VALIDATION OF ATHLET FOR BAYONET HEAT EXCHANGERS WITH NATURAL CONVECTION HEAT TRANSFER

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ABSTRACT

Small modular reactors (SMRs) are under construction or development in many countries. Because of their compact features, innovative heat exchangers are desirable to use as steam generators or within heat removal systems for many SMRs. In recent SMR design studies, bayonet heat exchangers (BHXs) have attracted attention, due to their compactness and ability to operate in a natural circulation.

On the other hands, thermohydraulic system codes which evaluate and maintain reactor safety should be improved to incorporate recent innovations in nuclear power plants.

To evaluate and validate ATHLET code in terms of modeling of the BHXs, input decks were created for two experimental setups. The methods and approaches for the modeling were described in the present study. Predictions of the ATHLET simulation were evaluated and compared with the experimental results. The results of this phase of the study serve to understand the capabilities of the code.

INTRODUCTION

Around the world, policymakers, nuclear power corporations and energy experts are increasingly interested in the SMRs because of the advantages which they offer [1]. The most important features are their compact design and safety systems, especially passive safety systems. With the recent developments in the nuclear power plants (NPPs), there has been an increased interest in the BHXs which are innovative heat exchangers in the NPP because of their compactness and ability to operate in a natural circulation. These innovations in the NPPs have led to the need to validate the capability of simulation tools that are widely accepted for the NPP safety analysis to simulate the innovative heat exchangers.

The thermal hydraulic system code- ATHLET (Analysis of Thermal-Hydraulics of Leaks and Transients, developed by GRS) has been developed mainly for the light water reactors, which use U-tube or straight tube steam generators and has no experience on modeling approaches of the BHXs, so far [2].

In this study, two different experimental facilities were selected to evaluate the capability of the ATHLET code to model the BHX in both single-phase and two-phase flow conditions. The PROPHET experimental setup investigated a single-phase flow condition, while two-phase flows were investigated in the HERO2 experimental setup. The experimental data of the PROPHET were obtained from the literature, the data of the HERO2 experiment were provided by ENEA within PASTELS project.

EXPERIMENTAL SETUPS

The physical layout of the experimental setups, PROPHET and HERO2, are shown in Figure 1 below.

The total height of the PROPHET is about 5 meters [3] [4]. It consists of a bayonet tube, a condenser, a hot and a cold leg. The heat source is provided by heating tapes which are wrapped around the bayonet outer tube and supplies an electrical power of 1.75 kW. The loop is filled with water, but air is trapped in the upper part of the upper connecting pipes and the upper part of the bayonet annulus. It cannot be evacuated from the loop because of the design of the facility. However, these parts are in positions that do not affect the circulation in the system and have no effect on the circulation [3].

The total height of the HERO2 is about 19 meters. It consists of 2 bayonet tubes, a pool condenser and a hot and a cold leg. Heat source to the loop is provided via a total of 210 electric resistors on the bayonet tubes and supplies an electrical power of 33.79 kW. The facility is thermally isolated with rock wool. In order to achieve the desired filling ratio of the loop (68%), the experiment starts with a complete filling of the loop with water, after which the heaters of the test section are switched on. With the increase of pressure in the system, steam generation and the initiation of the natural circulation, water and steam are discharged from the open line at the top of the loop. When the desired mass is discharged from the loop, the valve in the open line is closed, and after a while the test reaches the steady state.

