ASSESSMENT AND VALIDATION OF ATHLET-CODE FOR SIMULATING RESIDUAL HEAT REMOVAL VIA A TWO-PHASE LARGE-SCALE LOOP THERMOSYPHON

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ABSTRACT

Passive heat removal systems (PRHRS) are a common design feature in emerging Small modular reactors (SMRs). PRHRS rely on naturally-driven forces to transfer residual heat to an intermediate or ultimative heat sink (UHS). Loop thermosiphons (LTS) are considered suitable devices for PRHRS, especially for transporting residual heat from the emergency cooling tanks to the UHS, i.e. Sorroundings or air-cooling towers. Datasets from a large-scale atmospheric LTS-experimental facility were used to assess and validate the performance of LTS-models developed with ATHLET-code. A total of 18 stationary states for single and two-phase operation were analyzed in detail featuring variations in heat inputs and filling ratios. A proper data agreement and prediction of loop fluctuations for the two-phase operation was achieved, indicating that ATHLET is suitable for simulating LTS-facilities.

INTRODUCTION

Interest in Small Modular Reactors (SMRs) is gaining momentum over the last decades, as they offer an attractive alternative for a vast range of energy markets due to their flexibility, transportability and simplified manufacturing. SMRs are new generation reactors designed to produce up to 300 MW electric power, introducing advanced reactor technology and safety features [1]. Inherent reactor safety and passive residual heat removal systems (PRHRS) are common design features in emerging SMRs. PRHRS are responsible for the removal of residual core-generated heat after plant shutdown [2]. PRHRS rely on naturally-driven forces to transfer the residual heat to an intermediate heat sink, usually a water-filled emergency cooling tank (ECT) with a limited grace period. To avoid ECT-water depletion due to evaporation, the residual heat must be transferred via a tertiary loop to an ultimate heat sink (UHS), such as the environment or to an air-cooling tower (ACT). Multiple process schemes and models for indefinite PRHRS-operation in SMRs considering an UHS have been studied extensively [3]. A representative example of such process schemes is shown in figure 1. In this case, the PRHRS operates in case of emergency once the turbine upstream valve closes. The remaining decay heat produces steam in the secondary loop which is directed to the ECT via the PRHRS and condenses after releasing its heat to the ECT-water pool, causing a temperature rise of its water inventory. To maintain the pool water temperature below saturation point, a tertiary loop is required so that excess heat is transported to the ACT.

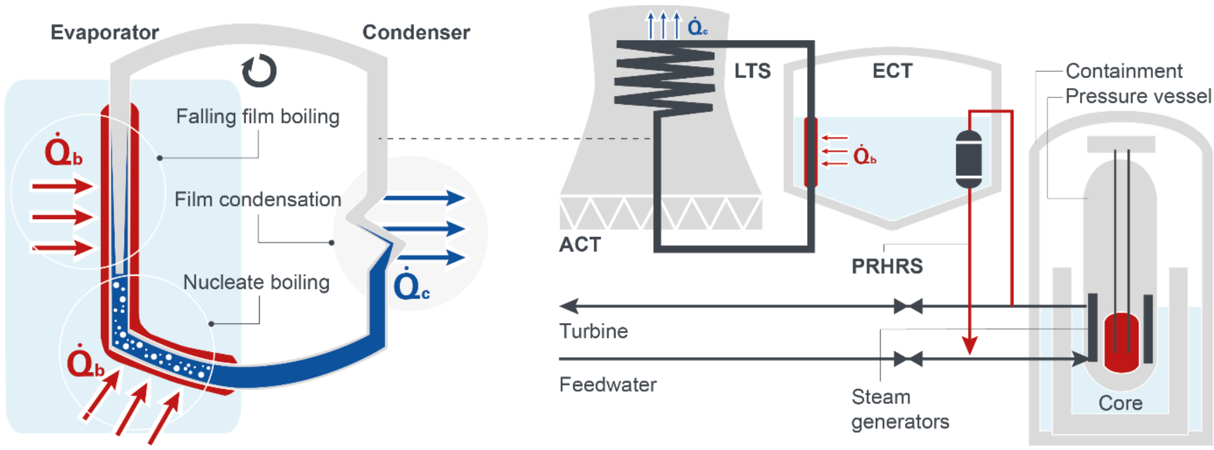

Figure 1. Indefinite PRHRS-operation concept for a pressurized water SMR featuring a LTS-configuration for heat transfer to an ACT

