VASiL – A joint project to cover innovative concepts to remove residual heat in LW-SMR in simulations using AC2

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ABSTRACT

Within the joint research project VASiL (Enhancement and **V**alidation of **A**C2 for **S**imulation of **i**nnovative **L**W-SMR) the thermal-hydraulic system code ATHLET is enhanced and validated to keep the code applicable also for nuclear new builds especially referring to SMR (**S**mall **M**odular **R**eactors). Focus of the project are the modelling of compact heat exchangers and investigations of natural convective heat transfer on high containment walls up to 15 – 20 m leading to Rayleigh numbers (Ra) up to 10^{15}. Finally, all models will be tested by generic simulations of different SMR designs. Project partners are GRS and the universities of Stuttgart and Bochum. The paper gives an overview about the project with selected results obtained so far.

INTRODUCTION

LW-SMR development for near-term deployment are pursued by multiple vendors internationally. The most promising LW-SMR designs in the view of GRS, which are likely to be built in Europe (e.g. NuScale, NUWARD, etc.) provide different kinds of residual heat removal systems and concepts. To assess the behaviour of those designs in normal and accident conditions, thermal-hydraulic system code analyses with good predictiveness must be possible. To ensure that, the joint German research project VASiL (Enhancement and **V**alidation of **A**C2 for **S**imulation of **i**nnovative **L**W-SMR) was started in 2020, led by GRS, to improve the code package AC^2 for innovative reactor designs specifically for passive residual heat removal systems. Besides GRS, partners in the project are the universities of Stuttgart (called IKE later on) and Bochum (called RUB later on).

Many SMRs use compact and so-called integrated designs, in which all the major components (e.g. core, pressuriser, steam generators and main cooling pumps) are located within the pressure vessel. Since space is very limited in such designs steam generators and also safety class heat exchangers inside the vessel need to be very compact. The heat exchanger types vary between the SMR designs. Examples are plate heat exchangers foreseen e.g. in the NUWARD design, helical coil steam generators (e.g. CAREM, NuScale) or bayonet type heat exchangers (e.g. SCOR). All of the mentioned heat exchanger geometries are treated within VASiL in terms of enhancement of ATHLET.

Another issue is the heat removal from the containment surrounding the reactor pressure vessel. Basically, four different options for containment cooling can be found in the various SMR designs:

- Horizontal or vertical containments, partially or fully immersed inside large water pools, designed so that after full evaporation of the pool inventory, heat transfer to the surrounding air is sufficient to cool the containment or provisions for refilling the pool in the long-term are foreseen.
- Vertical containments partially or fully immersed inside a large water pool cooled by heat pipes
- Containments on the oceans floor
- Containments integrated in swimming platforms below the water surface

The simulation of the heat transfer to large water pools need to tackle two main issues: Firstly, free convective heat transfer depends highly on the containment wall height. Correlations in literature to predict the correct Nusselt number like the McAdams correlation available in ATHLET [1] are applicable for heights up to ~1 m (Rayleigh number 10^{12}) but 15 m or even 20 m would be needed (Ra ~ 10^{15}). VASiL deals with that issue by enhancing ATHLET with heat transfer correlations for high containment walls validated against CFD analysis results, since currently no suitable experimental data is available. The second issue is the evaporation of water at subcooled conditions to the pool atmosphere due to the heat up of the pool. Depending on the scenario, the liquid level drop per day can be noticeable, as is the related heat transfer power.

SMR designs like CAP200 or SIMPLE provide cooling of the pool inventory by heat pipes to transfer the heat to the environment. In these cases, the evaporation zones of the heat pipes are located inside the water pool, while the air-cooled condensation zones are outside of the containment. Heat transfer by heat pipes was already a topic in the research project RS1543, in which ATHLET was enhanced for the simulation of such heat pipes. Validation of the models was done by experiments performed in the PALAWERO project of the IKE Stuttgart (FKZ 1501515). While the aim of PALAWERO was the demonstration of residual heat removal from fuel element storages by heat pipes, in which counter current flow of vapour and water in the same tube occurs (so-called thermo-siphons), in VASiL so-called loop heat pipes (loop thermo-siphons) are investigated in which vapour and water flow in separate tube locations. Compared with tube heat exchangers, they differ only in their low pressures.

Some SMR designs use containment atmospheres at low pressure conditions to minimise operational heat losses to the containment surrounding pool. One example is the NuScale design, in which the containment pressure under normal operation mode is at vacuum condition. The ATHLET property package for water was developed for cooling systems of LWR and has a two-phase parameter range between 1 kPa and 22 MPa [1]. In the low pressure region, large deviations from actual values can be observed. Therefore, within VASiL, the property package was tested by generic simulation of a LOCA into a low pressure containment. The ATHLET standard property package was investigated besides a more advanced method using the property using a spline based table look up methodology (SBTL) implemented by the Hochschule Zittau/Görlitz within the frame of a project with the FKZ 1501552 [2].

