Simulation of AP1000’s Passive Containment Cooling with the German Containment Code System COCOSYS

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ABSTRACT

In this paper the applicability of the German containment code system COCOSYS to the simulation of AP1000’s passive containment cooling is presented. For this purpose calculation results of an adopted nodalisation from Westinghouse’s WGOITHIC code and a nodalisation featuring a plume modelling are validated against experimental data of the Large Scale Test facility. This facility is used to experimentally investigate AP1000’s passive containment cooling system. The gained experience helps to perform conservative and best estimate calculations of AP1000’s containment response during a large break LOCA. Results of the validation show reproducibility of WGOITHIC results with COCOSYS and good agreement of the plume nodalisation with the experimental values. The LOCA peak pressure of AP1000 containment conservatively calculated by COCOSYS only differs about 0.1-0.2 bar from codes like MELCOR and WGOITHIC. A best estimate calculation considering plumes above the compartments of the steam generators results in a peak pressure 0.8 bar lower than the WGOITHIC calculation. The performed validation shows the applicability of COCOSYS’ present heat transfer models to a new application field like the passive containment cooling. In consequence COCOSYS is able to deliver reasonable results for both conservative and best estimate AP1000 PCS calculations.

1 INTRODUCTION

Many future nuclear reactor designs will include passive containment cooling systems (PCS) thus representing an evolutionary step in reactor safety technology. Such passive systems are proposed for next-generation Light Water Reactors (LWR) both for the primary circuit and the containment. The passive function of these systems relies on natural driving forces, such as gravity and natural circulation [1] Consequently, a passively cooled containment by means of an evaporating liquid film combined with a natural circulation of air through the annulus between containment and reactor building is proposed for the AP1000 design by Westinghouse Electric Company. In case of a loss of coolant accident (LOCA) the PCS limits the containment pressure by cooling the containment steel shell and thus maintaining the inside condensation of steam. The principal power plant design of the AP1000 reactor and the function of the PCS are reported in [2]. A cut view of the containment is presented later in figure 5 along with a proposed nodalisation for a lumped parameter simulation.

Containment code systems have been developed to investigate the complex thermal-hydraulics and their propagation within a containment during accidents. Lumped parameter codes offer the possibility to gain calculation results of postulated accidents within a limited amount of time in the order of hours along with reasonable consistency. The goal of
consistent results of calculations is accomplished by the validation of the codes against experimental studies considering a variety of thermal-hydraulic phenomena. For the successful licensing and deployment of evolutionary reactor designs in Europe it is worthwhile to consider well known European codes for containment assessment. The German containment Code System COCOSYS has been developed and maintained by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) [3]. However, to cope with the technological evolution of future containment systems COCOSYS has to be validated and improved further by GRS and its partners. For this purpose especially our institute (LRST) works on the enhancement and validation of COCOSYS for the application to passive containment cooling.

COCOSYS includes different models for heat transfer phenomena like convection, condensation or radiation. The wall condensation model CDW simulates the condensation of steam on surfaces of structures. A possible re-evaporation of the condensate by surface reheating has been addressed in this same model. By using CDW for the simulation of the evaporating liquid film cooling on the outside of the containment shell a new field of application of COCOSYS is being investigated. In the Large Scale Test facility (LST) [4] Westinghouse has evaluated PCS behaviour and uses experimental data for the validation of their in-house version of the computer code GOTHIC. This version of GOTHIC (WGOTHIC) has been developed to simulate the film cooling and a short description of the code can be found in [5]. A first step to validate COCOSYS’ CDW model is to simulate the LST experiment and to compare the results to experimental values as well as WGOTHIC calculations.

WGOTHIC also has been used for peak pressure analysis [6] and at SANDIA Labs assessments of the AP1000 passively cooled containment have been done by using MELCOR [7]. Both investigations are based on conservative assumptions. As accident scenario for containment peak pressure analysis a double ended guillotine break of the cold leg (ø 56 cm) is considered. The input deck used in COCOSYS for this conservative simulation is based on input data for WGOTHIC (confidential information of Westinghouse). Corresponding calculation results are compared to the other codes to gain information about the reproducibility of the containment response. However, also a different nodalisation for simulating the AP1000 with COCOSYS has been built at LRST. To achieve more realistic results it does not take into account the conservative assumptions and integrates experience of modelling buoyant plumes above the steam generator compartments. Thus, flow patterns likely to occur during LOCA like entrainment and convection loops are supposed to be achieved. As result a lower peak pressure during a large break LOCA is expected.

