COMPARATIVE ASSESSMENT OF CONDENSATION MODELS FOR HORIZONTAL TUBES

Andreas Schaffrath, Anne-Kathrin Krüssenberg, Ulrike Gocht[1] and Andrej Fjodorow[1]

1. Introduction

The condensation in horizontal tubes plays an important role for the prediction of the operation mode of horizontal steam generators of VVER reactors or passive safety systems for the next generation of nuclear power plants. Two approaches (KONWAR and HOTKON) for modeling this process have been applied by Forschungszentrum Jülich (FZJ) and University for Applied Sciences Zittau/Görlitz (HTWS) and were implemented into the 1D-thermohydraulic code ATHLET, which is developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH for the analysis of LOCA and transients in light water reactors [1].

Although the improvements of the condensation models are developed for different applications (VVER steam generators, SWR1000 emergency condenser) with strongly different operation conditions (HORUS: max. temperature difference 30 K, max. mass flow 0.025 kg/s, max. steam velocity 5 m/s, stratified counter-current gas-liquid flow, NOKO: max. temperature difference 260 K, max. mass flow 0.75 kg/s, max. steam velocity 35 m/s, annular, stratified, bubble, slug and plug counter-current gas-liquid flow) both models are now compared and assessed by Forschungszentrum Rossendorf FZR e.V. For that, post test calculations of four selected HORUS (horizontal u-tube steam generator) experiments were performed with ATHLET/KONWAR and compared with existing ATHLET and ATHLET/HOTKON calculations of HTWS.

2. Horus test facility

The HORUS II test facility was designed for the investigation of small break loss of coolant accidents (SBLOCA) in VVER reactors [2]. The crucial component of the separate effect test facility is the single steam generator tube (length L = 9.2 m, outer diameter D = 16 mm, wall thickness s = 1.5 mm) which is arranged in a tank (length L = 4.62 m, outer diameter D = 219.1 mm, wall thickness s = 8.2 mm). The tube is fabricated of the original stainless steel material (X8 CrNiTi 18 10). The design of the test facility allows to adjust the same initial and boundary conditions as during a SBLOCA (primary side pressure up to 8 MPa, secondary side pressure up to 6.4 MPa and primary and secondary side temperatures up to 300 °C). The tube is coupled with collectors at the beginning and the end. These collectors are used for the connection to the necessary support systems (e.g. the steam supply, the venting or the non-condensable injection system) and are volumetrically scaled in 1:1400. They agree in principle with the original collectors, but they serve essentially as separators. The HORUS II facility is densly equipped with measuring transducers for the acquisition of the thermohydraulic process parameters such as pressure, temperatures, water level at the primary and secondary side.

[1] University of Applied Science Zittau/Görlitz

3. Comparison of the condensation model improvements

The condensation model of the original version of ATHLET was developed for the calculation of heat transfer coefficients (HTC) in vertical tubes. The condensation process is characterized by symmetrical condensate films with an equal layer thickness over the cross section area. The HTC are calculated by the correlations of Chen [3], Nusselt [4], or Carpenter and Colburn [5], or a minimum of 20 W/(m²K). The maximum of these values is used in the further calculation.

