ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

EXPERIMENTS IN THE THERMAL STRATIFICATION TEST FACILITY AT NUCLEAR TECHNOLOGY DEVELOPMENT CENTER (CDTN)

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Abstract. *One phase thermally stratified flow occurs in horizontal piping where two different layers of the same liquid flow separately without appreciable mixing due to the low velocities and difference in density (and temperature). This condition results in a varying temperature distribution in the pipe wall and in an excessive differential expansion between the upper and lower parts of the pipe walls. This phenomenon can induce thermal fatigue in the piping system threatening its integrity. In some safety related piping systems of pressurized water reactors (PWR) plants, temperature differences of about 200 °C can be found in a narrow band around the hot and cold water interface. To assess potential piping damage due to thermal stratification, it is necessary to determine the transient temperature distributions in the pipe wall. Aiming to improve the knowledge on thermally stratified flow and increase life management and safety programs in PWR nuclear reactors, experimental and numerical programs have been set up at Nuclear Technology Development Center, a research institute of the Brazilian Nuclear Energy Commission (CDTN/CNEN). The Thermal Stratification Experimental Facility (ITET) was built to allow the study of the phenomenon as broadly as possible. The first test section was designed to simulate the steam generator injection nozzle and has the objective of studying the flow configurations and understanding the evolution of the thermal stratification process. The driving parameter considered to characterize flow under stratified regime due to difference in specific masses is the Froude number. Different Froude numbers, from 0.019 to 0.436, were obtained in different testes by setting injection cold water flow rates and hot water initial temperatures. Numerical simulations were performed with the commercial finite volume Computational Fluid Dynamic code CFX. A vertical symmetry plane along the pipe was adopted to reduce the geometry in one half, reducing mesh size and minimizing processing time. The RANS two equations RNG k-ε turbulence model with scalable wall function and the full buoyancy model were used in the simulation. Experimental and numerical results were compared in order to properly evaluate the numerical model.*

Keywords: *Thermal stratification, PWR type reactors, reactors cooling systems, thermal stress*

1. INTRODUCTION

One phase thermally stratified flow occurs in horizontal piping where two different layers of the same liquid flow separately without appreciable mixing due to the low velocities and difference in density (and temperature). This condition results in a varying temperature distribution in the pipe wall and in an excessive differential expansion between the upper and lower parts of the pipe walls. This phenomenon can induce thermal fatigue in the piping system threatening its integrity. In some safety related piping systems of pressurized water reactors (PWR) plants, temperature differences of about 200 °C can be found in a narrow band around the hot and cold water interface. To assess potential piping damage due to thermal stratification, it is necessary to determine the transient temperature distributions in the pipe wall (Häfner, 2004) (Schuler and Herter, 2004).

Aiming to improve the knowledge on thermally stratified flow and increase life management and safety programs in PWR nuclear reactors, experimental and numerical programs have been set up at Nuclear Technology Development Center, a researcher institute of the Brazilian Nuclear Energy Commission (CDTN/CNEN) (Rezende, 2012), (Rezende et al. 2012). The Thermal Stratification Experimental Facility (ITET) was built to allow the study of the phenomenon as broadly as possible. The first test section was designed to simulate the steam generator injection nozzle and has the objective of studying the flow configurations and understanding the evolution of the thermal stratification process. The driving parameter considered to characterize flow under stratified regime due to difference in specific masses is the Froude number. Different Froude numbers, from 0.019 to 0.436, were obtained in different testes by setting injection cold water flow rates and hot water initial temperatures.

Numerical simulations were performed with the commercial finite volume Computational Fluid Dynamic code CFX. A vertical symmetry plane along the pipe was adopted to reduce the geometry in one half, reducing mesh size and minimizing processing time. The RANS two equations RNG k-ε turbulence model with scalable wall function and the

ISSN 2176-5480

full buoyancy model were used in the simulation. Experimental and numerical results were compared in order to properly evaluate the numerical model.

2. THE THERMAL STRATIFICATION EXPERIMENTAL FACILITY AT CDTN

The Thermal Stratification Experimental Facility (ITET) was built in the Thermal-hydraulic Laboratory at Nuclear Technology Development Center (CDTN) to allow the study of the phenomenon as broadly as possible. The Laboratory is shown in Fig.1. The first test section was designed to simulate the steam generator injection nozzle. Figure 2 shows a drawing ITET with this test section that consists of a stainless steel tube (AISI 304 L), 141.3 mm in outside diameter and 9.5 mm thick. It was made of two pieces of this tube, a vertical and a horizontal piece respectively 500 mm and 2000 mm length, connected each other by a 90^{o} curve. A flanged extension of the tube was placed inside a pressure vessel, which simulates the steam generator. Thermocouples were placed in four Measuring Stations along the length of the test section tube. Measuring Stations I, II and III, located in the horizontal length of the tube were instrumented with thermocouples, measuring both fluid and wall temperature at several positions of each Measuring Station. Measuring Station A, positioned in the vertical length of the tube, was instrumented with three thermocouples just to determine the moment when the injected cold water reaches its position.

