Studies on steam condensation with non-condensable gases in a horizontal condenser tube for advanced nuclear reactors using RELAP5

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Abstract: Horizontal heat exchangers are used in advanced light water nuclear reactors in their passive cooling systems, such as Residual Heat Removal System (RHRS) and Passive Containment Cooling System (PCCS). Horizontal condensation studies of steam with non-condensable gases mixtures in these heat exchangers are very important. This work presents a comparison between simulation results and experimental data in steady state conditions for some inlet pressure, steam and non-condensable gases (air) inlet mass fractions. The test section was modelled and the simulations were performed with the RELAP5 code. Experimental tests were carried out for 200–400 kPa inlet pressure and 5%, 10%, 15% and 20% of inlet air mass fractions. Comparisons between experimental data and simulation results are presented for 200 kPa and 400 kPa pressure conditions and showed good agreement. New correlations for heat transfer coefficients in these steam-air conditions must be theoretically and experimentally studied and implemented in the RELAP5 code.

Keywords: steam condensation; non-condensable gases; RHRS; residual heat removal systems; PCCS; passive containment cooling systems; horizontal condenser tube; heat exchangers; advanced reactors; ESBWR; RELAP5; nuclear reactors; nuclear power; nuclear energy; simulations.


Biographical notes: L.A. Macedo is a Researcher of the Nuclear Engineering Center at the Nuclear and Energy Research Institute (IPEN/CNEN – SP). He is a Mechanical Engineer from the Engineering School of the Mackenzie University (1984), MSc and PhD from the São Paulo University in 2001 and 2008. He has been working in the experimental area with two-phase flow in the presence of the non-condensable gases.
1 Introduction

Horizontal heat exchangers have many industrial applications such as air conditioning, refrigeration machines and steam condensation for hydrocarbons distillation (Kakac and Liu, 1998).

These horizontal heat exchangers are widely used in advanced nuclear reactors systems and have been proposed for passive cooling systems, such as Residual Heat Removal System (RHRS) and Passive Containment Cooling System (PCCS). The latter is one of the engineered safety systems in the Economic Simplified Boiling Water Reactor (ESBWR). It is designed to self-activate following a Loss of Coolant Accident (LOCA) to condense steam released to the containment. In this way, the PCCS maintains the containment pressure below the design limit to preserve the integrity of the containment building, which is the final barrier to keep the radioactive materials from being released into the environment (Wu, 2005).

Extensive past experience has shown that horizontal heat exchangers offer several advantages over vertical ones such as higher heat transfer rates, less tube fouling and higher structural earthquake resistance. Consequently, there is a reduction in the containment building height and volume allowing a reduction in the costs and the increase of the plant safety.

Non-condensable gases on steam condensation cause heat transfer rates to decrease and are one of the major safety-related issues. Air and hydrogen represent the main non-condensable gases in nuclear power plants. While air exists naturally in the containment building, hydrogen can be formed in the case of a LOCA or a steam line break accident. The main hydrogen sources are the exothermic fuel cladding chemical reaction with steam, the radiolytic decomposition of water and the corrosion of certain metallic species present in the containment (Muñoz Cobo et al., 1996). Studies on steam condensation with non-condensable gases mixtures in horizontal heat exchangers for PCCS design are very important due to the multidimensional nature of the phenomena, and the condensate stratification effects. Figure 1 represents the PCCS layout for an advanced nuclear reactor.

This paper presents the comparison between experimental data from steam condensation tests with non-condensable gas (air), in steady state, with numerical simulations performed with a model developed with the thermal-hydraulic code RELAP5, the most detailed code developed to perform accident analyses in nuclear industry. Experimental data were obtained in a test section designed to measure local heat transfer coefficients of steam-air mixtures in horizontal condenser tubes (Wu and Vierow, 2006).
The work also presents a bibliographical review on horizontal condensation with non-condensable gases, a description of the experimental facility and test section, the horizontal condenser tube model developed with RELAP5 in steady state, a comparison between experimental data and simulation results and, finally, conclusions.

