump is used to circulate the liquid LBE through the loop. After leaving the pump, the LBE flows through the core tank simulator and is directly heated by four immersion heaters to a specific outlet temperature. The core tank was scaled so that the core region in the loop has a coolant inventory corresponding to one tube of the heat exchanger chosen in the XADS design. The outlet of the core tank is connected to a long vertical pipe, through which the LBE travels up to the expansion tank and then flows through the oxygen sensor and the HX where the LBE temperature is decreased to a specific value. The LBE leaves the heat exchanger and flows down through the long vertical pipe until it reaches the suction side of the pump. Finally, the LBE returns to the pump, completing the loop. A single tube heat exchanger (see Figure 6 item 14) was employed as the LBE–Glycerol heat exchanger. It is composed of an inner tube of 10-mm-I.D. and 1.5-mm-thickness steel, and an outer tube, with the primary fluid (LBE) flowing in the inner tube and the secondary fluid (glycerol) flowing in the annulus. The HX has an effective length 1.0 m. These parameters were specified after a comprehensive consideration of the inlet/outlet temperature, heat removal capacity, heat flux and flow resistance. The EM flowmeter (Figure 6, item 15) is designed to measure the flow rate of liquid LBE in the cold leg of the loop. Differential pressure transducers are available across the core tank and the HX. The core tank (Figure 6, item 2) holds the immersion heaters, which have a maximum of 28 kW of power. Thermocouples are used to obtain the temperatures in the loop; those used for experimental data and calculation results comparison in the present study are indicated in Figure 6 by the letter "*T*". All operations of the heaters, pumps and valves were controlled by an integrated electrical panel.

The technical specifications of TALL are as follows (from [19, 21]):
All parts in contact with LBE are made of 316 or 316L stainless steel, and the internal surfaces were oxidized before filling with LBE.

- The overall height of the facility is 6.8 m.
- Total electric power is 55kW.
- LBE flow velocity is up to 3 m/s in the heat exchanger tube.
- LBE volumetric flow rate is up to 2.5 m^3/h.
- Maximum LBE temperature is maintained at 500 °C.
- Maximum temperature difference across the heat exchanger is 150 °C.
- The pressure at the top is ∼1 bar and the bottom pressure is ∼8 bar.
- Maximum natural convection velocity is ≈50 cm/s.
- The LBE has the composition of 45% Pb and 55% Bi in weight, with the melting point of 123.5 °C. LBE purity is higher than 99.5%.
- Oxygen level in LBE is measurable and is controlled periodically.
- The working fluid in secondary loop is glycerol with the boiling point of 290 °C.

3.2. Test Matrix and Test Procedures

Two kinds of transients were performed on the facility: operational transients and safety related transients. The start-up and shut-down of the loop to and from the nominal operating condition were considered operational transient. The safety related transients were focused on the loss of heat sink, the loss of external driving head (pump trip), overpower, overcooling, the loss of both external driving head and heat sink, and the heater trip. The present paper focuses on the two operational transients, the heater trip, the loss of external driving head and the overcooling. Prior to each transient, steady-state conditions are usually established in the loop, which are the initial conditions of the transients. For the integrity and safety of the test facility, most transients were mitigated by re-starting the heat sink or reducing power when the maximum temperature reached the value of 465 °C. The transient tests performed are shown in Table I.

3.3. RELAP5/SCDAP Model Description

The TALL facility computational model (see Figure 7) has been developed to reproduce as close as possible the thermo-hydraulic phenomena of the facility but taking into account that the solutions adopted in this model will be adopted also in setting up the model of the ADS reactor. The model set up for this analysis fully comply with the nodalization strategies discussed in a previous study [20]. The “slice nodalization” approach was applied in the model to not introduce artificial gravity terms that could affect the natural circulation prediction. This technique consists in realizing the same nodes dimension of different zones (ascending and descending) of the nodalization simulating zones of the plant at the same elevation by virtually cutting the real loop by horizontal parallel plane.