Figure 1. Thermal-hydraulic Laboratory at Nuclear Technology Development Center (CDTN)

Before the beginning of each test the whole system is filled with cold water. Then it is pressurized and heated by steam supplied by a boiler. A temperature equalization pump ensures that the entire system is heated in a homogeneous way. After the heating process, the equalization pump is turned off and both the steam supply and equalization lines are isolated by closing valves V3, V5 and V6. The test itself begins then by injecting cold water from the lower end of the vertical tube after opening valve V4. The cold water flow rate was previously adjusted at a value planned in the test matrix. This flow rate and the system pressure are maintained stable through a set of safe (V1) and relieve (V2) valves at the upper side of the pressure vessel, which controls upstream pressure. The water flows from the injection nozzle simulator pipe to the steam generator simulator vessel through 11 holes at the upper side of the extension tube placed inside the vessel. These holes are 12 mm in diameter and they are displaced 42 mm from each other. The center of the first hole is 20 mm from the end of the tube.

ISSN 2176-5480

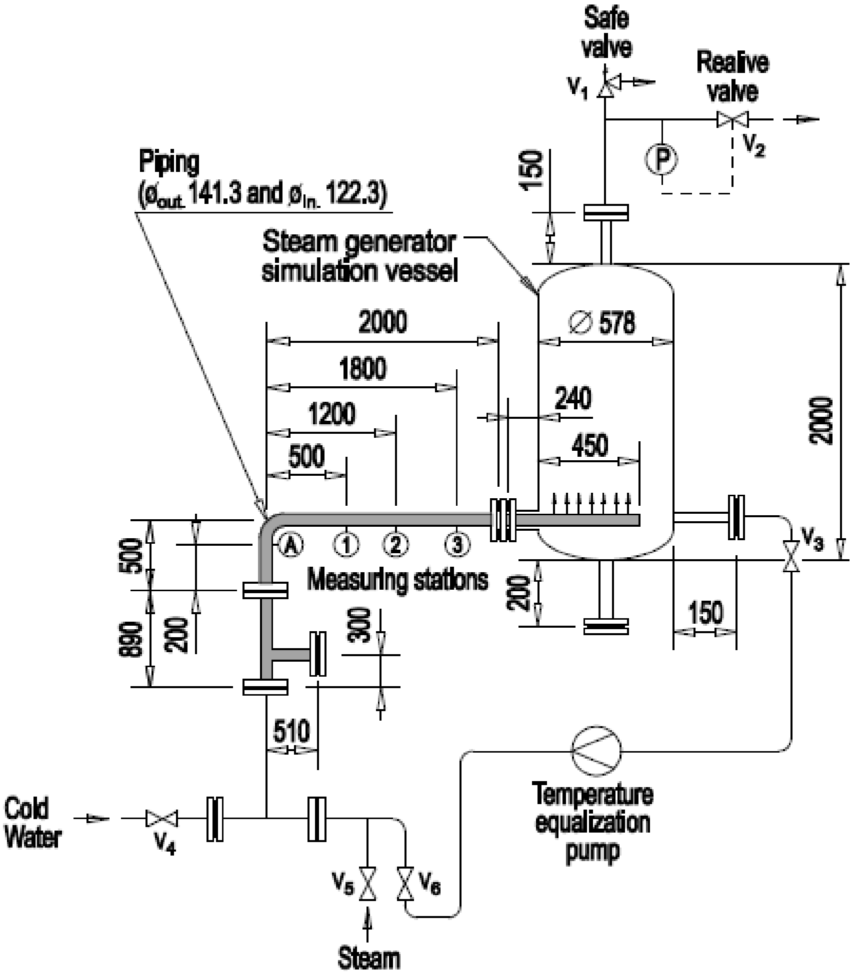

Figure 2. Position of the Measuring Stations A, I, II and III in the steam generator injection nozzle simulating test section

2.1 The Instrumentation

Measurement Stations I, II and III, positioned along the longitudinal length of the tube simulating the steam generator injection nozzle, as shown in Figure 2, were used for temperature measurements. Figures 3, 4 and 5 show the thermocouples distribution in Measuring Stations I, II and III, respectively. To measure fluid temperature on Measurement Station I a set of 12 thermocouples was angularly distributed along the tube's internal wall (3 mm from the wall), shown in Figure 3 by circle symbols. These internal thermocouples were named clockwise starting from the highest vertical position as T1I01, T1I02, …, T1I11 and T1I12. To measure the tube's wall temperature another set of 12 thermocouples was brazed on the outside wall at the same angular position as the internal thermocouples, displayed by triangle symbols in Figure 3. These external thermocouples were named clockwise starting from the highest vertical position as T1E01, T1E02, …, T1E11 and T1E12. Finally, a removable probe was placed along the cross section's vertical diameter, containing a set of 9 fluid thermocouples placed at the same vertical position of each of the internal thermocouples, shown by square symbols in Figure 3. These probe thermocouples were named from the highest to the lowest vertical position as T1S01, T1S02, ... T1S08 and T1S09.