Loop thermosyphons (LTS) are considered suitable tertiary loops for this heat transport purpose [4]. A simplified scheme of a LTS is displayed on Figure 1. LTS are a type of wickless two-phase operated heat pipes, featuring a closed-loop configuration with an evaporation and a condensation zone contained within a circuit-like flow channel. Even though two-phase LTS and heat pipes are built on the same principle of a density difference-based natural circulation for transporting latent heat over a vertical distance, LTS feature a distinct loop configuration instead of a vertical arrangement, making them more suitable for other kind of applications, where gas-liquid flow interactions are to be minimized [5]. In a LTS, an inside-loop working fluid is used as a heat transport medium, which takes up the heat in the evaporation zone and releases it in the condensation one, after transporting it a certain distance. For large heat transfer rates, a two-phase operation is preferred. Hence, appropriate pressure ranges must be selected, so that the saturation state of the working fluid is reached [5]. On the other hand, the ratio of working fluid to total system volume, also known as filling ratio (FR), is also of utmost importance to LTS performance, as it governs key thermal hydraulic phenomena within the loop [6].

In terms of SMR-licensing and design, thermal-hydraulic simulation tools (THS) are widely used to evaluate two-phase flows in PRHRS under various accident scenarios and thus require appropriate validation. An accurate prediction of the working fluid's mass flow is a decisive factor in assessing the reliability of THS [7]. In the present study, the performance of the system code ATHLET (Analysis of Thermal-Hydraulics of Leaks and Transients) regarding mass flow-and temperature profile prediction is evaluated and validated against experimental data from a large-scale LTS-experimental facility operating at atmospheric pressure [4]. Experimental data from further LTS-test facilities operating at sub atmospheric pressures is also available in the literature [8].

Alongside with experiments, LTS-models are available in the literature to predict heat transfer rates and loop efficiency under certain process conditions. Most of the existing models feature the supplied heat as an input parameter which determine the mass flow inside the loop, and consequently, the heat transfer coefficients. Hence, the experimental mass flow is a common parameter for model validation purposes [9]. On the other hand, further easily measurable model outputs, such as temperature profiles throughout the loop and pressure drop are widely considered for assessing the agreement of LTS-models with experimental data [10]. Most of the developed one-dimensional LTS-models are not coupled with analysis codes for advanced nuclear reactors directly, complicating the integration of other reactor systems in the overall plant safety assessment [10]. Henceforward, a validation of current codes for advanced nuclear reactors, e.g. ATHLET, in terms of LTS-simulation capability needs to be conducted. Extensive code validation activities for different configurations of heat exchangers is considered within ATHLET continuous improvement strategies. However, LTS-oriented code assessment has not been yet carried out [11].

METHODOLOGY

EXPERIMENTAL FACILITY AND MODEL BOUNDARY CONDITIONS

Experimental data from the tests conducted by [4] were used to validate the ATHLET-LTS model. A depiction of the LTS-facility is shown in Figure 2: It consists of a 66.0 m stainless steel closed loop pipe of 70 mm OD and 66 mm ID. Two 6.0 m horizontal sections and two 27.0 m vertical sections compose the main loop, where water flows in clockwise direction as working fluid. The evaporator section consists of 27 heating elements divided into four sets of resistances; wall temperatures were measured at their inlets/outlets (T_{E1}-T_{E8}). The evaporator section is isolated with ceramic fabric material. On the other hand, 10 sections of concentric-tube heat exchangers are placed in the horizontal and vertical sections of the loop to serve as condensers. Cooling water is used and its mass flow and inlet/outlet temperatures are also monitored. Moreover, the working fluid mass flow and loop pressure are recorded at the bottom of the loop. Further details on instrumentation and experimental layout are available in [4].