2 Bibliographical review

Many research groups have been investigating in-tube condensation for horizontal heat exchangers. Huhtiniemi and Corradini (1993) performed experiments on steam-air condensation on inclined surfaces. The test section was developed with a mechanism to allow condensation surface inclination (0–90°). The tests were performed for 0–87% inlet air mass fractions and for 1–3 m/sec of steam-air mixture velocities. In vertical position (90°), there was a decrease of 15–25% in the condensation heat transfer coefficients, depending on the inlet air mass fractions. Experimental data were compared with some previously published results and showed good agreement.

Herranz et al. (2000) described an analytical model called HTCFIN based on conservation and mass diffusion equations. This one-dimensional model was developed for studies on steam-air mixtures horizontal condensation. The calculated results were compared with experimental data showing acceptable agreement. HTCFIN model has become a powerful tool to estimate steam-air mixtures condensation heat transfer rates in advanced reactors containments.

Studies on steam-air mixtures horizontal condensation represent one of the most important factors in VVER nuclear reactors (steam generators) and for advanced nuclear reactors (PCCS and RHRS). In order to simulate this process, two different routines were developed (HOTKON and KONWAR) and performed on the ATHLET code, which is also widely used for accident analyses in nuclear power plants. The comparison between experimental data and calculated results using these new routines presented better agreement (Schaffrath et al., 2001).
3 Experimental facility and test section

Figure 2 shows the experimental facility and test section which were designed to simulate a horizontal condenser tube (single heat exchanger) of an ESBWR (Wu, 2005). The experimental facility was developed for studies on local heat transfer coefficients in the steam-air mixture condensation at the horizontal condenser tube (Wu and Vierow, 2005). It is assembled in the School of Nuclear Engineering at the Purdue University (Thermal Hydraulics and Reactor Safety Laboratory, TRSL, 2009).

The main components of the experimental facility are steam generator, test section, pumps, air compressor, instrumentation and data acquisition system. There are also air and water feed lines which are interconnected with storage tank systems. All heated components are thermally insulated with fibreglass insulation, except the cooling side of the test section (secondary). The test section consists of two horizontal concentric tubes containing pressure, temperature and flow rate sensors. The internal tube, called condenser, is where steam-air mixture flows and the external tube is a counter-current cooler with water flowing at low temperature.

The condenser tube is a 4.5 m long SS304 tube of 31.7 mm OD and 2.1 mm wall thickness with a heat transfer length of 3.0 m. The external tube is made of a square polycarbonate block with 63.5 mm internal diameter. Figure 3 shows a part of the test section near the steam-air mixture inlet. The tests were carried out for 200–400 kPa inlet pressure and for 5%, 10%, 15% and 20% of inlet air mass fractions.
The steam is produced in the steam generator and the steam flow rate is measured with a vortex flow meter. The air compressor provides the air flow rate that is measured by two flow meters calibrated for different ranges. The air inlet temperature is controlled by an air pre-heater at the air feed line. The air mass, steam and coolant flow rates and inlet pressure and coolant inlet temperature were kept constant during each test. The coolant flow rate is measured by a magnetic flow meter (Vierow et al., 2005).

Owing to the multidimensional nature of the horizontal steam condensation phenomena, a total of 98 thermocouples were used in the condenser tube and in the external tube for temperatures measurement. The thermocouples are 1.0 mm T type (copper – constantan) sheathed and are located at 14 axial positions ($z$) along of the test section. Table 1 presents the uncertainties of the instrumentation (Wu, 2005).

Figure 4 shows thermocouples radial positions in the test section (condenser tube and external tube). Table 2 presents some of thermocouples axial positions ($z$) along the test section.