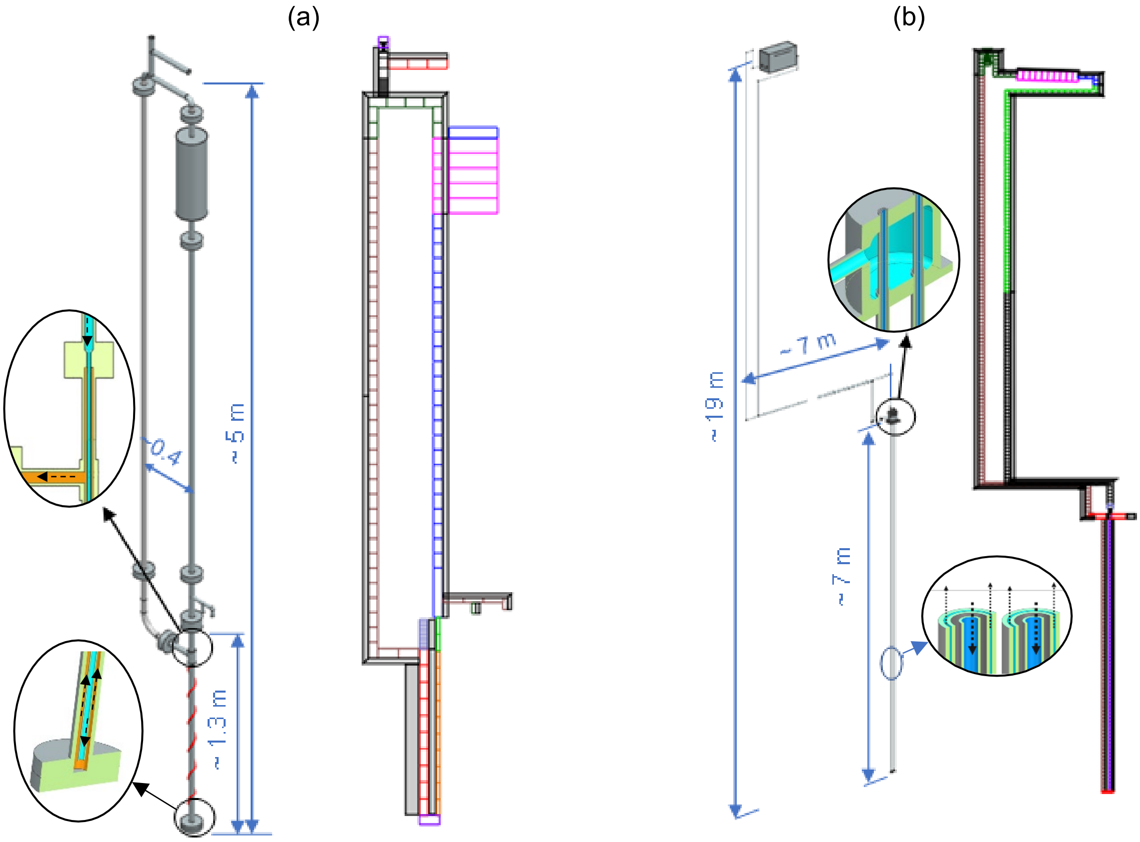


Figure 1: 3D Layout of the Test Facility and Nodalization* (a) PROPHET (b) HERO2

**Scaling is different between components.*

ATHLET MODELS

In general, modelling approaches used for the experimental setups are quite similar.

The simulations were performed by using standard thermo fluid dynamic objects (TFO), heat conduction objects (HCO) and General Control Simulation Module (GCSM) signals.

Pipe walls are represented as HCOs in the ATHLET model. HCOs were defined between the environment and the fluid system to model heat losses from the hot and cold legs. To model the regenerative heat transfer between descending and ascending water in the bayonet tube, the HCO was defined between the slave tube and the outer tube. Unlike PROPHET, the bayonet tubes of HERO2 consist of 3 tubes, namely slave tube, inner tube and outer tube. There is air between the slave and the inner tube to reduce the heat flow to the water in slave tube. The air layer is modelled as a material with the representative thermal conductivity in ATHLET model.

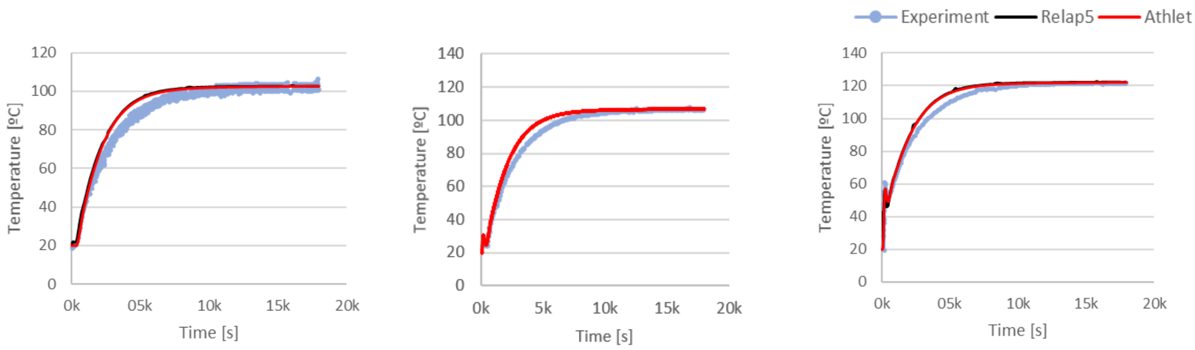
The phenomena within the loops are quite similar for both facilities. The water in the loop is still at the beginning of the simulation. As soon as the thermal power is activated, the water in the outer tube of bayonet heats up. The difference in density between the water in the slave tube and the outer tube initiates the natural circulation. The circulation water flows down the slave tube, reaches the inversion chamber and rises in the outer tube. The heated water flows back into the slave tube, losing heat through the hot leg, the condenser tube and the cold leg, respectively. Additionally, in the simulation of the HERO2 experiment, to reach the desired filling ratio in the loop, water/steam is discharged from the open line, which is located just before the condenser tube. Once the desired filling ratio is reached, the valve in the open pipe is closed and then the simulation converges to a steady state. The amount of water/steam that is discharged from the loop is controlled by the GCSM signal in the model. The heat transfer between the condenser tube and water in the pool was simulated using a simplified model approach in ATHLET. The condenser pool was not modelled in ATHLET. The experimental temperature of water in the pool was defined as the fluid temperature on the outer side of the HCO, which represents the wall of the condenser tube. The heat transfer coefficient was adjusted in order to get the correct outlet temperature at the exit of the condenser.

