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SIMULATION OF STEAM CONDENSATION IN THE PRESENCE OF NONCONDENSABLE GASES IN HORIZONTAL CONDENSER TUBES USING RELAP5 FOR ADVANCED NUCLEAR REACTORS

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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 (RHRS) and passive containment cooling system (PCCS). Condensation studies of steam and noncondensable gases mixtures in these heat exchangers are very important due to the phenomena multidimensional nature and the condensate stratification effects. This work presents a comparison between simulation results and experimental data in steady state conditions for some inlet pressure, steam and noncondensable gases (air) inlet mass fractions. The test section is three meters long and consists of two concentric tubes containing pressure, temperature and flow rate sensors. The internal tube, called condenser, contains steam-air mixture flow and external tube is a counter current cooler with water flow rate at low temperature. This test section was modeled and simulations were performed with RELAP5 code. Experimental tests were carried out for 200 to 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 and 400 kPa pressure conditions and showed good agreement. However, for 400 kPa inlet steam pressure and inlet air mass fractions above 5%, the simulated temperatures are lower than the experimental data at the final third from the inlet condenser tube, indicating a code overestimation of heat transfer coefficient. New correlations for heat transfer coefficient in these steam-air conditions must be theoretical and experimentally studied and implemented in RELAP5 code for better representing the condensation phenomena.

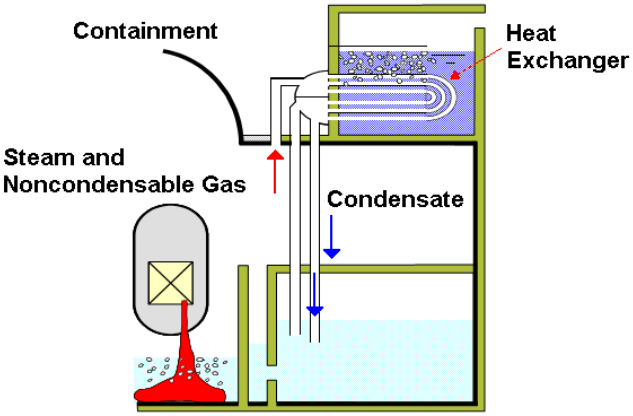
1. INTRODUCTION

Horizontal heat exchangers have many industrial applications such as air conditioning, refrigeration machines and steam condensation for hydrocarbons distillation [7].

In the nuclear industry, horizontal heat exchangers are widely used in advanced nuclear reactors and have been proposed for passive cooling systems, such as residual heat removal (RHRS) and passive containment cooling system (PCCS). This last is one of the engineered safety systems in the ESBWR. It was designed to self-activate following a Loss of Coolant Accident (LOCA) to condensate steam released to the containment and return the condensate to the reactor pressure vessel. 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 [8].

Extensive past experience has shown that horizontal heat exchangers offer several advantages over vertical heat ones. Some advantages are higher heat transfer rates, less tube fouling and higher structural earthquake resistance. There is a reduction in the containment building height and volume allowing an economic benefit and the increase of the plant safety.

The effect of noncondensable gases on steam condensation is one of the major safety-related issues, causing heat transfer rates decrease. Air and accidental presence of hydrogen represent the main noncondensable gases in nuclear power plants. While air exists naturally in the containment building, hydrogen can be formed in the case of a loss of coolant accident (LOCA) or 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 [3]. Studies on steam condensation with noncondensable gases mixtures in horizontal heat exchangers design for PCCS are very important due to the multidimensional nature of the phenomena and of the condensate stratification effects. Figure 1 presents the PCCS layout for an advanced nuclear reactor.



source: T. Yonomoto [11]

Figure 1. Passive containment cooling system (PCCS)

This paper presents the comparison of steam condensation experiments in the presence of noncondensable 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 the developed test section to measure local heat transfer coefficients of steam-air mixtures in horizontal condenser tubes [10].

The work also presents a short bibliographical review on horizontal condensation in the presence of noncondensable gases, a description of the used test section, the horizontal condenser tube model developed with RELAP5 in steady state, a comparison between experimental data and simulation results and, finally, a brief of the conclusions summary.