Figure 4 shows the thermocouple distribution on Measurement Station II. A set of 19 thermocouples was angularly distributed along the tube's internal wall (3 mm from the wall) to measure fluid temperature, shown in Fig. 4 by circle symbols. Close to the angular position of 90° a set of 5 internal thermocouples was positioned in close proximity, displaced 2 mm from each other, to capture fluctuations of the cold-hot water interface. In the opposite side 2 internal thermocouples were positioned in the same manner to capture asymmetrical behaviors of the interface. These internal thermocouples were named clockwise starting from the highest vertical position as T2I01, T2I02, …, T2I18 and T2I19. Another set of 14 thermocouples was brazed on the outside wall at the same angular position as the internal thermocouples (only 1 external thermocouple was positioned at the angular positions of 90° and 270°), shown in Fig. 4 by triangle symbols. These external thermocouples were named clockwise starting from the highest vertical position as T2E01, T2E02, …, T2E13 and T2E14. Finally, a removable probe was placed along the cross section's vertical

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diameter, containing a set of 10 fluid thermocouples placed at the same vertical position of each of the internal thermocouples, as shown in Fig. 4 by square symbols. These probe thermocouples were named from the highest to the lowest vertical position as T2S01, T2S02, ..., T2S09 and T2S10.

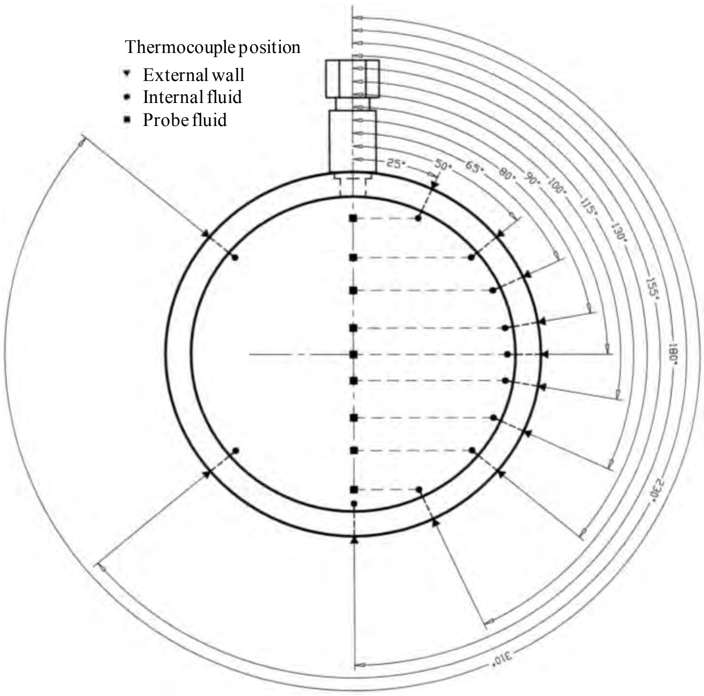

Figure 3. Positions of the thermocouples at Measurement Station I

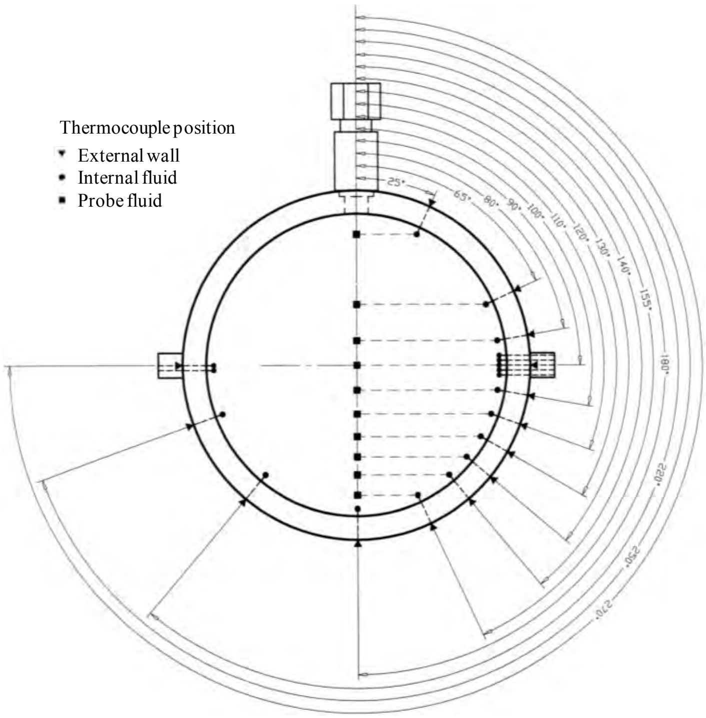

Figure 4. Positions of the thermocouples at Measurement Station II

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Figure 5 shows the thermocouple distribution on Measurement Station III. Close to the angular position of 90° a set of 4 internal thermocouples, named from the highest to the lowest vertical position as T3I01, T3I02, T3I03, and T3I04, was positioned 3 mm from the internal wall and displaced 2 mm from each other to measure fluid temperature. A fifth internal thermocouple, named T3I05, was placed at the angular position of 180°, shown in Fig. 5 by circle symbols. Two thermocouples, named T3E01 and T3E02, were brazed on the outside wall of the tube at the angular positions of 90° and 180° respectively, shown by triangle symbol in Fig. 5. Finally, a removable probe was placed along the cross section's vertical diameter containing a set of 6 fluid thermocouples, shown as square symbols in Fig. 5. These probe thermocouples were named T3S01, T3S02, T3S03, T3S04, T3S05 and T3S06 from top to bottom. They were placed respectively at the same vertical positions of thermocouples T2S03, T2S04, T2S05, T2S07, T2S08 and T2S10.