While a power loss of ~30% (including heat loss through the bayonet tube) is predicted for the experiment of the PROPHET, a power loss of ~20% (electrical loss only) is predicted for the experiment of HERO2. These ratios were determined based on previous experimental and analytical studies [3][5]. That is why, as a boundary condition, an electrical power of 1.2 kW for PROPHET and 27.5 kW for HERO2 was imposed to the wall of the outer tube of the the BHX. As initial conditions, the ambient temperature was set to 25 ℃ and the water temperature to 20 ℃ for both test simulations.

RESULTS OF ATHLET SIMULATIONS

PROPHET

The experiment in the PROPHET facility investigated a liquid single-phase natural circulation. Since the simulation results by the RELAP5 system code are also available in [3], it offers the possibility to make code-to-code comparisons. Figure 2 shows the time history of the fluid temperatures at the inlet and outlet of the BHX as well as at the inversion chamber. As can be seen from the figures, while there is a good match in the steady state condition, ATHLET and RELAP5 overpredicts slightly in the transient condition. A possible reason of the overprediction may be due to underestimation of the total system thermal inertia as the flanges and support elements in the system are not modeled [3]. Figure 3 shows the absolute pressure in the inversion chamber. The agreement between the code predictions and the experimental result is well in the transient and steady state condition. Figure 4 compares the predictions of the simulation tools for the mass flow rate. A comparison with the experiment was not possible since there was no mass flow meter in the facility. In general, the agreement is well, only the peak point of ATHLET is slightly lower than that of RELAP5.



(a) **(b)** **(c)**

Figure 2: Fluid Temperatures at (a) BHX inlet (b) inversion chamber (c) BHX outlet

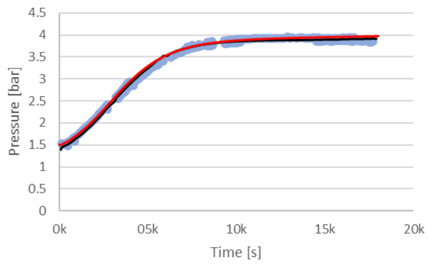


Figure 3: BHX - Inversion Chamber Pressure

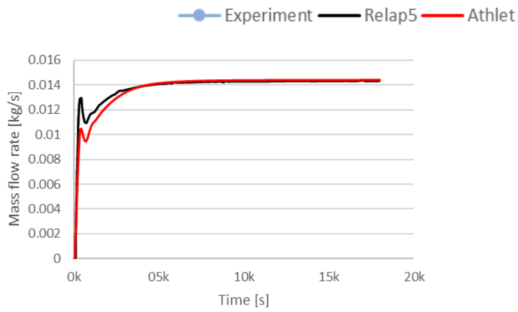


Figure 4: Mass Flow Rate Prediction

HERO2

The experiment in the HERO2 facility investigated a two-phase natural circulation. Figure 5 (a) presents the fluid temperatures at 8 different locations in the bayonet annulus. As can be seen from the figure, ATHLET predictions are consistent with the experimental data. The location of the transition from single phase to two phase flow, which is approximately fifth meter of the annulus, was correctly predicted by ATHLET. Pressure drop measurements were taken in several parts of the facility. The ones related to the BHXs part are listed in Figure 5 (b). The pressure difference between the inlet of the slave tube and the inversion chamber corresponds to the differential pressure DP12, while DP23 represents the pressure difference between the inversion chamber and the BHX outlet. DP13, DP14, DP15, DP16 indicate the differential pressures for each 1.4 m segment of the bayonet annulus. DP17 is the pressure difference between the upper part of the annulus and the outlet of the bayonet. The agreement for all these differential pressures is within the ±20% error. On the other hand, the pressure drops in the annulus are not expected to be perfectly simulated. The annular space contains multiple thermocouples as well as their cables. The presence of cables starts from the bottom and increases upwards, and they are taken out from the steam chamber. The pressure losses will be affected by the presence of the cables in the experiment. Their effect was not represented in the simulation.