2 THE WALL CONDENSATION MODEL CDW

Extensive information concerning the CDW model can be found in [8]. With the help of the wall condensation model CDW, COCOSYS calculates the condensation of steam as well as the evaporation of water films on surfaces of structures. A water film is supposed to form by steam condensation or water sources above the structure. An energy balance is calculated for the film on the surface of the considered structure taking into account in- and out-flowing water, condensation or evaporation on the film surface and heat transferred into the structure. The evaporation mass flow is based on Stephan’s law which is also valid for evaporation [9]:

\[ m_{evap} = A \cdot \beta \cdot \rho_{air,mix} \cdot \ln \frac{P_{tot} - P_{Sat}(T_{Film})}{P_{tot} - P_{Vapor}} \]  

(1)

The equation takes the mass transfer coefficient \( \beta \) into account which depends on a diffusion coefficient and the partial pressures of vapour and gases. Thus, it is obvious that this equation considers the evaporation as a boundary layer diffusion problem depending on the
amount of non-condensable gases near the film surface. By applying the equivalence of heat and mass transfer, $\beta$ is linked to heat transfer correlations.

The temperature difference between the wall and the film is given by equation 2 based on the assumption that the convective heat transfer is negligible compared to the heat conduction:

$$\varepsilon = T_{Wall} - T_{Film} = \frac{q_{Wall} \cdot \bar{\delta}_{Film}}{\bar{\lambda}_{Film}} = \frac{(q_{\text{evap}} + q_{in} - q_{out}) \cdot \bar{\delta}_{Film}}{\bar{\lambda}_{Film}}$$

The average film thickness $\bar{\delta}_{Film}$ is calculated with the help of Nusselt’s theory. It is depending on the incoming water flow and the condensation/evaporation rate. Both laminar and turbulent films are considered. Since the heat fluxes for evaporation ($q_{\text{evap}} = m_{\text{evap}} \cdot i_{\text{evap}}$) and the heat flux due to out-flowing water ($q_{out} = m_{out} \cdot i_F$) are both dependent on the temperature difference $\varepsilon$, an iteration of the film temperature is performed to satisfy the energy balance.

3 LARGE SCALE TEST FACILITY (LST) SIMULATION

Figure 1: Large-Scale Test Facility [4] and Nodalisation

The large scale test facility (LST) has been set up to investigate the main features of the PCS. It is a 1/8 scale model of the AP600 with a mounted fan on top to be able to artificially induce an air flow in the annulus. The gained results were affirmed to be valid as well for the up-scaled version AP1000. A scheme of the facility is presented in figure 1. Table 1 lists rough values of the LST geometry [4].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
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<td>vessel thickness</td>
<td>22 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.6 m</td>
<td>Short term heat sink surface above deck</td>
<td>22 m²</td>
</tr>
<tr>
<td>Volume</td>
<td>83 m³</td>
<td>Short term heat sink surface below deck</td>
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<tr>
<td>Cooled vessel surface</td>
<td>70 m²</td>
<td>Other internal structure surfaces</td>
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</tr>
</tbody>
</table>

Table 1: LST geometry data

For validating the CDW model of COCOSYS the experiment LST 212.1 A to C has been chosen. The experiment was divided into three phases with different steam injections each, i.e. 0.11 kg/s, 0.227 kg/s and 0.34 kg/s). The fan was operated at 530 RPM. The cooling
water mass flow was applied in a way that 100 % water coverage of the containment was likely to be achieved. However, water coverage reduced to 95.3 % during the last phase.

The steam injection was increased after a steady state had been reached resulting in a higher pressure level. A steady state had been reached when the heat removal by condensation/evaporation on the steel shell matched the inserted heat flow into LST in form of steam. The pressure rise during the experiment is presented in figure 2 along with the results of WGOOTHIC and COCOSYS calculations discussed hereafter.

![Figure 2: Vessel pressure response of LST 212.1](image)

Two different nodalisations have been set up. The first is the direct translation of the lumped parameter input deck used for calculations with WGOOTHIC which is proprietary of Westinghouse. The second maintains the total amount of volume and surfaces but allows for buoyant plumes to be formed above the steam injection zone. This nodalisation is shown in figure 1. In this input deck the number of control volumes has been reduced. The data has been normalized to respect its proprietary nature.

