STUDY FOR THE PREDICTION OF STRATIFIED PIPE FLOWS

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Abstract. *Stratified flows can occur when two different layers of the same liquid at different temperatures flow separately in horizontal pipes without appreciable mixing. This condition may lead to considerable top to bottom temperature gradient in the pipe wall and can eventually result in excessive differential expansion from upper to lower parts of the pipe threatening its integrity. This paper reports a thermal-hydraulic study for one phase stratified flows, under conditions similar to nuclear reactors cooling piping systems. An experimental facility simulates the steam generator injection nozzle of a pressurized water reactor. Numerical results obtained with a commercial finite volume CFD code CFX-5.7 are presented and compared with experimental data. Both results confirmed the occurrence of the thermal stratification in the simulated conditions.*

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

1. Introduction

One phase thermally stratified flow is the condition that can occur in horizontal segment of piping, where two different layers of the same liquid flow separately, without appreciable mixing due to low flow velocities and a great temperature difference (and density difference). In this condition, the colder (heavier) fluid occupies the lower position along the pipe, while the hotter (lighter) fluid occupies the upper position. This condition may lead to considerable top to bottom temperature gradient in the pipe wall, which can eventually result in excessive differential expansion of the upper and lower parts of the pipe threatening the integrity of the piping system. Three possible types of basic effects may occur in the pipe where stratification occurs, Kim et al. (1993) and Stephens et al. (2003):

– sustained bending moment stress, wherever a top to bottom gradient exists, due to restrains imposed by the pipe and its support system against the tendency for thermal expansion in the hotter upper half of the pipe and against contraction in the colder lower half;

– shear stress due to distortions of the tube in the cross-sectional plane;

– high frequency cyclic stress at the interface between the hot and cold fluids, due to turbulence and small oscillations of the interface, called “thermal striping”.

Some safety related piping systems connected to reactor coolant systems at operating nuclear power plants are known to be potentially susceptible to thermally stratified flows. Those include pressurizer surge lines, emergency core cooling lines, residual heat removal lines and also some segments of the main piping of the primary and secondary cooling loops, like the hot and cold legs in primary and the steam generator feedwater piping in secondary, Häfner (1990) and Schuler and Herter (2004). Temperature differences of about 200 °C can be found in a narrow band around the hot and cold water interface. To assess the potential for piping damage due to thermal stratification, it is necessary to determine the transient temperature distributions in the pipe wall.

The main parameters governing one phase thermally stratified flows in horizontal piping are fluid velocities, difference between specific mass of cold and hot fluids, geometry of the system and heat transfer in the internal piping system. The driving parameter considered to characterize flow under stratified regime due to difference in specific masses is the Froude number, given by:

$$Fr = \frac{U_0}{\left(gD\,\Delta\rho\,/\rho_0\right)^{1/2}}\,, \qquad (1)$$

Were,

U_0 is the average velocity of the injection water, in [m/s];
g is the acceleration of the gravity, in [m/s^2];
D is the inner diameter of the tube, in [m];
$\Delta\rho$ is the difference between the densities of the hot and cold water, in [kg/m^3]; and,
ρ_0 is the density of the cold water, in [kg/m^3].

This paper summarizes an experimental and a numerical methodology developed for the simulation of one phase thermally stratified flow in a nuclear reactor steam generator nozzle. Both the simulation use a Froude number of about $Fr \cong 0.1$. They have the objective of studying the flow configurations and understanding the evolution of the of thermal stratification process. The results of one experiment are also presented and compared to the numerical simulation.

2. Experimental Methodology

Figure 1 shows a diagram of the experimental facility test section. A pressure vessel simulates the steam generator tank and a standard stainless steel tube, instrumented with type K thermocouples, 0.5 mm in diameter, simulates its water injection nozzle. The thermocouples were distributed in some measuring cross sections (1, 2, 3 and A) to measure wall and fluid temperatures.

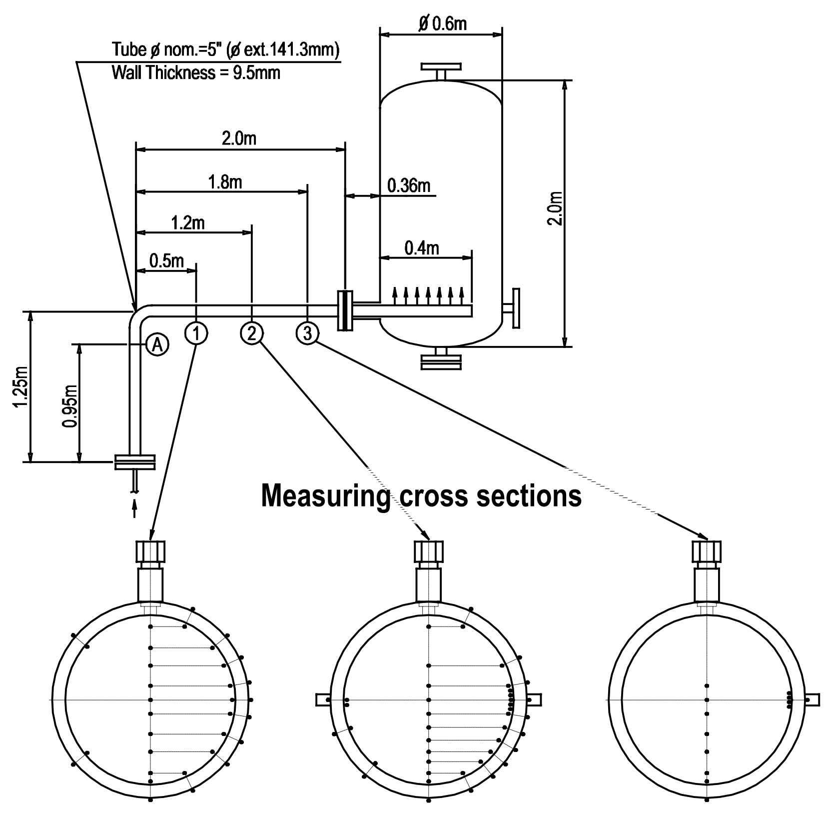

Figure 1. Diagram of the experimental facility test section and thermocouples distribution on its Measuring Cross Sections 1, 2 and 3.