2. BIBLIOGRAPHICAL REVIEW

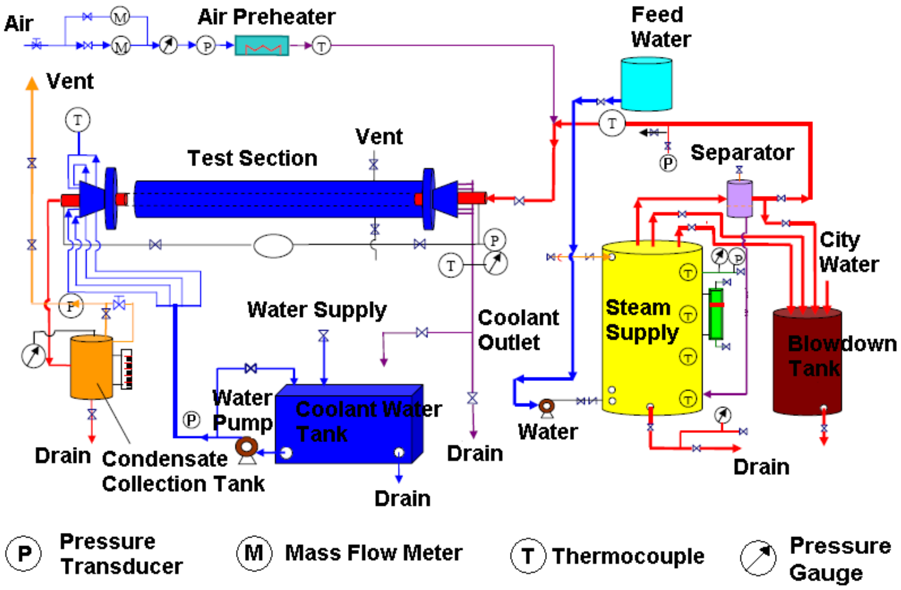
Many research groups have been investigating in-tube condensation for horizontal heat exchangers. Huhtiniemi and Corradini [2] performed experiments on steam-air condensation on inclined surfaces. The test section was developed with a mechanism to allow condensation surface inclination (0° to 90°). Tests were performed for 0 to 87 % inlet air mass fractions and for 1 to 3 m/s of steam-air mixture velocities. In vertical position (90°), there was a decrease of 15 to 25 % in 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 [5] 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. 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 steam generators design for VVER nuclear reactors, PCCS and RHRS for advanced nuclear reactors. 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 new routines improved the comparison accuracy between experimental data and calculated results [1].

3. EXPERIMENTAL FACILITY

Figure 2 shows the experimental facility (layout) that was designed to simulate a horizontal condenser tube (single heat exchanger) of an advanced nuclear reactor (ESBWR – Economic Simplified Boiling Water Reactor) [8]. The experimental facility was developed for determinating local heat transfer coefficients in the steam-air mixture condensation at the horizontal condenser tube [9]. It is assembled in the Thermal Hydraulics and Reactor Safety Laboratory (TRSL) in the School of Nuclear Engineering at the Purdue University [12].



source: K. Vierow [4]

Figure 2. Experimental facility layout

The main experimental facility components are: steam generator, test section, pumps, air compressor, instrumentation and data acquisition system. There also are air and water feed lines which are interconnected with storage tank systems. All heated components are thermally insulated with fiberglass insulation, except the cooling (secondary) test section. It consists of two horizontal concentric tubes containing pressure, temperature and flow rate sensors. Internal tube, called condenser, is where steam-air mixture flows and external tube is a countercurrent cooler with water flow rate 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 outer diameter is 63.5 mm. Figure 3 shows a part of the test section near the steam-air mixture inlet. Tests were carried out for 200 to 400 kPa inlet pressure and for 5, 10, 15 and 20% of inlet air mass fractions.