The results of the COCOSYS calculation show that the WGOOTHIC results can be reproduced using the same nodalisation. The nodalisation with the plume modelling (COCOSYS_plume) yields better results concerning the pressure rise and matches the experiment as well as the investigated convection flows which are indicated in the nodalisation scheme in figure 1.

![Figure 3: Condensation and evaporation rates of LST 212.1](image)

The condensation and evaporation rate are compared in figure 3 to the experimental data. The results show that both evaporation and condensation rates are in good agreement to the experimental values, although for the second and third phase a tendency to under estimate
the condensation is visible. The results for the evaporation rate differ about 15% during phase B. For the condensation rate during Phase C a difference of about 10% is achieved.

4 AP1000 LOCA SCENARIO DESCRIPTION

The mass and energy release tables for the considered double ended guillotine break of the cold-leg (ø 56 cm) can be found in the design certification document [4] for AP1000 and are plotted in figure 4. These values are input for all the reactor simulations presented hereafter.

During the first phase of blowdown, a two-phase flow of water and steam is released into the containment via the break below deck at the bottom of one of the steam generator compartments. After the blowdown phase (about 30 seconds after break) the re-flooding of the reactor circuit begins. Also the passive containment cooling system is actuated at that point. The injection of water into the reactor circuit, from the in-containment refuelling water storage tank (IRWST), starts at about 1000 seconds and the IRWST water level decreases. After about 1500 seconds the automatic depressurisation system (ADS) valves of the steam generators are opened and steam is released equally into both upper SG compartment. During the accident the water levels in the compartments below the operating deck rise until they equilibrate with the IRWST level after about 2.5 hr.

5 COMPARISON OF WGOOTHIC, MELCOR AND COCOSYS NODALISATIONS AND RESULTS

The investigated nodalisations for WGOOTHIC, MELCOR and COCOSYS are each nodalisations with multiple control volumes to better address containment atmosphere mixing. The input data includes suitable assumptions to obtain a conservative calculation. This includes the break flow mass and energy releases, the PCS water flow injection and the containment modelling. The PCS water flow applied is the estimated amount of water to be evaporated which is even less than the minimum design flow which is reported in [5]. The calculation of film cooling is started at the estimated steady state coverage of the whole containment after 337 seconds. The conservative assumptions regarding the containment modelling are as follows [7]:

- Heat transfer (HT) to floor surfaces is neglected
- Modelling of air gap (0.54 mm) between all steel-lined concrete structures
- No Heat transfer to selected structures in dead-ended compartments after blowdown
• Heat transfer coefficients on the inside of the containment shell are multiplied by 0.73
• Heat transfer coefficients on the inside of the containment shell are multiplied by 0.84
• Annulus friction loss is increased by 30% above the experimental determined friction

In addition to this, several short term heat sinks, like platforms or components have been conservatively neglected. Data concerning the WGOITHIC nodalisation is proprietary of Westinghouse Electric Company and cannot be presented here, however some information about the application of WGOITHIC to AP1000 simulation can be found in [5]. The MELCOR input and further discussion of calculation results which have been performed by SANDIA Labs are reported in [7].

For COCOSYS different nodalisations have been set up. The first is a translation of the WGOITHIC input attempting to consider the same conservatism, from now on referred to as COCOSYS_Cons. However, a major difference is inevitable. The heat transfer coefficients in COCOSYS cannot be altered by user-defined multipliers. The only way to consider reduction of the heat transfer is to reduce the heat transfer area of the containment shell by the most conservative factor of 0.73.

![Figure 5: AP1000 cut view [2] and nodalisation for COCOSYS](image)

Additionally, a different nodalisation for COCOSYS which takes the formation of buoyant plumes above the steam generator compartments into account has been developed, referred to as COCOSYS_Plume. In this input deck the number of control volumes has been significantly reduced. The free volume is about 58330 m$^3$ and maximum cooled containment shell surface is 5945 m$^2$ based on [4] and [6]. The input deck does not consider conservative assumptions for the containment modelling. Formerly neglected short term heat sinks are inserted and the PCS flow is set to its minimum design flow. The plume nodalisation reflects the very good experience that has been made by simulating the LST facility in the same way. The arrangement of the control volumes is symmetrical as can be seen in figure 5. Setting up two different input decks for COCOSYS in such a way as described above results in a higher and a lower boundary for the calculated peak pressure during DECL break.