### Table 1: Uncertainties of the instrumentation

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Parameters</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouples</td>
<td>Temperatures</td>
<td>±0.5°C</td>
</tr>
<tr>
<td>Flow meter</td>
<td>Steam flow rate</td>
<td>±1%</td>
</tr>
<tr>
<td></td>
<td>Air flow rate</td>
<td>±1.5%</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>Coolant flow rate</td>
<td>±0.25%</td>
</tr>
<tr>
<td></td>
<td>Inlet steam pressure</td>
<td>±0.2%</td>
</tr>
<tr>
<td></td>
<td>Air line pressure</td>
<td>±0.25%</td>
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</table>

### Table 2: Thermocouples axial positions ($z$) along of the test section

<table>
<thead>
<tr>
<th>$Z$</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
<th>$Z_3$</th>
<th>$Z_4$</th>
<th>$Z_5$</th>
<th>$Z_6$</th>
<th>$Z_7$</th>
<th>$Z_8$</th>
<th>$Z_9$</th>
<th>$Z_{10}$</th>
<th>$Z_{11}$</th>
<th>$Z_{12}$</th>
<th>$Z_{13}$</th>
<th>$Z_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section inlet (m)</td>
<td>0.013</td>
<td>0.114</td>
<td>0.318</td>
<td>0.521</td>
<td>0.724</td>
<td>1.029</td>
<td>1.334</td>
<td>1.689</td>
<td>2.07</td>
<td>2.451</td>
<td>2.934</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4 Simulations with RELAP5

The RELAP5 code version MOD3.2.2gama was adopted for the experimental data simulations (NUREG/CR-5535, 1995). This code is based on a non-homogeneous and non-equilibrium two-phase system model that is solved by a fast, partially implicit numerical scheme which allows an economical calculation of system transients. RELAP5 uses a seven conservation equations model, where there are three equations for each phase (liquid and steam) and an additional one for non-condensable gases. There is also an additional equation for dissolvable boron treatment.

The developed model in steady state represents the test section original geometry in detail. Table 3 presents the relation between code components and hydraulic regions. Test section nodalisation is presented in Figure 5.

<table>
<thead>
<tr>
<th>Test section region</th>
<th>Component number</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-steam mixture</td>
<td>100</td>
<td>TMDPVOL</td>
</tr>
<tr>
<td>Air-steam mixture inlet</td>
<td>150</td>
<td>TMDPJUN</td>
</tr>
<tr>
<td>Condenser tube</td>
<td>200</td>
<td>PIPE</td>
</tr>
<tr>
<td>Condensate outlet</td>
<td>250</td>
<td>SNGLJUN</td>
</tr>
<tr>
<td>Condensate tank</td>
<td>300</td>
<td>TMDPVOL</td>
</tr>
<tr>
<td>Coolant</td>
<td>400</td>
<td>TMDPVOL</td>
</tr>
<tr>
<td>Coolant inlet</td>
<td>450</td>
<td>TMDPJUN</td>
</tr>
<tr>
<td>External tube</td>
<td>500</td>
<td>ANNULUS</td>
</tr>
<tr>
<td>Coolant outlet</td>
<td>550</td>
<td>SNGLJUN</td>
</tr>
<tr>
<td>Coolant tank</td>
<td>600</td>
<td>TMDPVOL</td>
</tr>
</tbody>
</table>
The boundary conditions in the simulations were 45°C of constant inlet coolant temperature, $1.48 \times 10^{-3}$ kg/sec of coolant flow rate, inlet effects were considered at the first 0.3 m of the condenser tube and external tube was considered to be adiabatic.

5 Comparison between simulations and experimental data

Experimental tests were performed for 200–400 kPa inlet pressure and for 5%, 10%, 15% and 20% of inlet air mass fractions. Figure 6 represents the comparison between experimental and calculated temperatures for the 5% and 20% inlet air mass fractions and 200 kPa inlet pressure tests. The experimental temperatures were measured in the condenser tube centre line ($T_{Cl}$) and in the axial positions ($z$), presented in Table 1. The calculated temperatures are related with the following axial positions along the test section: 0.05, 0.45, 0.95, 1.45, 1.95, 2.45 and 2.95 m.