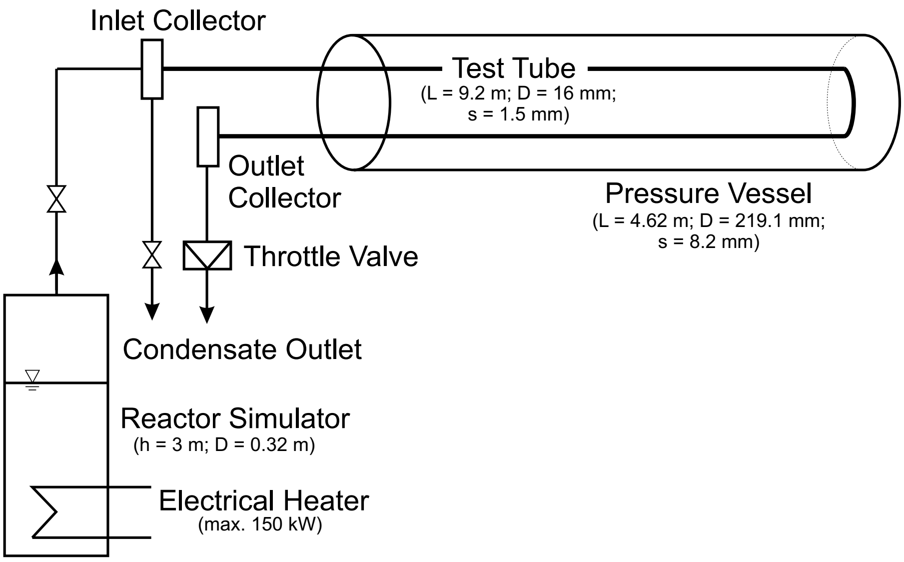

Fig. 1: Flow diagram of the HORUS test facility.

The condensation process in horizontal tubes is much more complicated than in vertical tubes. Over the tube length different flow regimes (e.g. spray, plug, slug, bubble and stratified flow) may occur (see fig. 2). Vapor enters the tube with a relatively high velocity and annular flow establishes with nearly equal condensate layer thickness in the cross section area. During the condensation the steam velocity decreases down to the liquid velocity. At moderate steam velocities the condensate collects at the bottom. It is assumed that film condensation takes place at the upper part of the tube cross section area. The condensate film is very thin and drains down driven by gravity forces. The stratified condensate layer in the tube sump flows along the bottom of the tube, often ripples or waves are generated at the phase surface [6]. To describe these complicated processes the condensation model in ATHLET had to be improved. Two different approaches, HOTKON and KONWAR, have been developed. In the four HORUS tests which are selected by HTWS for post test calculations, stratified flow is expected to occur along the whole tube. Therefore, in the following the attention is focussed on the calculation of the HTC during the stratified flow regime.

HOTKON [6] is based on Huhn's general film flow theory [7] with respect to filmwise condensation. Here the field equations governing the mass, energy and momentum transfer between the liquid and the vapor phases are simplified using the thin film approximation by taking into account

- the effects of frictional shear stresses (as a result of friction between the vapor bulk and the condensate film as well as between the vapor bulk and the droplets entrained from the condensate film),
- the gravity forces acting upon the condensate,

- the development of the stratified angle β (see Fig. 2) associated with the accumulated condensate layer at the bottom of the tube,
- the liquid volume fraction existing as droplets in the vapor region of the two-phase flow.

The influence of these parameters is evaluated with respect to the heat transfer at the condensate film inside horizontal tubes for both laminar and turbulent water and vapor flow. A solution for condensation may be obtained solving the momentum and energy equation using the similarity concept.

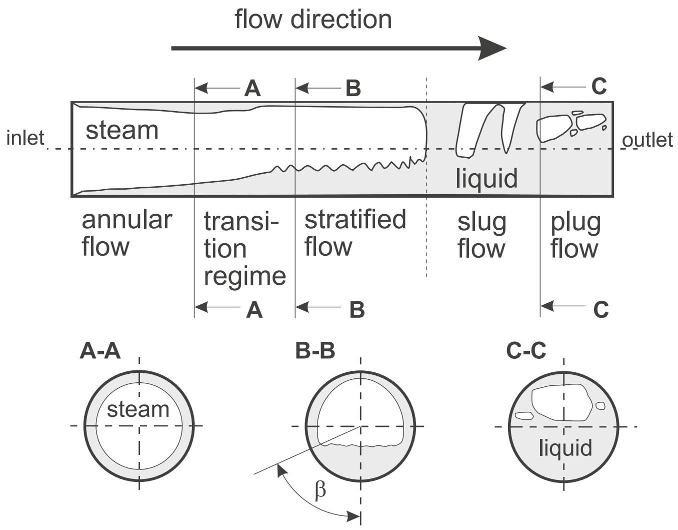

Fig. 2: Flow regimes during condensation in horizontal tubes [6]