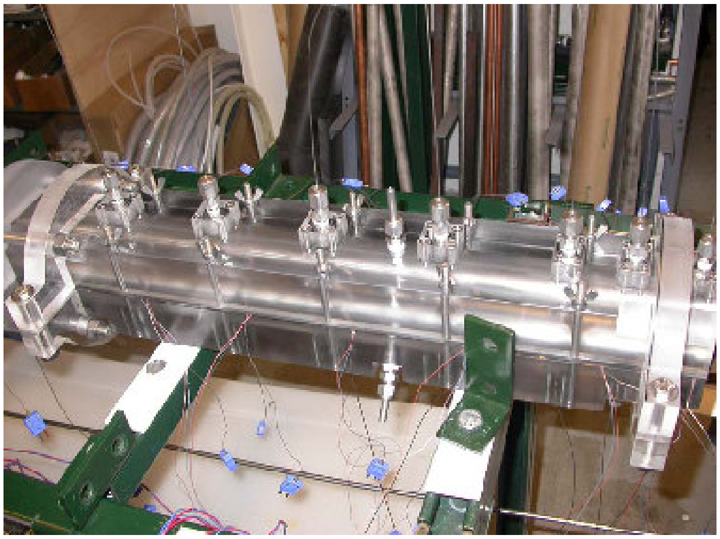


Figure 3. Test section – steam-air mixture inlet

Steam flow is produced in the steam generator and is measured with a vortex flow meter. Air flow rate is controlled by two flow meters calibrated for different ranges. Air inlet temperature is controlled by an air preheater at the air feed line. Air mass flow rate, steam flow rate, coolant flow rate, inlet pressure and coolant inlet temperature were kept constant during each test. Steam flow rate was kept steady through a control valve in the steam line. Coolant flow rate is measured by a magnetic flow meter [4].

Due to the multidimensional nature of the horizontal 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 (cooper – constantan) sheathed and are located at 14 axial positions (z) along of the test section. Table 1 presents the uncertainties of the instrumentation [8].

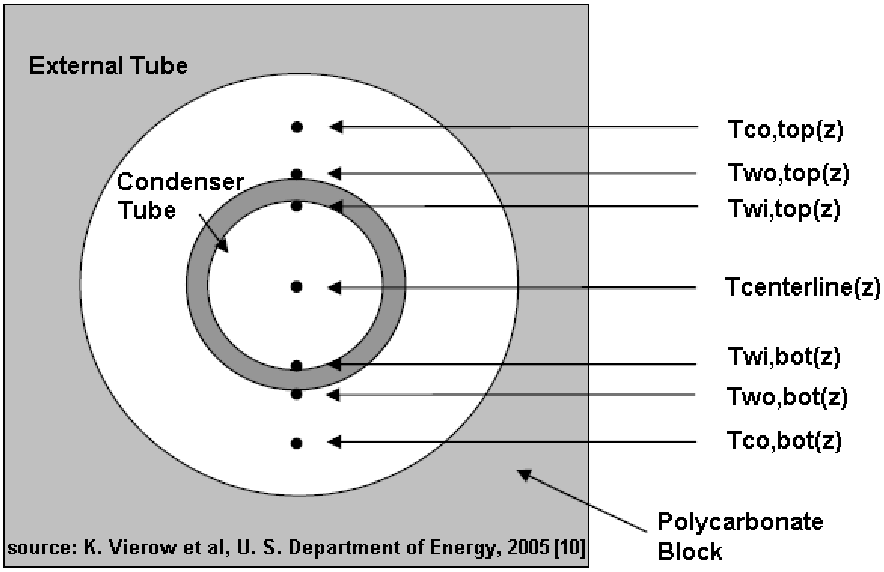
Table 1. Uncertainties of the instrumentation

Instruments	Parameters	Uncertainties
Thermocouples	temperatures	± 0.5 °C
Flow meter	Steam flow rate	± 1 %
	Air flow rate	± 1.5 %
	coolant flow rate	± 0.25 %
Pressure transducer	inlet steam pressure	± 0.2 %
	air line pressure	± 0.25 %

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

Table 2. Thermocouples axial positions (z) along of the test section

z	z_1	z_3	z_5	z_7	z_8	z_9	z_{10}	z_{11}	z_{12}	z_{13}	z_{14}
Test section inlet (m)	0,013	0,114	0,318	0,521	0,724	1,029	1,334	1,689	2,07	2,451	2,934



source: K. Vierow et al, U. S. Department of Energy, 2005 [10]

Figure 4. Thermocouple radial positions in the test section

4. NUMERIC SIMULATIONS WITH RELAP5

RELAP5 (R5) thermo-hydraulic and accident analysis computer code was adopted for experimental data simulations. 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. R5 code uses a seven conservation equations model, where there are three equations for each phase (liquid and steam) and an additional one for noncondensable gases. There is also an additional equation for dissolvable boron treatment. Test section simulations were performed with the MOD3.2.2gama code version [6].

The developed steady state numeric model represents the test section original geometry in detail. Table 3 shows the relation between code components and hydraulic regions. Test section nodalization is presented in Fig. 5.