In the frame of VASiL cooperation, the partners GRS, IKE and RUB share the work on the above mentioned task:

- Compact heat exchanger geometries
  - Helical coil heat exchangers → RUB
  - Bayonett type heat exchangers → IKE
  - Loop thermo-siphons → IKE
  - Plate heat exchangers → GRS
- Free convective heat transfer on large pool walls
  - CFD simulations → GRS (CFX), RUB (OpenFoam)
  - ATHLET enhancement → GRS
- Development of an evaporation model → GRS
- Testing of low pressure containments → GRS

At the end of the project, all implemented models are used to simulate generically different SMR designs with different residual heat removal strategies based on the heat exchanger design they are working on in the first part of the project.

In the following sections show some selected results obtained so far in VASiL.

DEVELOPMENT OF AN EVAPORATION MODEL

MOTIVATION

In some SMR designs, the passive cooling systems provide the safety function residual (or decay) heat removal during design basis accidents and design extension conditions, e.g. a Station Black Out (SBO) event. The decay heat of the core is transferred to the heat sink by the one- or two-phase natural circulation. In some SMRs such like NuScale [3], the heat sink is a large water pool as the reactor itself is submerged in this pool. Thus, it is essential for safety analysis and safety demonstration of SMRs with such systems to accurately simulated how much heat can be removed to the pool and how fast its water level decreases by the evaporation. Moreover, a best-estimate model of evaporation can help to predict how much water should be refilled daily during routine operation.

NEW EVAPORATION MODEL IN ATHLET

The previous implementation of the evaporation model in ATHLET 3.2 is derived from the energy transfer by the temperature gradient between the water surface temperature and the saturated temperature of the partial pressure of water vapor. Then, the energy transfer is converted into the mass transfer divided by the latent heat of evaporation. However, this implementation has the following limitations. First, the driving mechanism by the concentration (or density) difference is not directly taken into account. Second, fluid properties of the liquid phase are taken to determine the heat flow although the physical phenomenon of mass transfer by evaporation occurs in the gaseous phase. Thus, the evaporation model is improved in the new release ATHLET 3.3.

Developing the evaporation mass flow rate out of film theory using Fick's law and the analogy between heat and mass transfer lead to Stefan's law expressing the mass flow rate as a function of partial pressure gradients and a mass transfer coefficient. The latter is determined by correlations for the Grashof (Gr) and Schmidt (Sc) number as well as by the diffusion coefficient. Within VASiL certain possibilities from literature to express these parameters were tested using experimental data. The best prediction of evaporation was achieved using the following equations. The evaporation mass flux E (taken from [4]) is:

$$E = \beta \rho_{air,0} \left(W_{v,0} - W_{v,\infty} \right)$$

Here, $\rho_{air,0}$ is the density of air at the water surface and W is the specific humidity defined as:

$$W_v = \frac{M_v}{M_{air}}$$

which is the ratio of water vapor mass M_v to the air mass M_{air}. The subscript 0 and ∞ indicate the properties evaluated at the surface and in the ambient (above the boundary layer) respectively. The properties of the water vapor at the surface are obtained at saturated conditions for the water surface temperature T_s, and the properties of the other variables are calculated by the ideal gas law with the corresponding temperatures and partial pressures. The mass transfer coefficient β can be calculated with Grashoff and Schmidt number from [5]:

$$\beta = 0.14 \cdot (\mathrm{Gr} \cdot \mathrm{Sc})^{1/3} \frac{D}{L}$$

In this equation, D is the diffusion coefficient and L is the characteristic length. The diffusion coefficient is taken from [6]:

$$D = \frac{10^{-7} T^{1.75} \left(1/\bar{M}_v + 1/\bar{M}_{air} \right)^{1/2}}{\left(p/p_{ref} \right) \left(v_v^{1/3} + v_{air}^{1/3} \right)^2}$$

In this equation, T is the temperature, p is the pressure and p_{ref} is atmospheric pressure (101.325 kPa). The parameter v is the atomic diffusion volume given tabled also in [6] for several gases. Finally, Grashof [7] and Schmidt numbers are defined here as follows:

$$\mathrm{Gr} = \frac{g \left(\rho_{mix,\infty} - \rho_{mix,0} \right) L^3}{\bar{\rho} \nu^2}, \qquad \mathrm{Sc} = \frac{\nu}{D}$$

In these equations, g is the gravity constant, ρ_{mix} the mixture densities of vapour and air in the gaseous bulk and at the surface, $\bar{\rho}$ is the mean density of mixture densities and v the kinematic viscosity.