Table I. Test matrix and Transient Description

#	Case ID	Primary Side Initial Condition (steady State)	Transient Procedure
1	Start-Up	LBE: T = 200 C, u = 0.0 m/s	Pump and heater switch on at the same time
2	Loos of Heat Sink	THX: i = 300, 350 or 400 C, ΔTHX = 50 or 100 C, u = 1, 1.5 or 2 m/s	Switch off the oil pump, or reduce the oil flow rate (partial loss of heat sink)
3	LBE Flow Loss	THX: i = 300, 350 or 400 C, ΔTHX = 50, 80 or 100 C, u = 1, or 2 m/s	Switch off EM pump, or reduce the LBBE flow rate (partial loss of flow)
4	Overpower	Steady State Forced Convection	Increase the heater power by 50% or 100%
5	Overcooling	Steady State Forced Convection	Increase the oil flow rate by 50% or 100%
6	Heater trip	THX: i = 350 C, ΔTHX = 100 C, u = 1 m/s	Switch of the heater for 5, 10 and 15 s
7	Shut-down	Steady State Forced Convection	Switch off the heater. Keep the oil flow and LBE forced flow
8	Primary and Secondary side driving head loss	THX: i = 400 C, ΔTHX = 100 C, u = 1 m/s	Reduce the LBE and oil flow rate at the same time

The LBE side of the circuit has been model in detail. The circuit pressure is imposed in *tmdpvol-214* and the flow is driven by the pump component (*pump-250*). The core tank is modelled by the *pipe-105* and the HX by the *pipe-230.* The K-loss factor for concentrated pressure drops have been evaluated using formulas available in literature [24], the same choices made in previous work [20] have been applied in the present study. Due to the lack of information on the secondary side circuit design only the HX component has been modelled with the inlet temperature imposed in *tmdpvol-500* and the inlet mass flow imposed in *tmdpjun-502*. A careful modelling of the facility structure is important to well simulate the thermal inertia of the facility, which plays an important role in the fluid thermal-hydraulic behaviour during the transients. The heat structures were simulated using cylindrical or slab geometry. The heating elements are represented by *htstr-1105*, the core tank internal by *htstr-3105* and the core tank by *htstr-2105*. The single tube HX is simulated by *htstr-1230* and the heat exchanger tank by *htstr-510*. Heat losses to the environment have been simulated for both the primary side and secondary side. As no experimental heat losses characterization tests were available steady state temperature drop along the HL and CL were used to tune the heat losses along the circuit. The overcooling, loss of primary flow and shut down of operation transients were, in this respect, analysed to fix the appropriate heat losses. It is important to underline that the heat losses are an invariant for the simulations performed.

The geometrical differences between the model and the facility for the following quantity has been evaluated and compared with the acceptability criteria described in [25]. The quantities used for the comparison are: non-active structure heat transfer area, active structure heat transfer area, non-active structure heat transfer volume, active structure heat transfer volume, volume versus height curve (only for the primary side, component relative elevation 0.01m, flow area of components like valves, pumps orifices and generic flow area. SIMULATION RESULTS

The comparison between the RELAP5/SCDAP simulation and the experimental results is discussed in the present section. Detailed description of the experimental tests procedures and transient progression can be found in [19].

A necessary condition for performing a transient simulation is to start from a steady state condition. Temperature and mass flow in the primary side were the parameters that have been checked for the steady state validation. The criteria followed are described in detailed in [9]. The temperatures at the core and HX inlet and outlet have an accuracy of 0.5% (except for the core inlet in the heater trip transient). The mass flow has an error lower than the acceptable 2%. Each of these parameters show a drift lower than 0.1% over 100 s during the steady state.