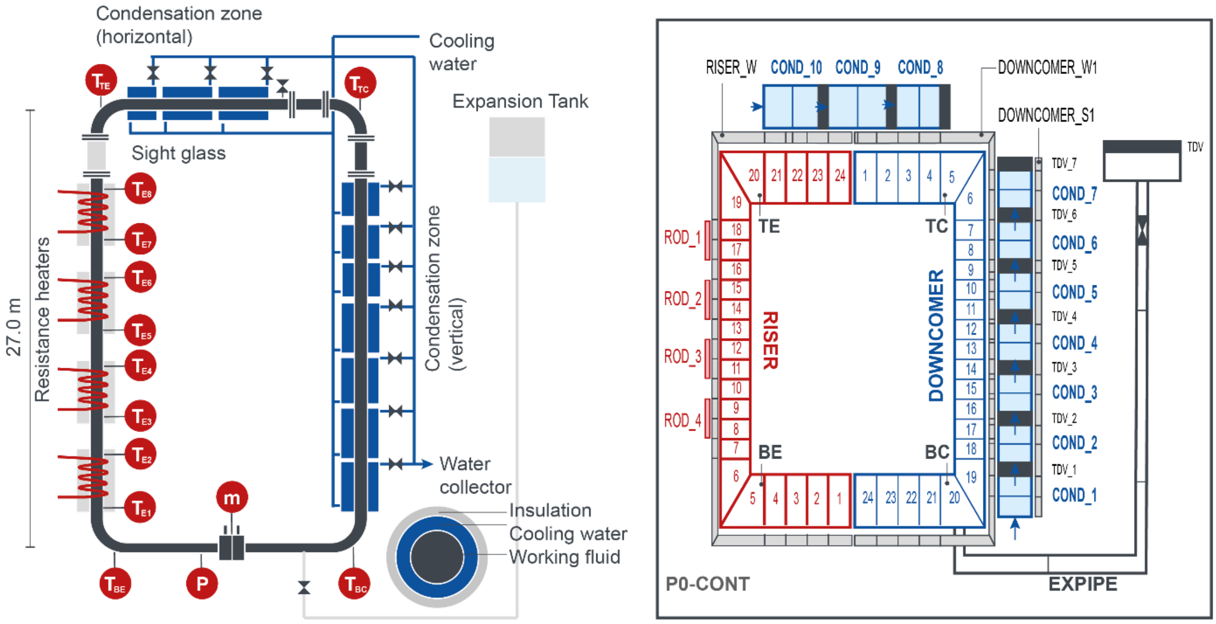

Figure 2: LTS-experimental facility and ATHLET model nodalization

An ATHLET-model of the test facility was developed to assess the suitability of the already built-in features of the code regarding LTS-simulations. Simulations were performed with ATHLET 3.2 with a 6-Balance equation approach. Figure 2 illustrates the nodalization that represents the experimental facility. The first thermo-fluid system is the main loop and it comprises four thermo-fluiddynamic objects (TFOs) arranged in two priority chains (PR): RISER, DOWNCOMER, EXPIPE and TDV. The first PR closes the loop between RISER and DOWNCOMER, whereas the second one attaches EXPIPE to the horizontal lower section of DOWNCOMER. Every TFOs is divided in a particular number of control volumes (CVs) as shown in Figure 2. CVs are enumerated for the main loop, as output data from selected CVs will be extracted, processed and compared to the experimental data.

Heat losses and interactions with the sorroundings were modelled through an additional TFO: P0-CONT, which is an air-filled object conceted to the outer sided of the relevant HECOs. The local heat transfer coefficient in the P0-CONT side was computed via a control signal (GCSM) as a function of the wall temperatures with a natural convection correlation developed by [12]. A total of 18 stationary states (SS) were used for model validation. Process conditions for single and two-phase experiments are presented in Table 1. Variations in the Heat Input (HI) and the volumetric total Filling Ratio (FR) were considered in the experimental matrix and used as initial conditions for the model: Initial water inventory in the loop and heat load on every electric resistance. Initial experimental loop pressure and cooling water process conditions were also model inputs.

Table 1: Experimental stationary states (SS) for model validation

Single-phase experiments								
SS N°	**HI (kW)**	**FR (%)**	**SS N°**	**HI (kW)**	**FR (%)**	**SS N°**	**HI (kW)**	**FR (%)**
1	1.2	100	4	7.1	100	7	13.2	100
2	3.4	100	5	8.9	100	8	14.8	100
3	5.5	100	6	11.1	100	9	16.7	100
Two-phase experiments								
SS N°	**HI (kW)**	**FR (%)**	**SS N°**	**HI (kW)**	**FR (%)**	**SS N°**	**HI (kW)**	**FR (%)**
10	18.2	100	13	18.2	90	16	18.2	70
11	19.4	100	14	19.4	90	17	19.4	70
12	20.5	100	15	20.5	90	18	20.5	70

PARAMETRIC SWEEP AND AGREEMENT OPTIMIZATION

The insulation thickness and the magnitude of the local heat transfer coefficient in the surroundings side are the selected parameters for optimizing the model agreement, so that the heat losses match the experimental ones. An objective function considering the quadratic error between the measured and simulated fluid temperatures (i) (T_{TE}, T_{TC}, T_{BE}, T_{BC}) over time (t) for all SS (j) was built and used to find an optimal parameter combination. A total of 400 combinations were simulated.