A set of three thermocouples was positioned at Measuring Station A to detect the instant when the injected cold water reaches its position. The thermocouples were placed inside the tube 3 mm from the wall, at the center of the cross section by a probe and at the external wall.

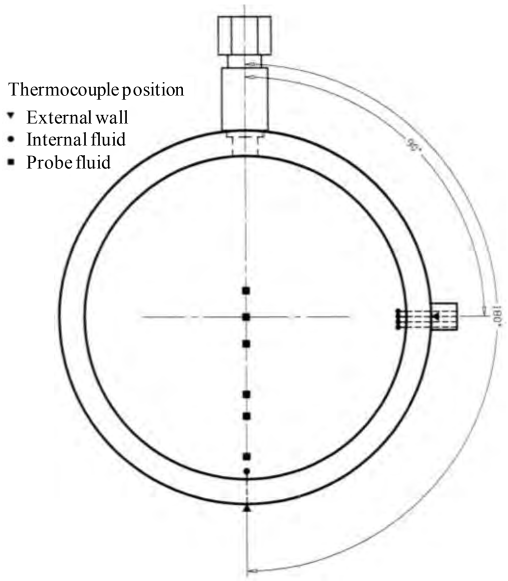

Figure 5. Positions of the thermocouples at Measurement Station III

Figure 6 shows a photograph of the test section pipe after the brazing of the thermocouples. Figure 6 shows in detail the outside of Measuring Station I. The external thermocouples were brazed directly to the pipe and the internal thermocouples were brazed through special stainless steel injection needles. Some aluminum brackets for the thermocouples are seen in the back, which were only used during the assembly of the experimental facility. Figure 7 shows the Measuring Station I internal thermocouples. Figure 7 shows a photograph of the ITET, including the horizontal tube of the injection nozzle, the pressure vessel simulating the steam generator and the cold water tank.

Other measurements performed were:

– injection flow rate of cold water, using a set of orifice plate and differential pressure transmitter;

– water temperature in the cold water tank, using an isolated type K thermocouple of 1 mm in diameter;

– water temperature in the cold water injection pipe, both close to the orifice plate and also close to the point of injection to the nozzle simulation tube, using two isolated type K thermocouples of 1 mm in diameter;

– temperature inside the steam generator simulation vessel, using an isolated type K thermocouple of 1 mm in diameter;

– pressure inside the steam generator simulation vessel, using a gauge pressure transducer;

– pressure in water injection line, using a gauge pressure transducer;

– water level in the cold water tank using a differential pressure transmitter.

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Figure 6. The test section's horizontal pipe after the thermocouples brazing, and detail of the measuring station 1

Figure 7. The internal thermocouples in the Measuring Station I, and the Thermal Stratification Experimental Facility (ITET) during assembly

2.2 The Measuring Uncertainty

The measuring uncertainties for the main parameters, obtained according to ISO (1993), were:
– 2.4°C for the temperature measurements;
– 2.4 % of the measured value for the flow rate measurements; and,
– 1.5 % for the gauge pressure measurements.