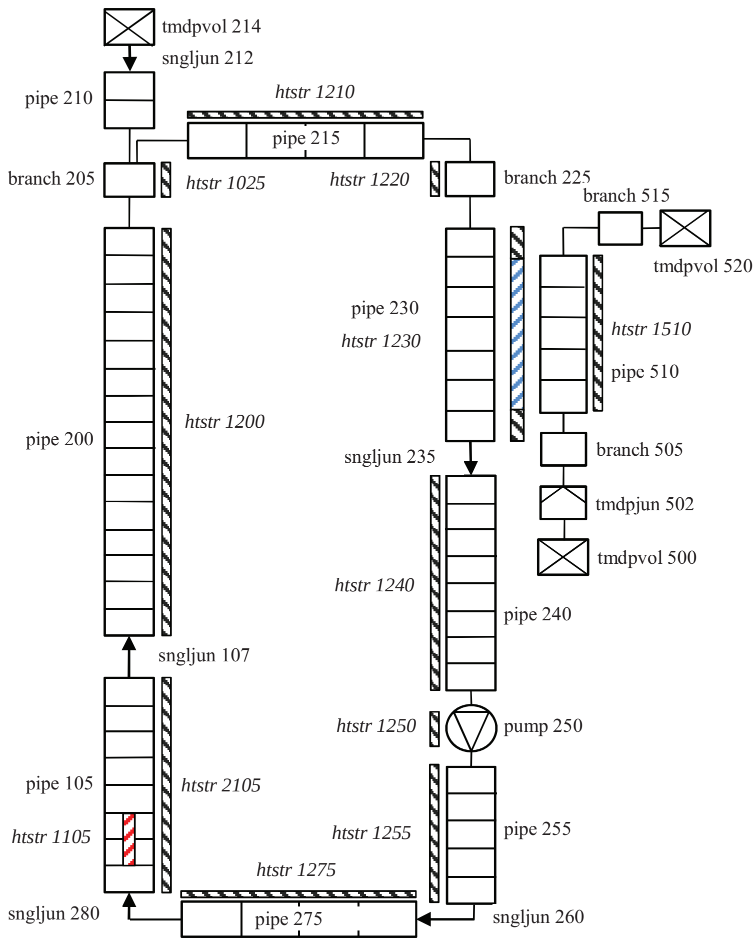


Figure 7 RELAP5/SCDAP model of the TALL facility.

4. SIMULATION RESULTS

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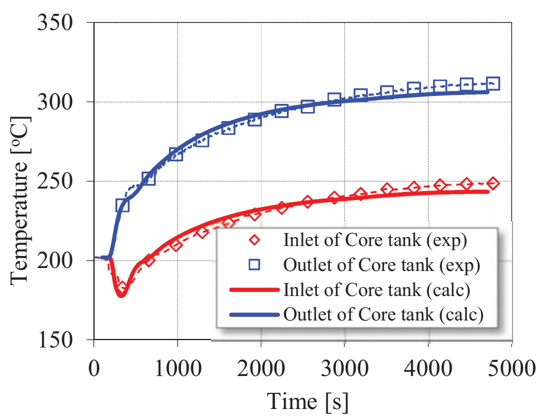
4.1. Start-up of Forced Circulation

The start-up of the facility is considered an operational transient. At the beginning of the transient the two loops were considered to be in equilibrium at 200 °C, with a mass flow of 0.0 kg/s for the LBE and glycerol. At the start of the transient (~140 s), the core power was switched from an initial value of 0.0 kW to the final power of ~8.5kW, together with the LBE pump and the secondary side pump. The final LBE flowrate was 0.91 kg/s, and the final Glycerol flowrate stabilized at 0.69 kg/s. It should be noted that for the supposed initial stationary conditions, i.e. zero primary and secondary flow, there exists a variation in the temperatures around the primary coolant circuit due to heat loss through the insulation to the environment and the use of the heating rope. These two conditions produce a residual mass flow in the LBE loop that was not taken into account by the computational model. It is then impossible to exactly reproduce the real initial condition.



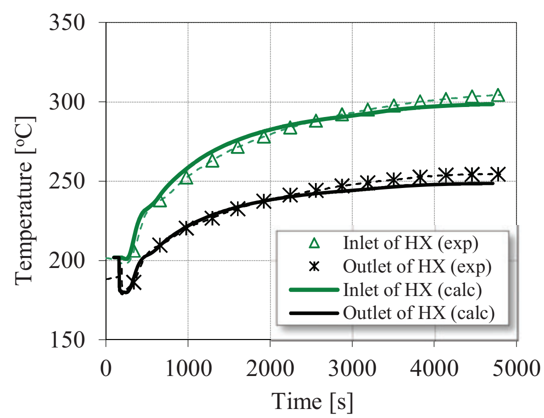


Figure 8 Core Temperature (left) and HX Temperature (right) during Start Up Operation.

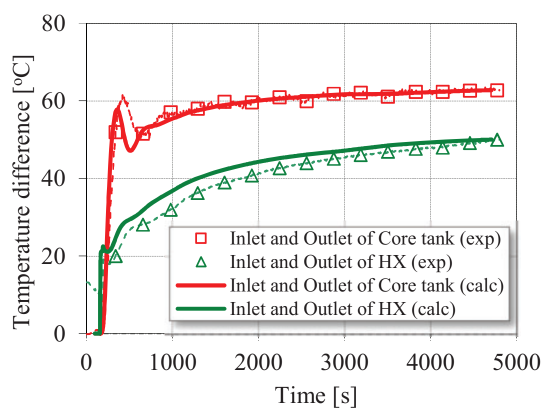


Figure 9 Core and HX Temperature difference during Start Up Operation.