$$OF = \frac{1}{4t_f}\sum_{j=1}^{18}\sum_{i=1}^{4}\sum_{t=0}^{t_f}\left(T_{it,e} - T_{it,s}\right)^2$$

RESULTS

The model was initially validated with experimental data from 18 stationary states (SS). Every SS comprises initial transient records characterizing the dynamics needed to reach a stable operation. Figures 3a and 3b show the transient needed to reach SS-10. A proper agreement between simulated and experimental data was reached in terms of the fluid temperature profile around the loop. Minor temperature fluctuations are appreciated in the model output once the two-phase operation is reached (After 10.000 s). Prediction of the working fluid mass flow was very accurate during the single-phase stage of the transient. As Churn flow is developed in the loop (two-phase stage of the transient), it becomes experimentally challenging to record precise values of the fluid mass flow rate, as they are constantly oscillating. Nevertheless, as the mass flows were measured with a relatively high frequency (3 values per second), a high-density data region with representative more accurate average values was developed for every SS in the two-phase operation. Simulated values of two-phase mass flows are within the experimental order of magnitude and match the values of higher data density, as seen in Figure 3b. Regarding the comparison with stationary state values, Figures 3c and 3d illustrate the average values of fluid temperatures and mass flows for three selected SS. The experimental average values were computed over a 2.000 s time for every SS once process parameters were stable. No major discrepancies are found for the single-phase SS in neither, temperature profiles nor working fluid mass flow. As the heat input is increased (Comparing SS-1, SS-4 and SS-7), a temperature rise around the loop was expected and properly represented by the model. Regarding SS-10 to SS-16, a decrease in the loop filling ratio triggered experimental increments in the upper loop temperatures, while fairly keeping the bottom temperatures constant. This behavior was captured by ATHLET as well. The relatively larger disagreements between experimental and simulated data occurred in the mass flow of the two-phase SS. However, they do not exceed an 8.0% error after comparing between average values.

Results for the agreement optimization are shown in Figure 4, where the heat losses to the environment in the evaporator section were adjusted by sweeping between insulation thicknesses from 0.5 to 8.5 cm and heat transfer coefficient multipliers from 1.2 to 10 in the surroundings side. A local minimum value for the objective function was found to be within low multipliers for the heat transfer coefficient (Around 1.6) and insulation thicknesses of 5.5 to 7.5 cm, indicating that the parameter combination represents in this case the heat losses of the experimental facility more properly. Other local minimums are found at high multipliers (5.0) and low insulation thicknesses (1.0 cm).