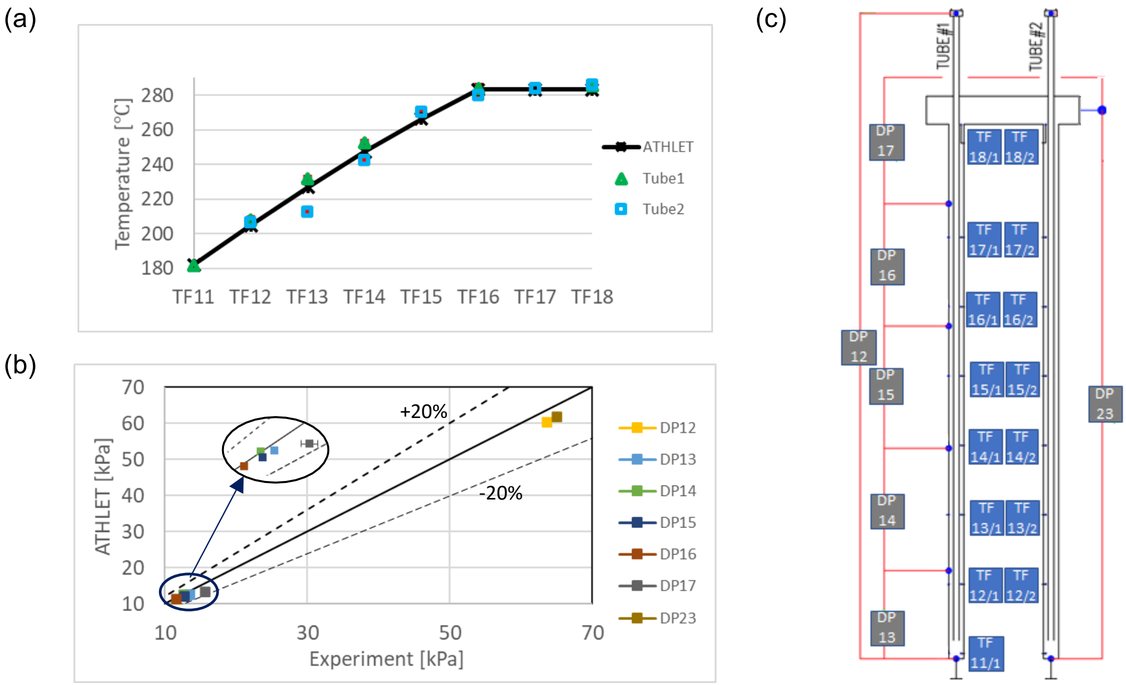


Figure 5: Analysis of the Bayonet Tube (a) Fluid Temperatures (b) Differential Pressures (c) Location of the Sensors

Table 1 shows the inlet and outlet temperatures of the BHX section and the condenser tube. All temperatures lie within a ±3% error range. And the mass flow rate results can be seen in Table 1 as well. The agreement is good, the overestimation of the mass flow rate is about 3%.

Definition	Experiment	ATHLET
Condenser inlet Temp [℃]	283.2 ± 1.6	281.7
Condenser outlet Temp [℃]	185.1 ± 2.3	187.4
BHX section outlet Pressure [bar]	66.85 ± 1.6	66.78
BHX section inlet Pressure [bar]	67.25 ± 1.6	67.16
Mass flow rate [g/s]	35.87± 2.8	36.86

Table 1: Comparison of the Temperature, Pressure and Mass Flow Rate

On the other hand, the test data of HERO2 are available for 21 different test cases in which the power and filling ratio were changed. Just one of the cases was mentioned above. When all the simulations were performed, it was noted that the mass flow rate could not be correctly predicted for the tests with a filling ratio of less than 60%. The studies of this issue are still ongoing.

Since the focus of this study is the BHXs, a second model, with only the BHX, was modeled. Mass flow rate and enthalpy of the fluid at the inlet as well as the corresponding pressure at the outlet which are obtained from experiment at the steady state condition were given as a boundary condition for the simulations. A schematic view of the model can be found in Figure 6. Figure 6 represents all temperatures at 8 different locations in annulus. In general, for the all-test cases the agreement is good.