The heat transfer coefficient for laminar stratified flow is determined by the modified Nusselt model [7], which takes into account the decrease of the heat transfer surface due to the collection of condensate in the tube sump. The heat transfer coefficient for this case is calculated by

$$\alpha_{ls} = C \left(\frac{\rho_L (\rho_L - \rho_V)\, g \;\, r \;\, \lambda}{\eta \;\, D\, (T_S - T_W)} \right)^{0.25}$$

with respect to the peripheral angle β of the condensate layer in the tube (Fig. 2), which can be determined from the local void fraction ε. In HOTKON the value for C = 0.296 is taken over from Russian reactor safety experiments in original VVER steam generators [8], which means C is averaged over the tube length.

KONWAR [9] was developed by FZJ for the investigation of the operation mode of the emergency condenser of the SWR1000. KONWAR uses the flow regime map of Tandon for the determination of the actual flow regime and switches to flow regime dependent semi-empirical correlations for the calculation of the HTC (spray flow: Soliman, laminar annular flow: Nusselt, turbulent annular flow: Kosky and Staub, stratified flow: Rufer and Kezios, bubble, slug and plug flow: Breber - all models were described in detail in [9]).

Both improvements HOTKON and KONWAR use the same (modified Nusselt) model, for the calculation of the HTC. They differ in the choice of the sump coefficient. A review of sump coefficients is e.g. presented by Shah [10]. The author shows that the condensation rate decreases with increasing L/D ratio and upward inclination of the tube, in tubes with downward inclination the heat transfer coefficient increases.

The different geometry parameters and flow conditions in the HORUS and the NOKO tubes are considered by choosing different sump coefficients in HOTKON and KONWAR. In HORUS, the steam generator tube is arranged exactly horizontal: the L/D ratio is about 700 and condensate and steam are flowing first in co-current and after the filling of the outlet collector in counter current direction. In this second phase the thickness of the condensate film is maximum at the end of the tube. In NOKO, the tubes are arranged with an inclination of 1.6° in the upper and 3.2° in the lower leg and includes a 180° bend in the middle. The L/D ratio is about 250 and the condensate sump thickness increases along the tube length. Both, steam and condensate flow into the same direction.

Because the sump coefficient in HOTKON describes exactly the conditions inside the VVER steam generator tubes and was derived from experiments in original geometries and with typical initial and boundary conditions [8], this coefficient was taken over to KONWAR for this case, too. Therefore, the results of the post test calculations with ATHLET/HOTKON and ATHLET/KONWAR are expected to be very similar.

4. Post test calculations

Four HORUS tests (PCHS23, PCHS25, PCHS30, PCHS36) were selected by HTWS for post test calculation with ATHLET/KONWAR. The results of these calculations are compared to the experimental data and calculations with the original version of ATHLET, and ATHLET/HOTKON [6]. To avoid user-influence the same input decks were used for all calculations.

In the following, the results of the calculations of the test PCHS30 are presented and discussed in detail. The test run PCHS30 simulates the fourth phase of a small break loss of coolant accident with a cold leg loop seal, which is characterized by the following conditions:

- the water level in the reactor pressure vessel lies under the hot leg connection,
- at least one hot leg loop seal is cleared

and

- the heat removal out of the core is realized by steam condensation in one or more steam generators.