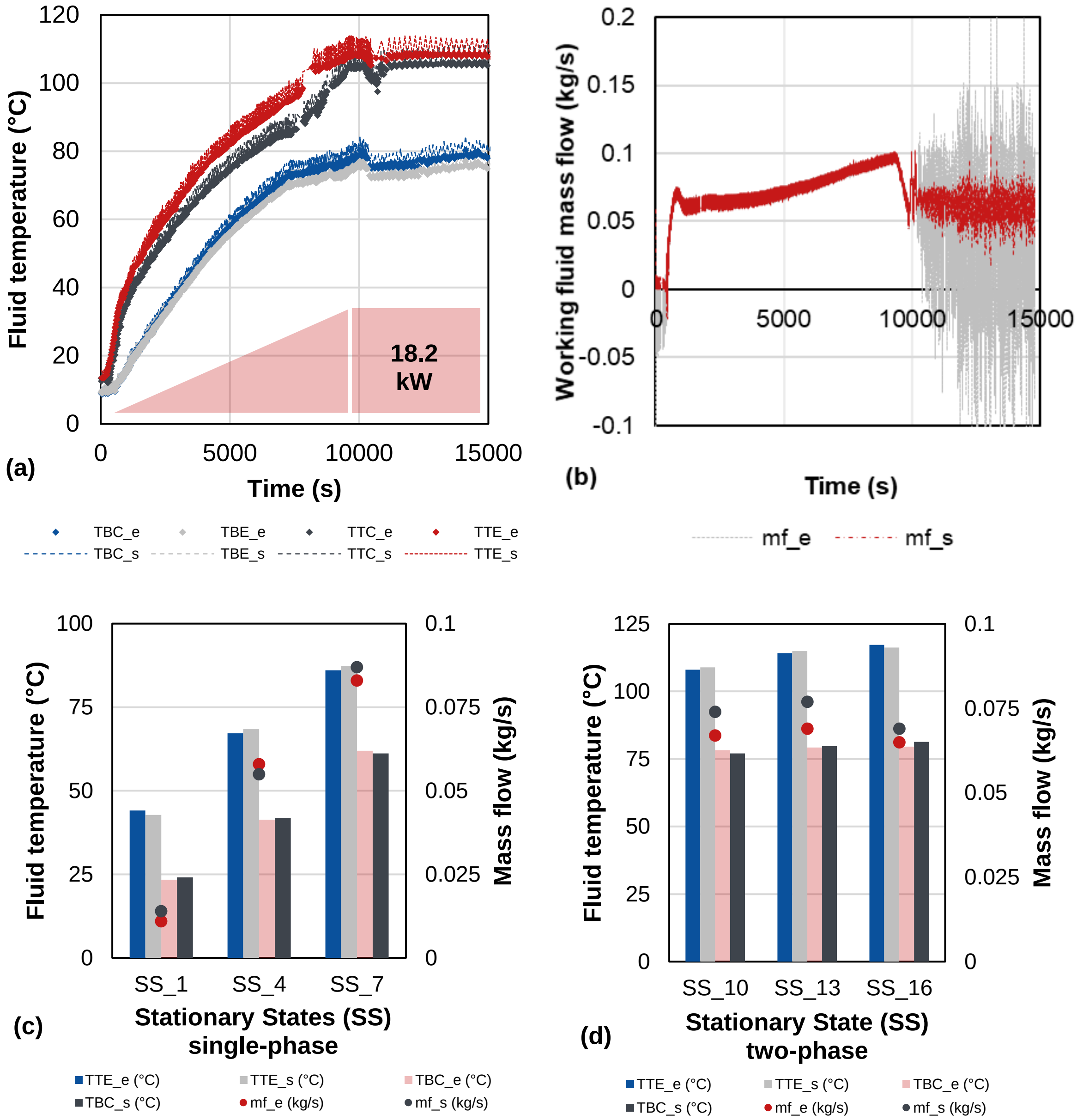

Figure 3: (a) Transient until SS 10 is reached, fluid temperature profile; (b) Transient until SS 10 is reached, mass flow; (c) average values single phase operation; (d) average values two-phase operation. Sub-indexes e & s: experimental and simulated, respectively.

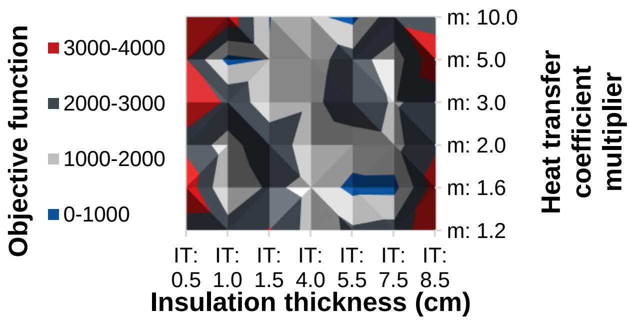

Figure 4: Results of agreement optimization for different combinations of insulation thickness and a heat transfer coefficient multiplier in the surroundings (Air-filled TFO)

CONCLUSION

Aimed to assess the reliability of ATHLET built-in features for simulating residual heat removal from SMRs via LTS, a model of a large-scale LTS-facility was developed and evaluated. The 27.0 m height LTS-facility offered 18 sationary states and their corresponding starting up transients. An ATHLET LTS-model of the facility was built and validated with fluid temperature and mass flow measurements for single- and two-phase operations: Its agreement with experimental data was further uptimized via parametric sweeps adjusting the heat losses to the surroundings. The agreement between model and experimental data was evidenced for both, single- and two-phase SS. Minor deviations in the fluid temperature profiles were appreciated and temperature dynamic increments were accurately represented by the model. On the other hand, the full amplitude of the experimental mass flow fluctuations for two-phase SS was not fully captured by the model. However, the predicted values correspond to the areas of high-density of recorded data and represent experimental average mass flows properly. After conducting the parametric sweep, it was shown that the experimental heat losses can be represented with a model applying a heat transfer coefficient multiplier of about 1.6 in the surroundings side, and an insulation thickness of around 5.5. cm. Overal, ATHLET is a suitable code to represent LTS-facilities, nevertherless, integration of heat transfer correlations for computing coefficients in the air-filled TFOs should be carried out to avoid the use of GCSM functions for that porpose.

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