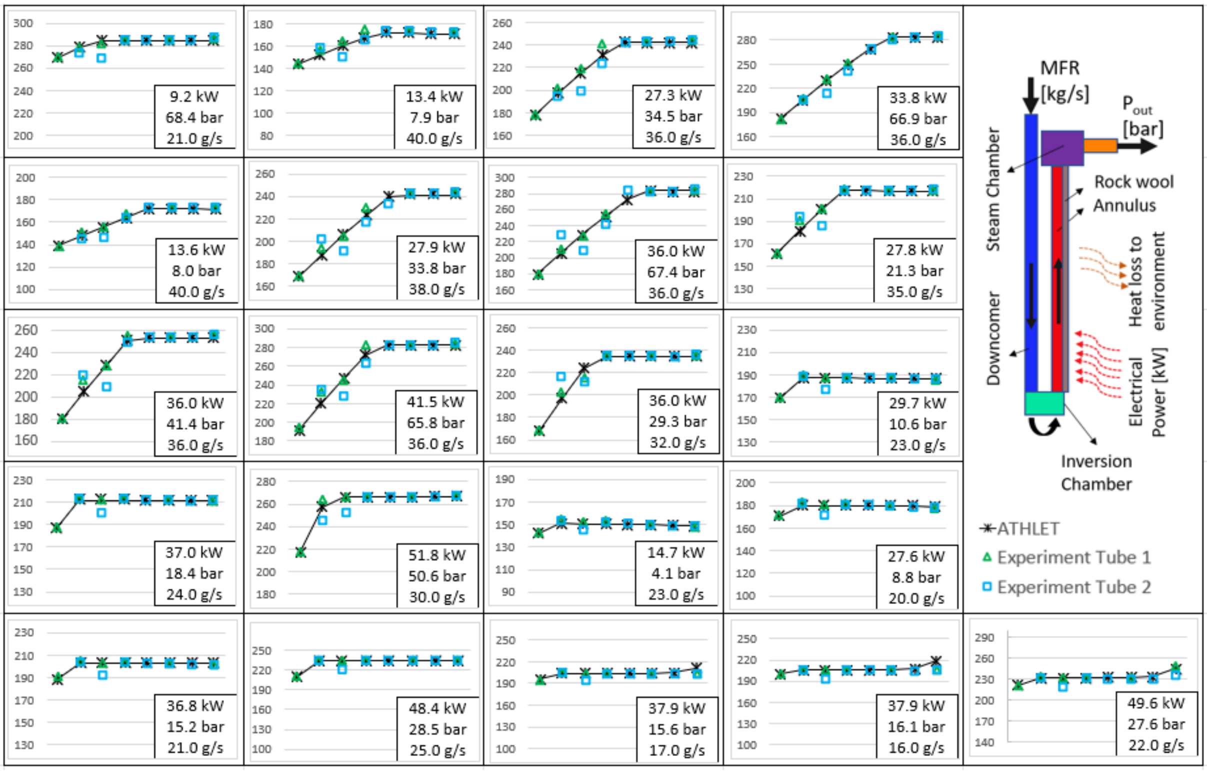


Figure 6: Fluid Temperatures at 8 Different Locations in the Bayonet Annulus

CONCLUSION

The thermal hydraulic system code- ATHLET has been developed mainly for the light water reactors, which use U-tube or straight tube steam generators [2]. However, due to the increasing interest in BHXs with innovations in the nuclear sector, it was required to investigate the modeling capability of the ATHLET code for the bayonet tubes, as well. With this purpose, the simulations were performed for two different experimental setups with natural circulations, single-phase and two-phase flow conditions.

The assessment for the single-phase flow condition was performed using the data from the PROPHET facility which was obtained from the literature. While the temperatures are well predicted in the steady state, they are slightly overestimated in transient state. However, it is assumed that this is due to an underestimation of the thermal inertia of the system, since the existing support elements and flanges in the system were not modeled. On the other hand, code-to-code comparison was performed with RELAP5, and the agreement between the codes is well.

The experimental data from the HERO2 facility, provided by ENEA, were used to evaluate the two-phase flow condition. Since all experiments in the HERO2 are steady-state investigations, all comparisons are performed for the steady-state condition. ATHLET was able to predict well the temperatures in the annulus and the location of the transition from single phase to two phase flow. The pressure drop predictions were reasonable, as well. It was able to initiate the natural circulation by itself and predicted value for the mass flow rate is in reasonable agreement with the experimental data. In addition, based on the preliminary simulation results of the other test cases, it was noted that the mass flow rate predictions for the tests with a low filling ratio were not compatible. Further studies should be conducted in this area. On the other hand, only the bayonet model was created for these all test conditions and the investigations focused on the bayonet. From this study it can be concluded that the heat transfer for given input conditions is calculated by ATHLET with sufficient accuracy.

Although preliminary validation of the ATHLET was performed for the modeling of the BHXs in this study, further validation and verification is required prior to its use for design and safety analyses.

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