3. SIMULATION RESULTS

The experimental results of thermal stratification carried out at the Thermal Hydraulics Laboratory of CDTN/CNEN were used for comparisons with CFD results. These numerical simulations were performed with the commercial finite volume Computational Fluid Dynamic code CFX. A vertical symmetry plane along the pipe was adopted to reduce the geometry in one half, reducing mesh size and minimizing processing time. The RANS two equations RNG k-ε turbulence model with scalable wall function and the full buoyancy model were used in the simulation.

Following, there are presented some results of the numerical simulation of two experiments, which were performed in a simplified geometry (Rezende et al, 2011b and 2011c) using CFX 13.0 code (ANSYS, 2010). This simulating geometry is shown in Fig. 8. Its main simplifications were the omission of the flanges and most of the lower inlet geometry and presented no significant influence on the results. Table 1 shows the input parameter of both experiments, whose main difference is the flow rate.

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Table 1. Setup parameters for the experiments and simulations

Experiment	Flow rate [kg/s]	P_{gauge} [bar]	T_{hot} [^oC]	T_{cold} [^oC]
1	0.76	21.1	219.2	31.7
2	1.12	21.4	217.7	28.7
$\delta^{(1)}$	0.03	0.5	2.4	2.4

(1) Global uncertainty

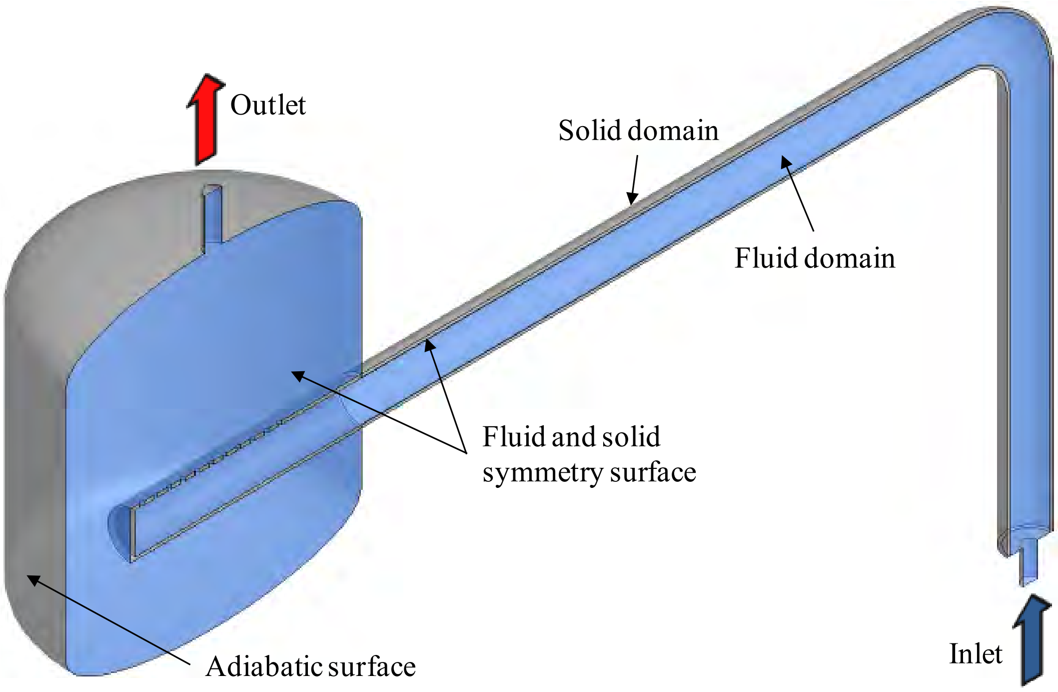

Figure 8. Computational model domains and boundary conditions.

The computational model was generated with two domains: one solid, corresponding to the pipes, and one fluid for the water in its interior. A vertical symmetry plane along the pipe was adopted to reduce the mesh size in one half, minimizing processing time. The walls in the vessel region were considered adiabatic as the external tube walls. Mass flow inlet and outlet conditions were defined at the bottom end of the pipe and high end of the vessel, respectively. Figure 2 shows the computational model's details.

The initial conditions shown in Table 1 were used in the simulations. Water properties like density, viscosity and thermal expansivity were adjusted by regression as function of temperature with data extracted from Table IAPWS-IF97, in the simulation range (25 ^oC to 221 ^oC). The RANS - Reynolds Averaging Navier-Stokes equations, the two equations of the RNG *k*-*ε* turbulence model, with scalable wall functions, the full buoyancy model and the total energy heat transfer model with the viscous work term were solved. The simulations were performed using parallel processing with up to six workstations with two 4 core processor and 24 GB of RAM. All simulations were performed using the high resolution numerical scheme (formally second order) for the discretization of the conservation and RNG *k*-*ε* turbulence model equations terms and second order backward Euler scheme for the transient terms. A root mean square (RMS) residual target value of 10^{-6} was defined as the convergence criteria for the simulations in double precision.