Several experiments available in the literature have been simulated using these equations for prediction of the evaporation mass flow rate instead of the previous ATHLET standard correlations. One example is the experiments conducted by Boelter [8]. The experimental setup was a so-called evaporation pan with a diameter of 0.3048 m and a height of 0.1524 m. A heater was attached at its bottom to control water temperature. The temperature range was about 24.0 – 94.2 °C.

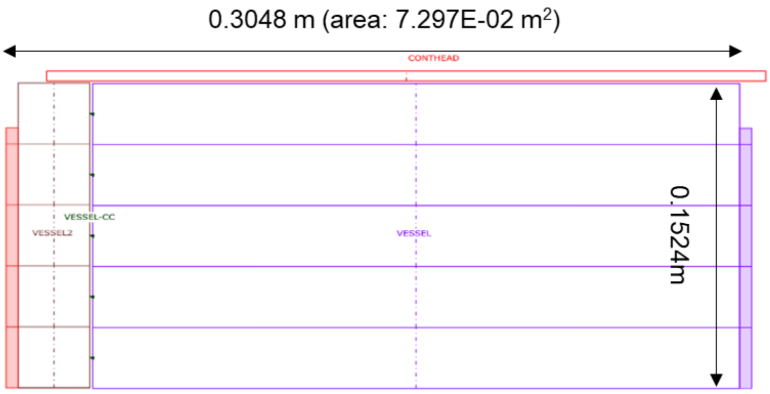

Figure 1 ATHLET nodalisation of the evaporation pan used by Boelter

The evaporation pan nodalisation is shown in Figure 1. It was axially divided into 5 uniform nodes and modeled with two Thermo-Fluid dynamic Objects (TFOs) by having 90 % and 10 % of total volume to enable the natural circulation of water inside the pan. The initial elevation of the mixture level was assumed to be 0.15 m. A Time-Dependent Volume (TDV), CONTHEAD, was linked at the top of the pen TFOs, and the boundary conditions of air – temperature and humidity were imposed there. Two Heat Conduction Objects (HCOs) were attached at the bottom of each TFO to model a heater. They were turned on and off when the water temperature deviated more than 0.1 K from the reference temperature. The calculation ran until simulation time t = 35 min.

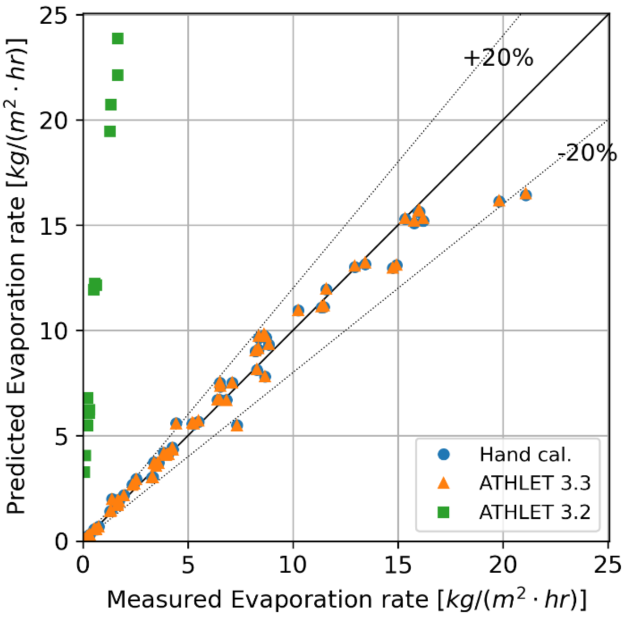

Figure 2 Comparison of evaporation rate hand calculation and ATHLET against measured data

The ATHLET calculation is compared with to experiment data and hand calculations as shown in Figure 2. The ATHLET 3.2 results are also included for reference. As shown in the figures, the original model heavily overestimates the evaporation rate. On the other hand, the new evaporation model excellently agrees with the hand calculation by 1.1 % RMS error, so it is able to predict well the measured evaporation rate. The new evaporation model performed reasonably at other pressure and temperature ranges and replaces the previous model in version ATHLET 3.3.

While the the new evaporation model was very briefly described in this paper, deeper insight in the analytical investigation as well as other verification and validation work is documented in [9].