The containment pressure response is plotted in figure 6 with a logarithmic time scale to better investigate the short-term pressure rise during the blowdown phase until the containment peak pressure. The results for the blow-down peak pressure in the conservative calculations of the codes at about 20 seconds spread from 3.85 to 3.95 bar and are therefore in good agreement. Greater differences occur at the start of PCS calculation. The WGOITHIC results lie between by COCOSYS_Cons and the MELCOR results. COCOSYS_Cons differs
slightly more and is the upper boundary. The peak pressure is reached at about 1500 seconds and ranges from 4.9 to 5.15 bar. It has to be pointed out that the COCOSYS result lies slightly beyond the design pressure of 5.1 bar. After that time, more energy is removed by the PCS than is released into the containment and thus the containment pressure decreases. In the long-term phase of the accident COCOSYS_Cons results lie slightly over WGOTHIC results as well. Both higher peak pressure and long-term pressure level seem to be due to the reduction of heat transfer surface instead of considering two different heat transfer multipliers.

Figure 6 also presents the results of COCOSYS_Plume. It is known that in the first phase of a LOCA short term heat sinks, like steel surfaces of components, have significant impact on the condensation. This can be observed here, resulting in a lower pressure peak at the end of the blowdown which is about 0.3 bar lower compared to the WGOTHIC results. The pressure is decreasing after the blowdown significantly due to further condensation. Also, the peak pressure is much lower and about 0.8 bar below the WGOTHIC peak pressure. The pressure difference between blowdown peak pressure and containment peak pressure is 0.6 bar and thus less than for COCOSYS_Cons which shows a difference of about 1.25 bar. These observations can be explained by the massively enhanced heat removal of the cooled steel shell with the original surface area and the PCS water flow increased to the minimum design flow. In the long-term phase of the accident the pressure in the containment is about 0.7 bar lower compared to the WGOTHIC and COCOSYS_Cons results and falls below 2 bars at the end of the accident sequence. The containment convection flows that occur during the long-term phase are presented within the nodalisation scheme in figure 5. It can be observed that the main flow path is upwards through the plume zones because of the injection of hot steam. Surrounding atmosphere is being dragged into the plume zones. After being redirected in the dome the convection flow leads downwards along the control volumes adjacent to the steel shell due to cooling of the gas. This flow pattern supposed to develop has been investigated in the LST facility already, and has been reproduced in the simulation.

6 CONCLUSION

It has been shown that only by translating a WGOTHIC input to COCOSYS, the WGOTHIC results of the LST facility and AP1000 can be reproduced. The results of a further developed input deck for LST considering the formation of a plume above the steam injection point are in good agreement with experimental results of pressure rise, condensation and
evaporation rates. In consequence, COCOSYS can be considered suitable with its present heat transfer models to simulate a PCS as proposed for AP1000. The reactor simulation of a large break LOCA and comparison to WGOTHIC and MELCOR calculations show that COCOSYS results are most comparable. However, COCOSYS_Cons represents the upper boundary of the calculations because the containment surface has been reduced to consider conservative heat transfer. In contrast, COCOSYS_Plume represents the lower boundary with a maximum peak pressure difference to WGOTHIC of 0.8 bar. The great influence of short term heat sinks has been proven because a lower blowdown peak has been observed as well. The increased heat removal through the containment shell results in a lower long-term pressure peak. The simulation of plumes above the steam generators in the AP1000 simulation is reasonable as has been shown by calculating LST facility with a plume. The expected flow pattern has thus been reproduced. In conclusion, it has to be stated that COCOSYS has the ability to simulate a PCS based on an evaporating water film on the outside of a containment just with the presently featured heat transfer models. COCOSYS thus can deliver valuable results considering different accident scenarios in AP1000 mitigated with the PCS and thus being a basis for general safety studies or licensing issues.

With the present input decks for both LST and AP1000 further investigation of containment phenomena can be conducted. In the next steps experiments in LST with the injection of helium and passively induced air flow in the annulus will be calculated. Thus, the influence of non-condensable gases on the PCS is investigated. The same kind of nodalisation with plumes will be used for AP1000 investigations concerning accidents with release of hydrogen. Furthermore, an extensive evaluation of the influence of the PCS performance on containment pressure during accidents will be studied.

REFERENCES