Table 3. Code components and hydraulic regions

Test section region	Component number	Component
Air-steam mixture	100	TMDPVOL
Air-steam mixture inlet	150	TMDPJUN
Condenser tube	200	PIPE
Condensate outlet	250	SNGLJUN
Condensate tank	300	TMDPVOL
Coolant	400	TMDPVOL
Coolant inlet	450	TMDPJUN
External tube	500	ANNULUS
Coolant outlet	550	SNGLJUN
Coolant tank	600	TMDPVOL

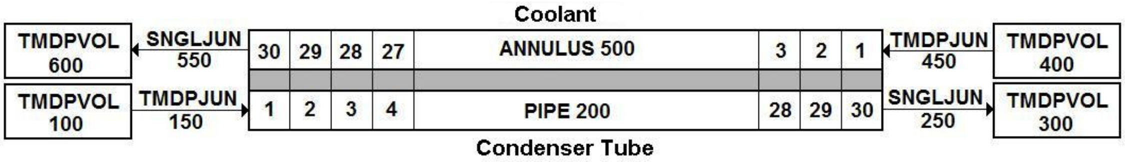


Figure 5. Test section nodalization

The adopted boundary conditions in the test section steady state simulations were: 45 °C of constant inlet coolant temperature ; 1,48.10^{-3} kg/s 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 to 400 kPa inlet pressure and for 5, 10, 15 and 20 % of inlet air mass fractions. Figure 6 presents 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 (T_{cl}) center line and in the axial positions (z) showed at 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.

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 noncondensable gases in the heat transfer rates were not significant for smaller air mass fractions. Temperatures decrease 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. For higher inlet air mass fractions the steam partial pressures are smaller and, consequently, smaller temperatures were observed.

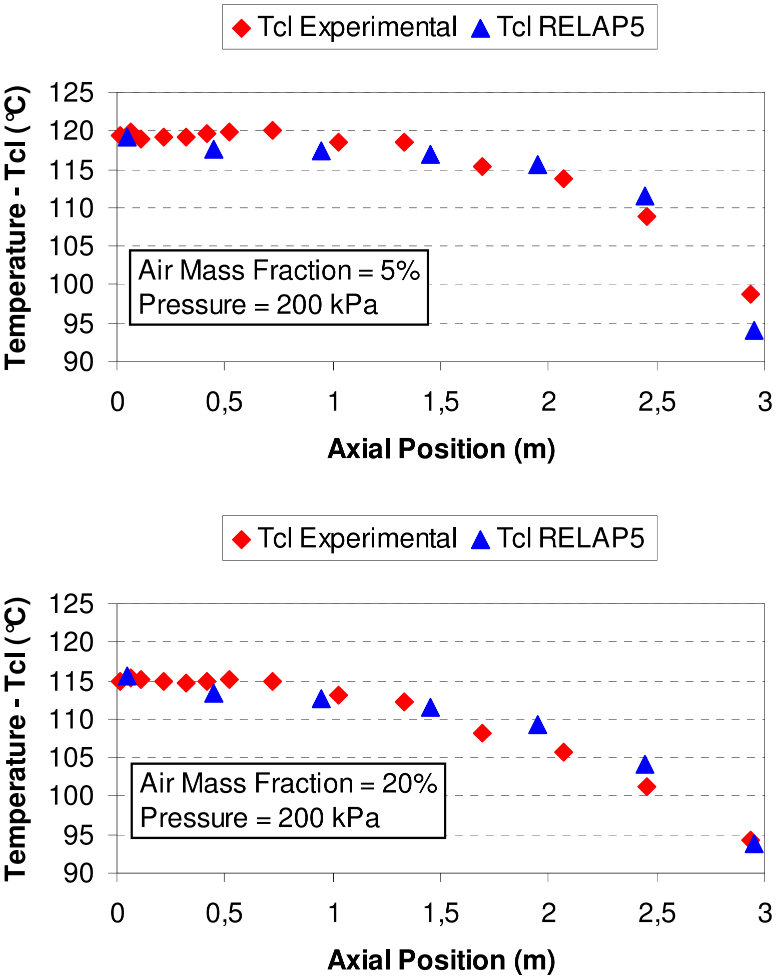


Figure 6. Temperatures (Tcl) – 200 kPa and 5 and 20 % air mass fractions

Comparison between experimental and calculated temperatures for the tests with 5 and 20 % of inlet air mass fractions and 400 kPa inlet pressure is showed in the Fig. 7. Calculated and experimental temperatures presented good agreement and showed the same behavior. At the test section inlet, higher temperatures are observed (≈ 140 °C) when compared with the smaller inlet pressure (200 kPa) temperatures (115 to 120 °C).