Figure 8 shows the comparison between the experimental and computational temperature variations across the core and HX during the TALL facility start-up process, while Figure 9 shows the corresponding temperature differences across the core tank and the HX. The code accurately reproduced the transient behavior both in the case of the fast properties change (i.e. the first 400 s of the transient) and the slower progression of the startup procedure. The temperature drop across the HX (see Figure 9) is slightly overestimated in the first part of the transient. With the establishment of the steady state condition the calculated results are better compared to the experimental data. The characteristic transient times of the change in the coolant temperatures are dependent on coolant inertia in the primary loop, the heat exchange with the secondary side and the heat losses to the environment. The good agreement between the RELAP5 results and the experimental ones validate the modelling assumptions and user choices made during the nodalization set up.

4.2. Overcooling Transient

At the beginning of the transient, the two loops were in steady state condition. The HX inlet temperature was about 440 °C, the temperature drop across the HX was ~105 °C and the LBE velocity in the HX ~1 m/s. At the start of the transient (~140 s), the core power was ~17kW.

This transient was started by increasing the coolant flow rate by a factor of ~2.4 during the experiments and by a factor of ~1.6 during the simulation at about 330s into the experiment. The decrease in the heat exchanger exit coolant temperature caused by the increased coolant flowrate propagates around the primary circuit with a decrease in the core tank inlet temperature, the core tank exit temperature and the HX inlet temperature. The final outcome of the overcooling transient is a decrease in the operational temperature level. After the initial cool-down, the primary circuit temperatures slowly approach a new steady-state, with the temperature differences (Figure 11) approaching their original values. Figure 10 and Figure 11 show a very good agreement between the calculated the experimental results for the primary circuit temperature. To reach such results however, it was necessary to tune the coolant flow rate to have an HX heat flux compatible to the best prediction of the observed temperatures in the LBE/Glycerol heat exchanger. The difference in the increase in the Glycerol flow rate (~2.4 times in the experiment versus the ~1.6 in the calculation) is probably due to uncertainty in the experiment's glycerol properties. As from [19]: "…an additional investigation demonstrated, there is a large uncertainty in the viscosity of Glycerol, which in turn depends strongly on the temperature and water content. This uncertainty results in a potential discrepancy between the measured and calculated values of the Glycerol Reynolds number and therefore heat transfer for a given value of the flow rate and velocity…"

4.3. Loss of Primary Flow

The transient was started by reducing the pump rotational speed from the nominal value to zero in ~2 s at ~550 s. The sudden decrease in LBE flowrate results in a sharp reduction in the LBE temperature at the HX outlet (see Figure 12). At the same time, the decreased primary side flowrate triggers the LBE temperature increase at the core tank outlet. Subsequently, the temperature also increases at the HX inlet.

The calculated results (see Figure 12 and Figure 13) compared very well to the experimental data for all of the primary coolant parameters. To reach such results however, it was necessary to tune the coolant flow rate to have an HX heat flux compatible to the best prediction of the observed temperatures in the LBE/Glycerol heat exchanger. The experimental glycerol flowrate was ~1.45 kg/s, the imposed one in the calculation ~0.7 kg/s. The coolant flow rate was the "free parameter" used in the calculation to satisfy the experimental condition of a given pressure drop across the HX (see Table I).