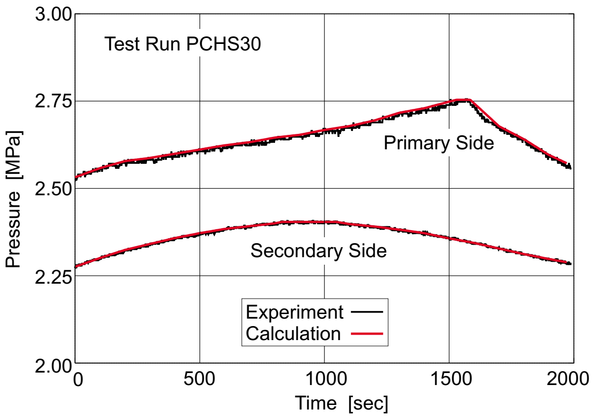

Fig. 3: Primary and secondary side pressure boundary condition

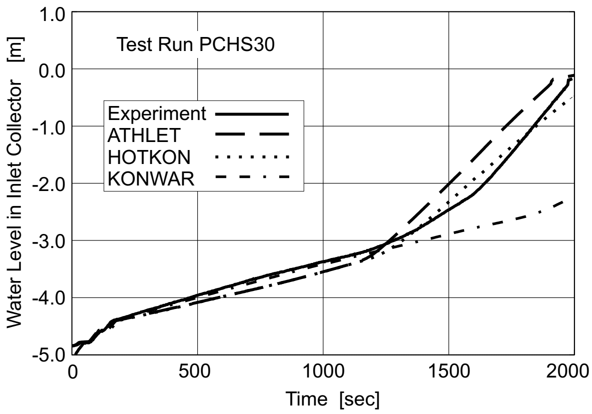

Fig. 4: Water level in the inlet collector

Therefore the experiment is performed with a closed throttle valve at the outlet collector (see fig. 1). The adjusting steam flow conditions are only caused by the condensation rate, which depends on the driving temperature differences between the primary and secondary side of the tube. The following initial conditions are adjusted: primary side pressure 2.53 MPa, primary side temperature 224.8 °C, secondary side pressure 2.28 MPa.

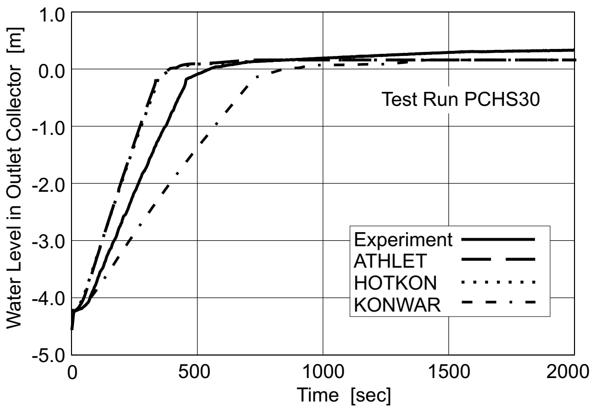

Fig. 5: Water level in the outlet collector.

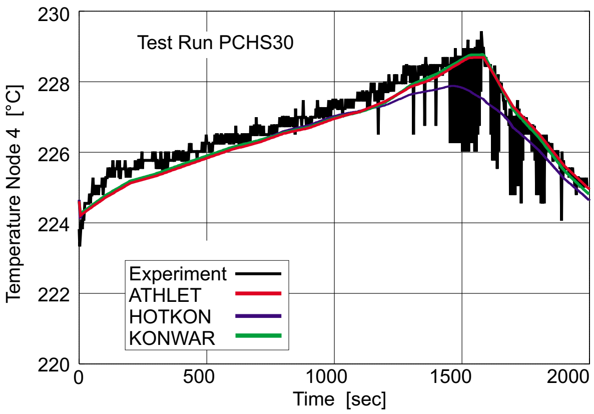

Fig. 6: Fluid temperature in node 4

The records of the primary and secondary side pressure are shown in fig. 3. The power in the reactor simulator is constant during the first 1590 seconds. Because the steam generation dominates over the condensation the pressure increases. After switching off the electrical heater the pressure decreases. For a better condensation model comparison it was decided to adjust the pressure boundary conditions via time dependent volumes.