Figure 9 shows the evolution of the temperature differences between the average temperatures on the highest and lowest positions of the horizontal tube calculated through the Equation 13 for the internal and external thermocouples.

$$DT = \left[\left(T_1^u + T_2^u\right) - \left(T_1^l + T_2^l\right)\right]/2 \qquad (13)$$

where the superscripts *u* and *l* are relative to the upper and the lower positions and subscripts 1 and 2 to the first and the second measuring station of the horizontal tube.

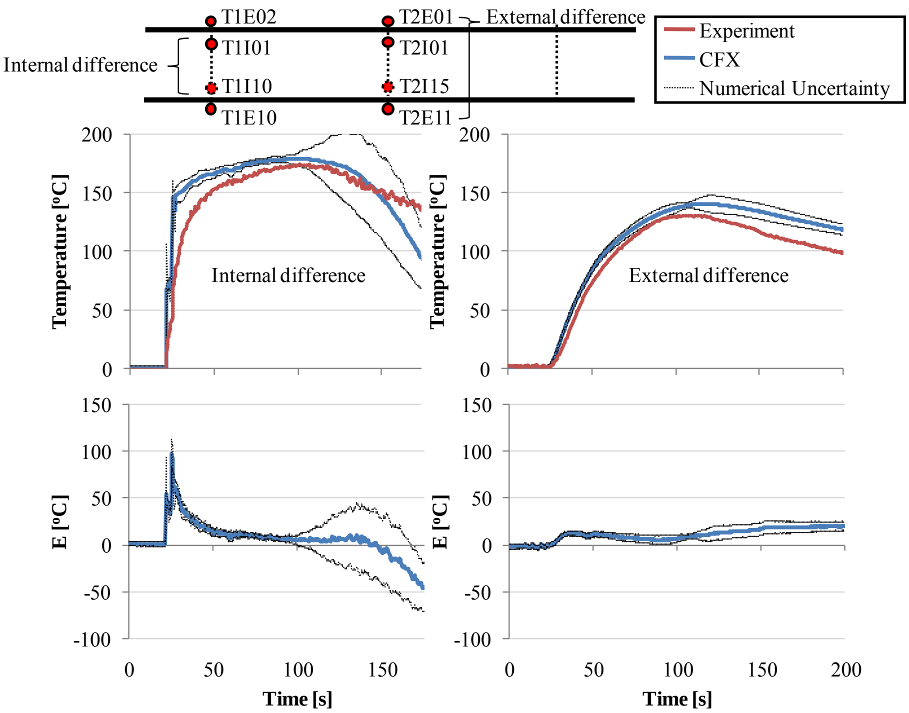

Figure 9. Validation results for the temperature difference between upper and lower thermocouples positioned internally and externally.

Figure 9 shows that for the region of highest temperature difference, and therefore, most critical for the piping integrity, the validation error is relatively low and well predicted. It is also observed that the external temperature difference agreement between experimental and numerical results is very good during the evaluated time.

Figure 10 shows a comparison between numerical results obtained by the presented model for two flow conditions. By the results it is possible to conclude that thermal stratification occurs for both flow rates with similar intensity and temperature differences levels.