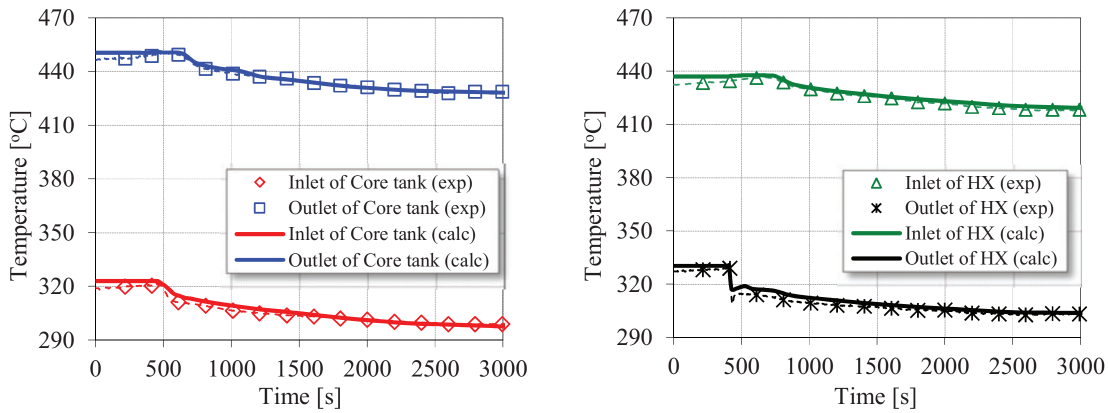


Figure 10. Core Temperature (left) and HX Temperature (right) during Overcooling Transient.

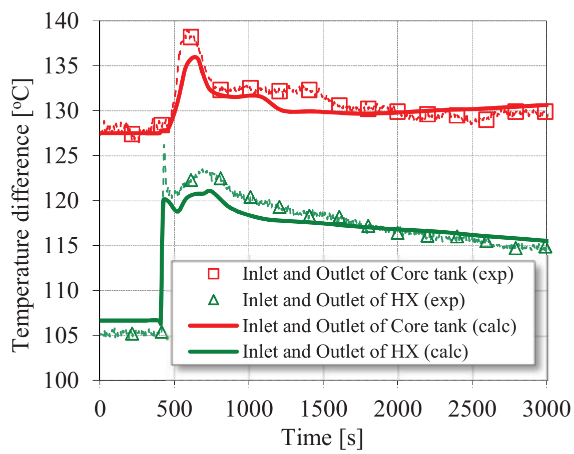


Figure 11. Core and HX Temperature difference during Overcooling Transient.

Such a difference in the mass flow rate implies a higher HTC calculated in the secondary side of the HX for a given glycerol velocity. As stated in the previous section, the probable cause of a different heat transfer on the secondary side could be related to the wide variation in the physical properties of Glycerol [19]. The time-dependent characteristics of the calculated and experimental results are also in excellent agreement, which for the transient simulated requires a good model of the primary loop thermal inertia. The consistent prediction of the temperature trends confirm a good modelling of the heat losses and pressure drop along the loop, which play an increased role in natural flow circulation regimes.

4.4. Heater Trip Transient

This transient is started at ~160 s by switching the immersion heater rods off for 25s and on for 15s. In this way the input power moves from full power to zero and vice versa. On average, the power is reduced to ~37.5% of the steady state level. At the beginning of the transient, the two loops were in steady state condition. The HX inlet temperature was about 400 °C, the temperature drop across the HX was ~100 °C and the LBE velocity in the HX ~1 m/s and the core power was ~14.7kW. The only effect noticeable in TALL facility was a temperature reduction of the LBE to a new balance point. As the heater wall temperature is not measured in the tests [21] the challenging oscillation in the rods wall temperature could not be compared with the simulation. The calculated results show a good general behavior with the experimental one (see Figure 14 and Figure 15). The primary side cooling is predicted to happen faster by the model. This might be due to an higher imposed secondary side mass flow rate. The secondary side mass flowrate was imposed constant at ~0.7 kg/s compared to the experimental one of ~1.15 kg/s (the explanation of the discrepancies has been given in the previous two sections).

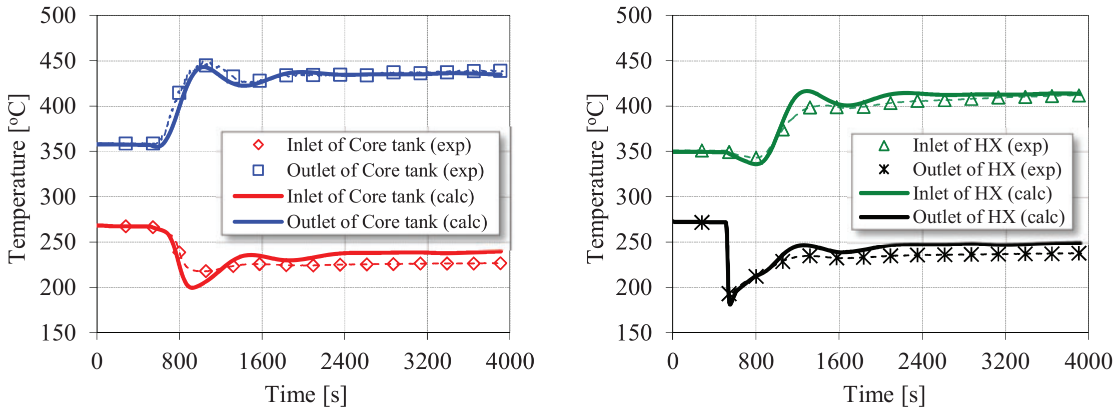


Figure 12. Core Temperature (left) and HX Temperature (right) during LBE Flow Loss.