CHEVRON TYPE PLATE HEAT EXCHANGERS

MOTIVATION

When most of the primary side components of a reactor are integrated inside the reactor pressure vessel, space is very limited. Therefore, compact components need to be provided. In the NUWARD design for example, as we understand, plate heat exchangers are used for steam generators as well as for residual heat removal heat exchangers. While plate-type heat exchangers are innovative in the nuclear field, they are well established in the chemical and process industry. Normally, these type of heat exchangers are composed of a number of plates stacked above each other. Primary and secondary fluid alternately flow between the plates. The surfaces of the plates are normally engraved with e.g. sinus-shaped chevrons making the stack very robust and enhancing heat transfer [10]. In VASiL, correlations for the single-phase form loss and heat transfer for such heat exchanger types were added to ATHLET to better simulate such components.

THE MODEL

The correlations for pressure drop calculation as well as single phase heat transfer were taken from the VDI Heat Atlas [10]. The form loss coefficient mainly depends on the Reynolds number of the flow (Re) as well as of the rotation angle of the chevrons with respect to the normal flow direction. The correlation covers the longer flow paths along wave troughs, flow reversals at borders of the corrugations, crossing of partial flows and the replacement of crossflow by longitudinal flow. The heat transfer correlation given in [10] is based on Prandtl (Pr) and Reynolds number but additionally depends on the form loss coefficient (ζ) as well as on the chevron angle (φ):

$$Nu = c_q \cdot Pr^{1/3} \left(\frac{\eta}{\eta_W}\right)^{1/6} [\zeta \cdot Re^2 \cdot \sin(2\varphi)]^q$$

The temperature dependency of the viscosity η is taken into accound by the fraction of the viscosities of bulk and wall (subscript W).

In order to verify the implemented correlations, two different experimental facilities were simulated with the developer version of ATHLET. Experimental data can be found in [11] and [12]. In both experimental facilities, the pressure drop and heat transfer dependencies on Reynolds number and chevron angle were investigated. Simulations of these experiments with ATHLET showed a good agreement in transferred heat for all chevron angles and investigated Reynolds numbers as shown exemplarily in Figure 3 left side using the newly implemented models (here for the so-called Johannesburg experiment [12]). Without these models, ATHLET underestimates the heat transfer. Deviations from the experimental data are below 20 % for all angle (small, mean and large) types using the new models (dashed lines show 20 % difference between simulation and experimental data).

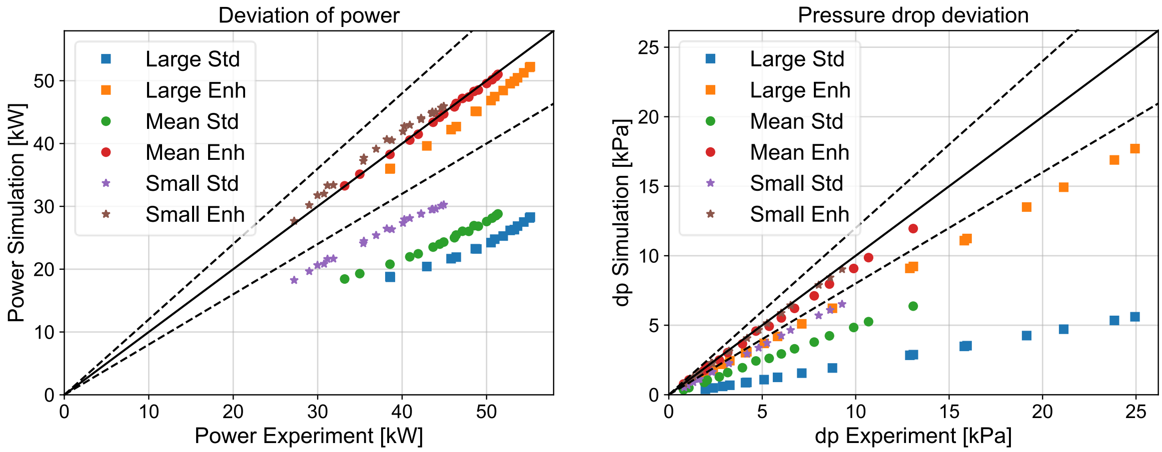

Figure 3 Transferred heat comparison between experiment and ATHLET simulations for Johannesburg experiment [12]

However, pressure drop simulations show differences of more than 20 % for large chevron angles (see Figure 3 right side) even when using the newly implemented models. The differences become lower in lower angle cases. Without the ATHLET enhancement, the pressure drop is underestimated but the predictions becomes better with lower angles, since the flow becomes less turbulent.

Finally, it must be noted, that a more detailed description about the ATHLET development with respect to plate heat exchangers can be found in [13].

SUMMARY

The system code ATHLET is enhanced in the VASiL project for the applicability of new LW-SMR designs. Important milestones have been achieved so far as shown exemplarily with respect to plate heat exchangers and the evaporation of liquid in pools. Besides the enhancements for the other heat exchanger geometries the new implemented models will be tested in the last phase of the project by the performance of generic simulations of different SMR designs.

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