ISSN 2176-5480

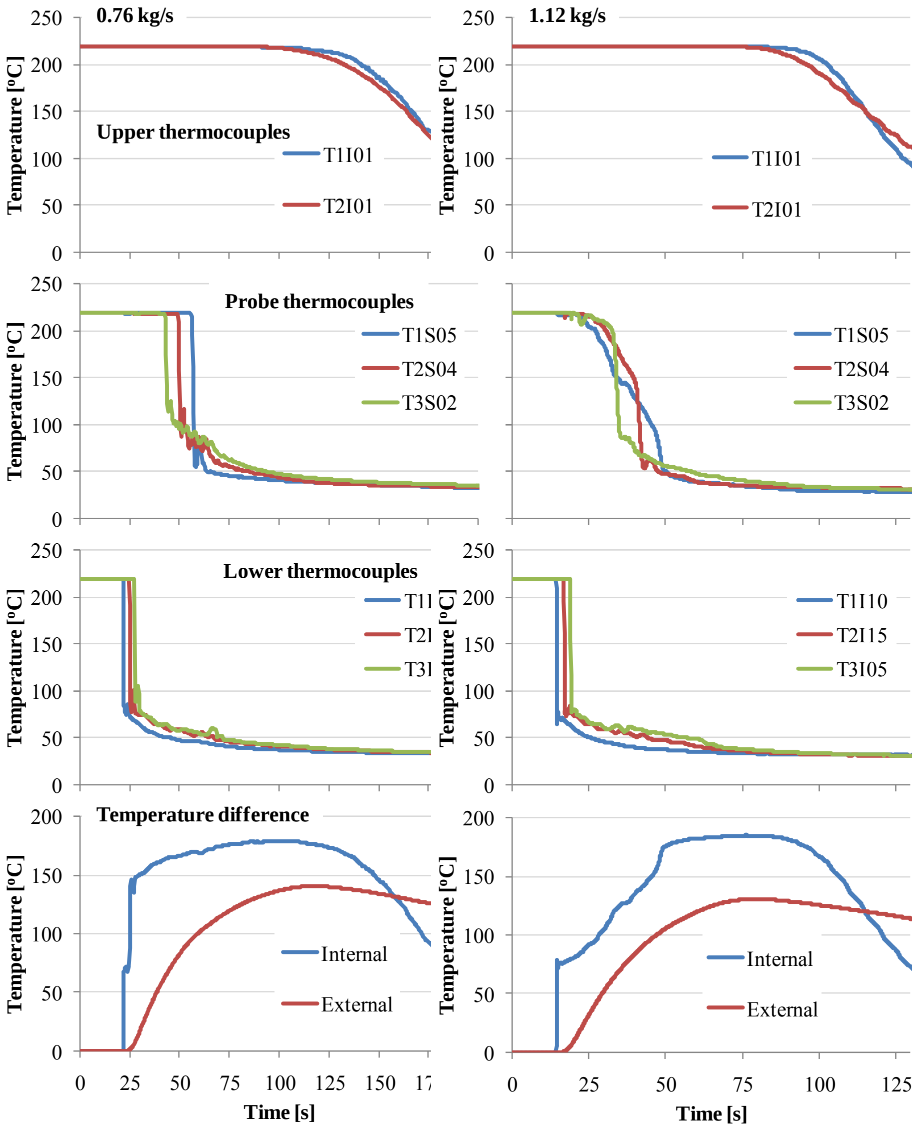

Figure 10. Comparison of numerical results obtained for two flow conditions.

Figure 11 shows the cold water front evolution obtained numerically for the flow rate of 1.12 kg/s. It can be observed that a cold water "head" is formed as the cold water front advances in the horizontal pipe. It can also be observed a change in the direction of the cold water front after reaching the end of the tube.

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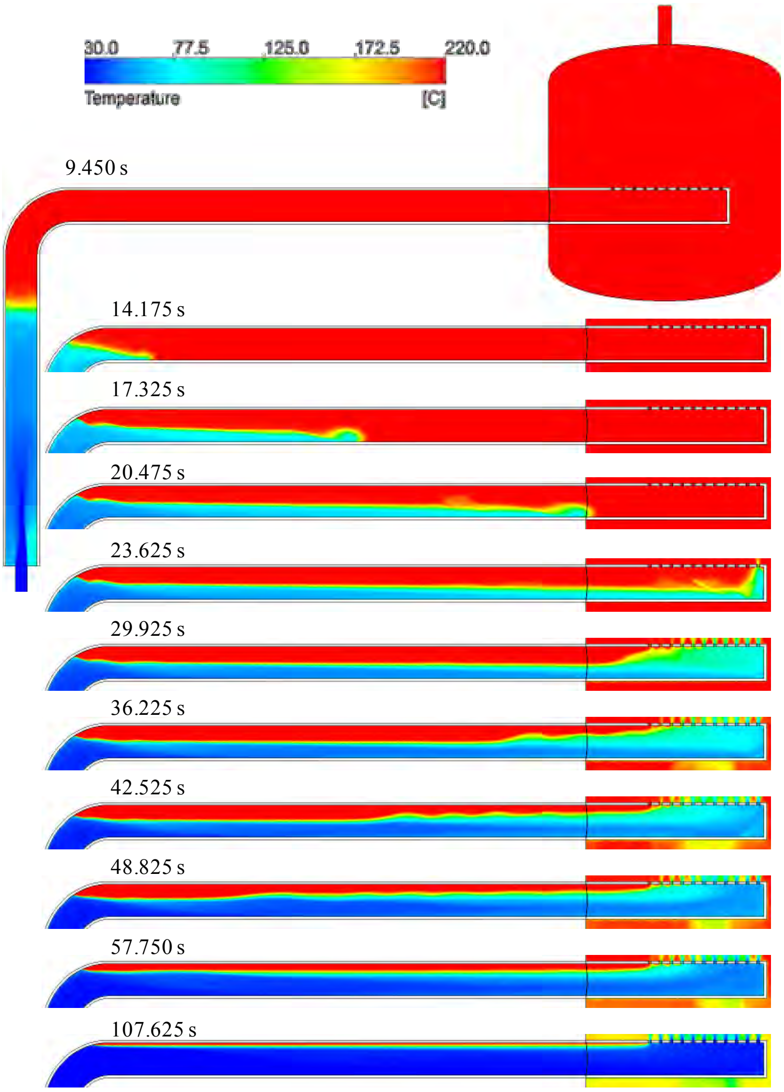

Figure 11. Temperature contours along time for flow rate 1.12 kg/s.