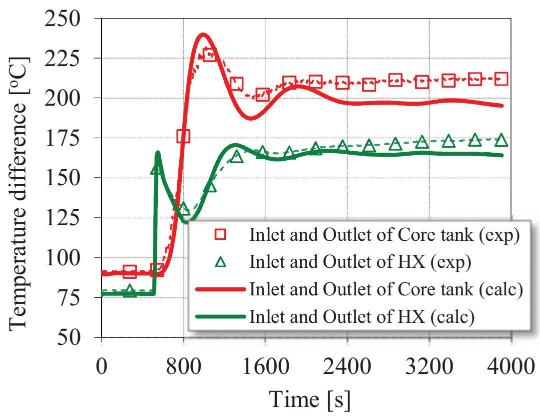


Figure 13. Core and HX Temperature difference during LBE Flow Loss.

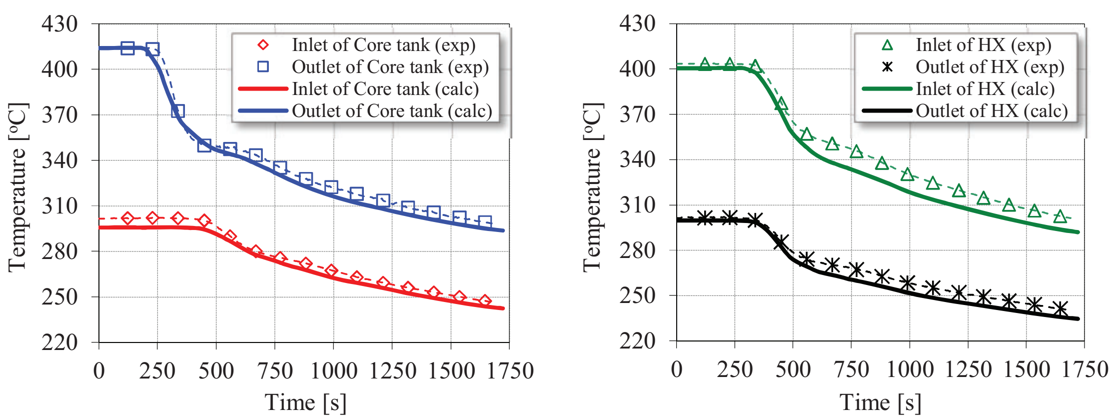


Figure 14. Core Temperature (left) and HX Temperature (right) during Heater Trip Transient.

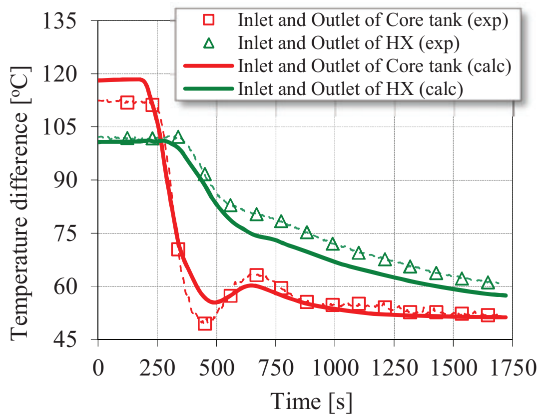


Figure 15. Core and HX Temperature difference during Heater Trip Transient.

4.5. Shut Down of Operation

This transient was started at ~280 s by switching the immersion heater rods off, and stop when the loops are cooled to the target temperature of ~200 °C. At the beginning of the transient, the two loops were in steady state condition. The HX inlet temperature was about 420 °C, the temperature drop across the HX was ~115 °C and the LBE velocity in the HX ~1 m/s and the core power was ~17.0kW.
The temperature differences through the core tank and the heat exchanger during the transient are shown in Figure 16 and Figure 17. There is good agreement between RELAP5/SCDAP calculation results and the experimental data.