Figure 6  Temperatures ($T_{Cl}$): 5% and 20% air mass fractions – 200 kPa
The calculated and experimental temperatures showed good agreement for the 200 kPa pressure and for the 5% and 20% inlet air mass fractions. Global effects of the non-condensable gases in the heat transfer rates were not significant for smaller air mass fractions. Temperatures decrease by 5°C for 20% of inlet air mass fraction at the inlet of the test section (±1.0 m). These temperatures represent the steam partial pressures of the mixture. The steam partial pressures for higher inlet air mass fractions are smaller and, consequently, smaller temperatures were observed.

Comparison between experimental and calculated temperatures for the tests with 5% and 20% of inlet air mass fractions and 400 kPa inlet pressure is shown in Figure 7. The calculated and experimental temperatures presented good agreement and showed the same behaviour. Higher temperatures are observed (≈140°C) for 400 kPa when compared with the temperatures (115–120°C) obtained for 200 kPa inlet pressure at the test section inlet (see Figure 6).

The simulation for higher inlet air mass fraction (20%) showed that the calculated temperatures are smaller than the experimental at the final third of the inlet condenser tube, indicating an overestimation of heat transfer coefficients in this region by RELAP5.
For experimental conditions with higher inlet pressure (400 kPa) and smaller inlet air mass fraction (5%) higher temperature differences were obtained between the test section inlet and outlet ($\Delta T \approx 70^\circ C$) when compared with experimental conditions of 20% inlet air mass fraction ($\Delta T \approx 40^\circ C$) for the same inlet pressure. The heat transfer coefficient is degraded by the higher presence of the air along tube condenser for 20% inlet air mass fraction. Hence, the experimental temperatures are lower at the outlet of the tube condenser.

6 Conclusions

The simulations of steam condensation in a horizontal condenser tube with non-condensable gases (air) were performed with the RELAP5 code. These simulations were carried out for 200 kPa and 400 kPa inlet pressure and for 5% and 20% of inlet air mass fractions. Experimental data were obtained in a test section designed to measure condensation heat transfer coefficients for steam-air mixtures.

The developed model with RELAP5 is able to simulate the steam-air mixture condensation phenomena in a horizontal condenser tube. Global effects of the non-condensable gases in the heat transfer rates were not significant for smaller air mass fractions (5%).

The simulations showed a temperature decrease of $5^\circ C$ caused by the inlet air mass fraction increase at the first meter of the test section. The temperatures represent the steam partial pressures. The steam partial pressures are smaller for higher inlet air mass fractions and, consequently, smaller temperatures were observed.

The comparison between calculated results and experimental data showed good agreement for 200 kPa inlet pressure, independently of the inlet air mass fraction. The calculated results and experimental data showed reasonable agreement for 400 kPa inlet pressure, keeping the same behaviour. For the higher inlet air mass fraction simulation, the calculated temperatures were smaller than the experimental temperatures at the final third of the inlet condenser tube, indicating a RELAP5 overestimation of heat transfer coefficients. The heat transfer coefficient is degraded by the higher presence of the air along tube condenser for 20% inlet air mass fraction. Hence, the experimental temperatures are lower at the outlet of the tube condenser.

As future work, an experimental facility will be developed to study the steam-air mixture condensation in a horizontal tube (single heat exchanger) in the Nuclear Engineering Center (CEN) at IPEN (CNEN/SP) with financial support of the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) by the Instituto Nacional de Ciência e Tecnologia de Reatores Nucleares Inovadores (INCT). This research project will allow the studies of new correlations for steam-air condensation heat transfer coefficients for the RELAP5 code. Simulations will also be performed with the CFD (Computational Fluid Dynamics) software.

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References


Thermal Hydraulics and Reactor Safety Laboratory (TRSL) (2009) School of nuclear engineering, Purdue University, USA. Available online at: http://cobweb.ecn.purdue.edu/~trsl