Figure 12 shows details of the flow behavior and flow velocity evolution in the simulation of flow rate 1.12 kg/s. It can be observed that as the cold water front enters the horizontal pipe it accelerates due to stratification and that the front induces a recirculation flow of the hot water at the top of the pipe, as mass must be conserved. Figure 12 highlights the previously observed behavior, i.e., as the cold front reaches the end of the pipe it starts filing the pipe in the inversed direction eliminating almost all of the recirculating hot water. However, some hot water remains imprisoned at the top of the pipe as the injected cold water takes control of all water exits. This phenomenon is observed experimentally and causes the thermal stratification at the top of the pipe to persist for many minutes depending on the flow rate.

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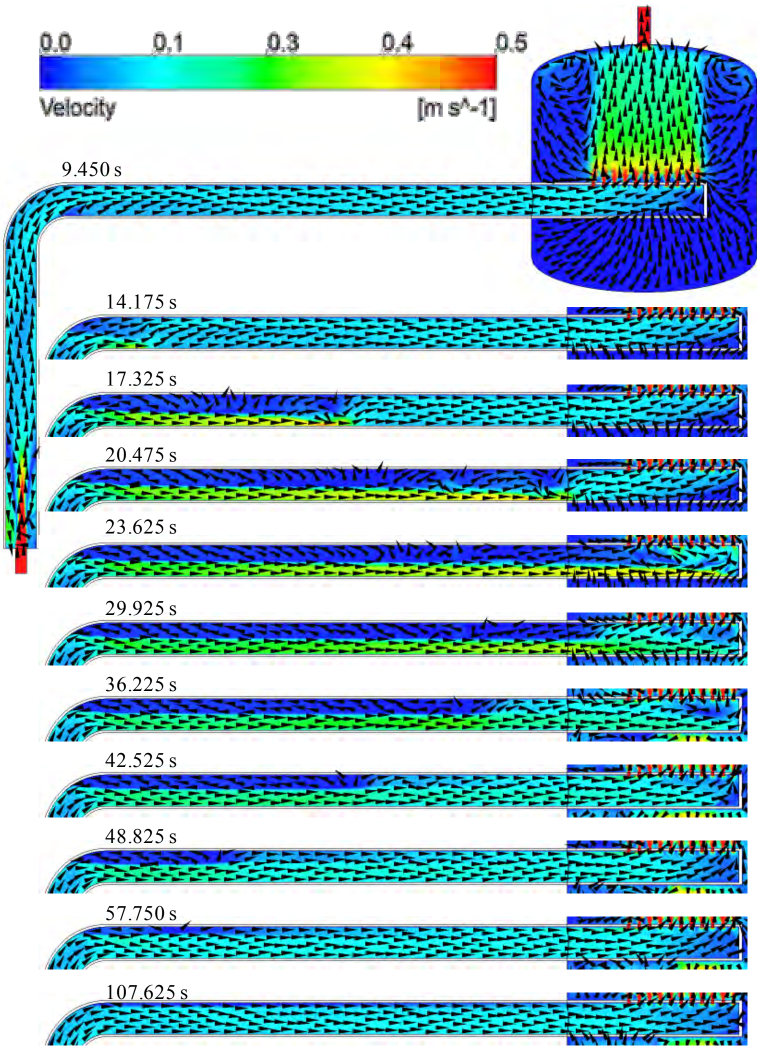

Figure 12. Flow velocity and behavior along time for flow rate 1.12 kg/s.

4. CONCLUSION

The numerical simulation of one phase thermally stratified flow experiments in a pipe, similar to the steam generator injection nozzle at the secondary loop of a Pressurized Water Reactor (PWR), was proposed. The simulations were done using CFD codes (Rezende et al. 2011b). Although considerable error were observed the qualitative agreement between experiment and simulation can be considered good as most of the behavior observed was reproduced. The performed validation process showed the importance of proper quantitative evaluation of numerical results.

5. ACKNOWLEDGMENT

This research project is supported by the following Brazilian institutions: Nuclear Technology Development Centre (CDTN), Brazilian Nuclear Energy Commission (CNEN), Research Support Foundation of the State of Minas Gerais (FAPEMIG), and Brazilian Council for Scientific and Technological Development (CNPq).

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7. RESPONSIBILITY NOTICE