5. CONCLUSIONS

In this paper, RELAP5/SCDAP of the safety related transient experiments performed in the TALL test facility were presented. The code modification necessary to perform the calculation were also discussed. The transients are focused on two operational procedures: start-up and shut-down; and safety related transients: loss of external driving head, overcooling and heater trip. The present work is of outmost importance to assure the capability and accuracy of the available computational tools at our institute and to qualify the nodalization rational and user choice made. The following conclusions may be drawn, based on the experimental results:

- The experimental and calculated results comparison for the transients discussed in this study shows excellent agreement for the primary side (LBE) parameters. This demonstrates that RELAP/SCDAP code is capable to reproduce complex system transient behavior.
- The excellent agreement between the experimental and calculated data also validates the nodalization strategies and user choices that are at the base of the experimental database under development in our institute.
- For the secondary coolant (Glycerol), the calculated velocities and flow rates are approximately one-half of the measured values. The main cause of the differences for the secondary side parameters might be ascribed to the wide variation in the physical properties of glycerol and the uncertainty in its heat transfer coefficient in annular channel. It was stated by personnel at KTH that the glycerol properties unexpectedly degraded (i.e. decomposition of the organic oil). The difference in the code prediction thus are not to be ascribed in the impossibility of the code to reproduce the nominal secondary fluid thermal hydraulic properties, but to degradation of the organic fluid properties itself.

A full validation of the code capability to reproduce the LBE phenomena was however not possible as no heater wall temperature measurement were available for these set of experiments.

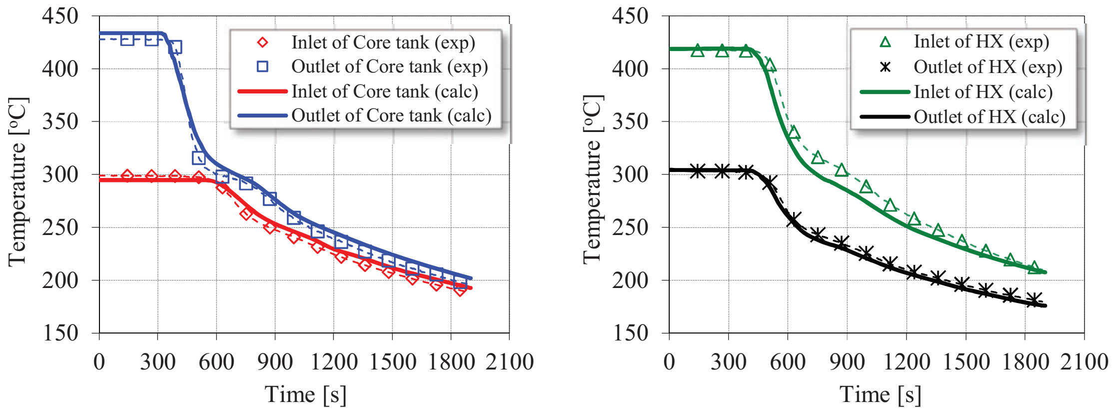


Figure 16. Core Temperature (left) and HX Temperature (right) during Shut Down Operation

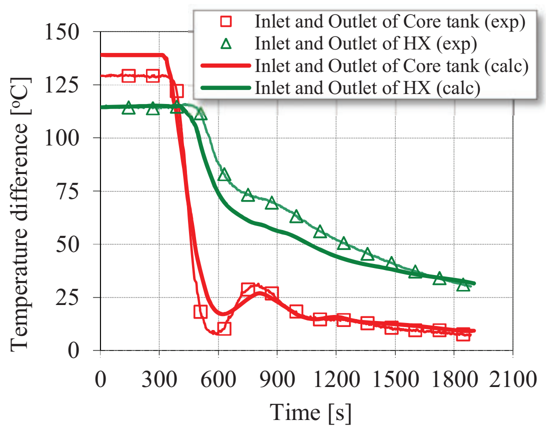


Figure 17. Core and HX Temperature difference during Shut Down Operation.

NOMENCLATURE

Nu	Nusselt adimensional Number
Re	Reynolds adimensional number
Pr	Prandtl adimensional number
Pe	Peclet adimensional number
P	Pitch value
D	Diameter
Cp	Specific Heat
K	Thermal Conductivity
μ	Viscosity

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