Fig. 4 and 5 show the water levels inside the inlet and outlet collector. It can be seen that the calculations with the improved versions of the condensation model agree significantly better with the experimental data than the calculation with the original condensation model. The condensate flows forward and accumulates in the outlet collector in the first time period. After approx. 500 seconds the outlet collector is totally filled with water and the condensate collects in the tube. The tube is filled from the outlet to the inlet collector. The condensate reaches the inlet collector at 1300 seconds.

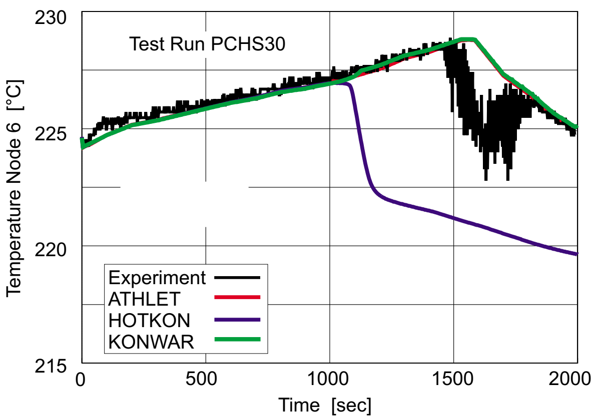

Fig. 7: Fluid temperature in node 6

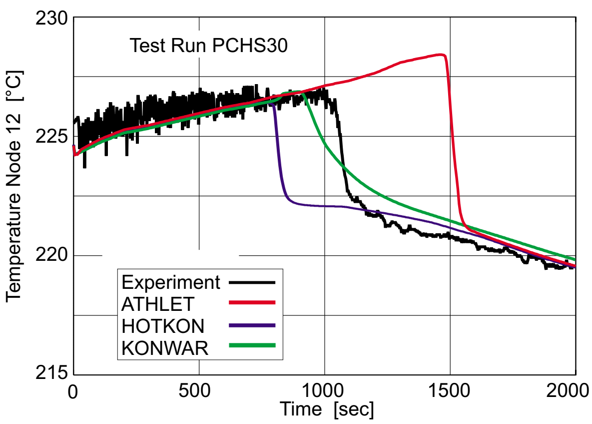

Fig. 8: Fluid temperature in node 12

This is indicated by a significant increase of the inlet collector water level. The slow increase of the water level in the inlet collector during the first 1300 seconds can be explained with the collection of condensate from the steam feed line, which connects the reactor simulator and the inlet collector. The water level of both collectors shows a better agreement with the experimental data than the calculation with the original ATHLET version, although the improved ATHLET versions overestimate the condensate accumulation in the outlet collector moderately.

Figure 6 - 9 show the fluid temperatures inside the HORUS tube. As discussed above, the tube is filled with condensate from the end to the outlet to the inlet collector. The HORUS tube is divided into 19 control volumes, each about 0.5 m long. At the beginning and the end two control volumes with half length are located. The indices of the control volumes increase from the inlet to the outlet collector. This nodalization is adapted to the arrangement of the thermocouples. At the beginning, the HORUS tube is totally filled with steam and the readings of the thermocouples show saturation temperature. After the nodes are filled with water, the temperatures decrease. The figures confirm, that both improved versions of ATHLET meet - with exception of node 6 - the time points, when a temperature decrease indicates the filling with condensate, better than the original version of ATHLET. It can be seen that the nodes with higher indices, that means the nodes at the end of the tube, are filled earlier. The comparison of the calculated data of the two improved versions of ATHLET show a slight overestimation of the condensate temperatures (reading of the thermocouples after temperature decrease). This is an effect of the modified Nusselt model. During stratified flow, film condensation takes place in the upper part of the tube, while in the sump the condensate flows along the bottom. The water in the sump is slowly cooled down by convective heat transfer. The efficiency of the condensation heat transfer is much higher than the efficiency of the convection heat transfer. Therefore, this convective heat transfer is neglected in HOTKON and KONWAR.