Simulation performed with 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 a code overestimation of heat transfer coefficients in this region. Higher experimental inlet pressure (400 kPa) and smaller inlet air mass fraction (5 %) resulted in higher temperature differences between the test section inlet and outlet (ΔT ≈ 70 °C) when compared with 20 % inlet air mass fraction (ΔT ≈ 40 °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.

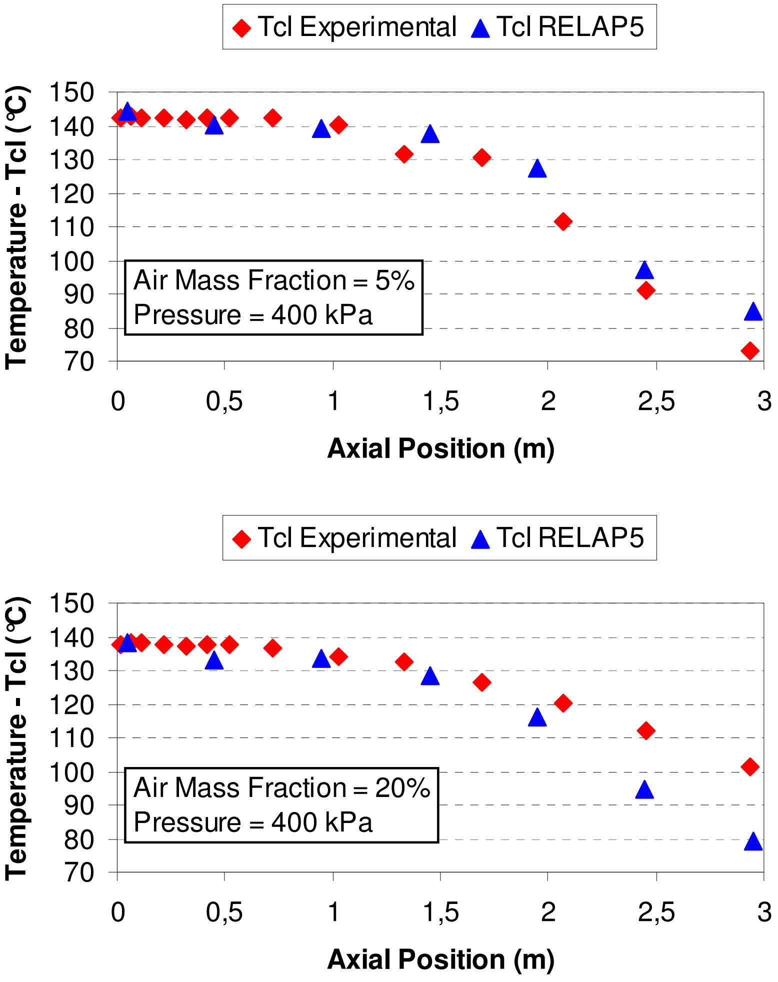


Figure 7. Temperatures (Tcl) – 400 kPa and 5 and 20 % air mass fractions

6. CONCLUSIONS

Simulations of steam condensation in a horizontal condenser tube with noncondensable gases (air) were performed with the RELAP5 code, currently used for thermo hydraulics and accidents analysis. These simulations were carried out for 200 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 code is able to simulate the steam-air mixture condensation phenomena in a horizontal condenser tube. Global effects of the noncondensable gases in the heat transfer rates were not significant for smaller air mass fractions (5 %).

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

Comparison between calculated results and experimental data showed good agreement for 200 kPa inlet pressure, independently of the inlet air mass fraction. For 400 kPa inlet pressure, calculated results and experimental data showed reasonable agreement keeping the same behavior however. For the higher inlet air mass fraction simulation, calculated temperatures were smaller than the experimental temperatures at the final third of the inlet condenser tube, indicating a RELAP5 code 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 design and assembly will be developed to study the steam-air mixture condensation in a horizontal tube (single heat exchanger) in the Centro de Engenharia Nuclear (CEN) at IPEN – CNEN/SP with financial support of the INCT - Instituto Nacional de Ciência e Tecnologia de Reatores Nucleares Inovadores (CNPq). This research project will allow the development of new steam-air condensation heat transfer correlations for the RELAP5 code. Simulations will also be developed and performed with the ANSYS – CFX (Fluid Flow Analysis and Design Optimization Software).

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