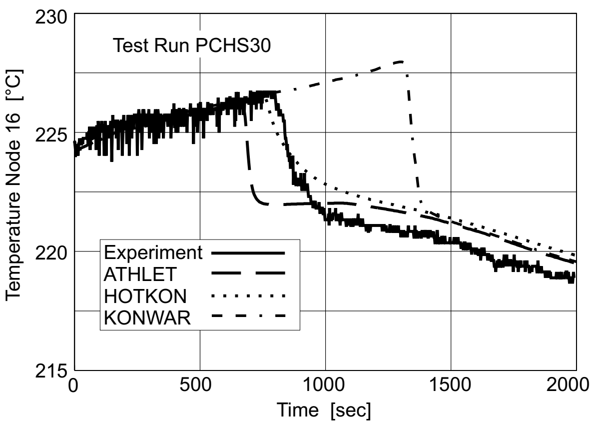

Fig. 9: Fluid temperature in node 16

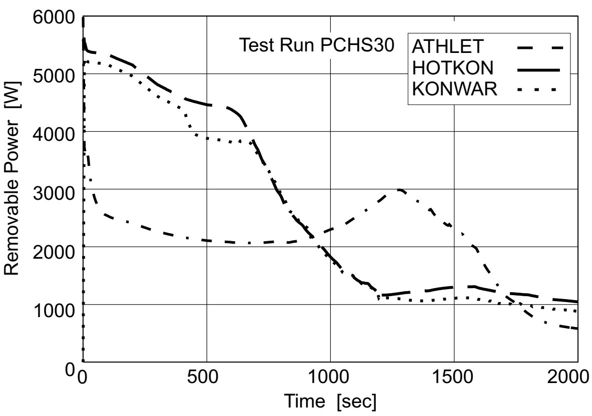

Fig. 10: Removable Power

At last in fig. 10 the resulting calculated removable power of the condenser tube is compared. As expected the calculations with the improved condensation models agree very well and are almost two times higher than the calculation with the original condensation model. Therefore both collectors are filled earlier. After filling of the HORUS tube with condensate the tube surface is covered with water and the removable power of the tube decreases strongly.

5. Conclusion and outlook

Two different approaches for modeling the condensation in horizontal tubes - HOTKON by University for Applied Sciences Zittau (HTWS) and KONWAR by Forschungszentrum Jülich (FZJ) - have been implemented into the 1D-thermohydraulic code ATHLET. These models were originally developed for post test calculations of the HORUS and NOKO experiments, which differ extremely concerning the operation conditions. The aim of the performed investigation was to broaden the scope of the condensation model improvement KONWAR and to check the applicability to post test calculations of HORUS experiments. Therefore, four HORUS experiments were calculated with ATHLET/KONWAR, and the results were compared with the experiments and the calculations with the original version of ATHLET and ATHLET/HOTKON, respectively. To avoid a user-influence exactly the same input decks were used for all calculations.

The post test calculations of the selected HORUS experiments show that the calculations with the improved condensation models are capable of performing proper calculations. The results of the calculations with the improved condensation models are very similar. During these experiments stratified flow occurs inside the tubes and both condensation model improvements use the same (modified Nusselt) model for the determination of the HTC in this flow regime. This model takes into account the decrease of the heat transfer surface, due to the collection of condensate in the tube sump. The HTC calculated by the Nusselt model has to be multiplied with an empirical sump coefficient. The value of this coefficient depends on several geometric values (inclination of the tube, length/diameter ratio) and flow conditions (co- or counter-cur-rent flow of steam and condensate). Therefore, it has to be fitted to the concrete application. A further generalization, that means a model without any empirical coefficients which allows calculations of arbitrary geometrical configuration, requires a mechanistic model for the modeling of the sump influence. That’s why new and well equipped condensation experiments with high time and spatial resolution measurements of local parameters are needed.

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