Wall thermocouples were positioned on the wall outside and fluid thermocouples were positioned in two different ways: along the inside wall and along the tube vertical diameter. Figure 1 also shows the Measuring Cross Sections 1, 2 and 3 thermocouples distribution. The Measuring Cross Section A has just a pair of wall and flow thermocouples to determine the time when the cold water reach its vertical position. The fluid thermocouples positioned along the inside wall have their hot junctions positioned 3 mm away from the wall, distance that corresponds to 6 times the diameter of the thermocouple and that is considered enough not to be influenced by the wall temperature. For each one of these fluid thermocouples, a wall thermocouple was positioned in the same angular position, measuring external temperature, so that it is possible to obtain the temperature difference across the wall thickness. Three probes were positioned along the vertical diameter of the measuring cross sections, where fluid thermocouples were positioned one for each thermocouple along the inside wall, at its same height. The water temperature is also measured with type K thermocouples in the injection piping and in the cold water tank. The injection water flow rate is measured with an orifice plate and a differential pressure transducer. Finally, the system pressure is measured with a gauge pressure transducer.

Before the starting of a test, both the tank and the tube are filled and pressurized with hot water. The cold water flow rate is set up together with the piping pressure, but with the flow returning back to the cold water tank. The test begins by acting on a valve in such way that the cold water flows in the nozzle simulator pipe, through its lower end. The system pressure is maintained at the set value by a relief valve. The tests finish after a planned time. Here are presented the results of a test carried out with the following setting parameters values, that corresponds to a Froude number of about $Fr \cong 0.1$:

- System pressure of 22.0 ± 0.5 bar;
- Initial hot water temperature of 219 ± 2 ^{o}C;
- Injection cold water temperature of 28 ± 2 ^{o}C; and,
- Injection cold water flow rate of 0.54 ± 0.03 kg/s.

3. Numerical Methodology

The numerical simulation used a commercial code CFX 5.7 (AEA Technology plc., 2003) based on the finite volumes method. The code uses five modules to perform a simulation: the *DesignModeler* to construct the geometric form, the *CFXMesh* for mesh generation, the *CFXPre* to define the physic and boundary conditions, the *Solver* to compute and the *Post* to post processing and visualization of the results.

Two simulation domains were created: one solid, corresponding to the pipe, and one fluid for the water in its interior. The vertical symmetry plane along the pipe was adopted to reduce the geometry in one half, reducing the mesh size and minimizing processing time. Unstructured mesh with tetrahedral elements was defined inside the pipe. Prismatic structured volumes with defined number and thickness were built close to the surfaces in the solid domain. It was necessary a located mesh refinement in the region of the exit holes due to the local contractions that generate high pressure and speed gradients. Simulations were performed with several refinement levels before adopting a pattern of appropriate mesh. Figure 2 presents, in the plane of symmetry, details of the mesh adopted for the simulation, with 371850 elements in the fluid domain and 257554 elements in the solid domain.

In this simulation the initial temperature of the piping and of the water was 215 ^{o}C, with an internal pressure of 23 bar. Water was injected then through the bottom end of the pipe, at the temperature of 25 ^{o}C and at the flow rate of 0,25 kg/s (corresponding to the simulation of ½ of the complete geometry). The same water flow rate was considered at the exit holes in the other end of the pipe. Water properties like density, viscosity and thermal expansivity were adjusted by regression as function of temperature with data extracted from the Table IAPWS-IF97, in the simulation range (25 ^{o}C to 215 ^{o}C). No heat transfer was considered through the external wall of the pipe (adiabatic wall boundary condition). The turbulence RNG k-ε model with scalable wall functions and the full buoyancy model were adopted.

The RANS - Reynolds Averaging Navier-Stokes equations with the two turbulence model equations were solved then by the module *Solver* of CFX 5.7. A transient of 200 s was simulated in parallel using two personal computers Pentium 2.8 Ghz HT, with 512 of RAM and 100 Mbps ethernet card. The total processing time was 114 h and 4 min.

4. Results

The values of the main parameters obtained during the experiments were not exactly the same used in the numeric simulation, which was performed previously. The small differences observed do not invalidate, however, a qualitative comparison between the two methodologies.

Figure 3 shows the results for the temperature evolution at five termocouples positions on the vertical probe in the Measuring Cross Section 1. A good qualitative agreement between the experimental (E) and numerically calculated (C) behaviors can be seen. Figures 4 and 5 show these results for the Measuring Cross Sections 2 and 3 and repeat the same qualitative agreement. Figure 6 shows the temperature distribution along the three vertical probes at the time 80 s after the test start up. A temperature gradient of about 150 ^{o}C in the interface can be seen in both experimental (E) and numerically calculated (C) results between 50 mm and 90 mm high on the vertical diameter of the tube.

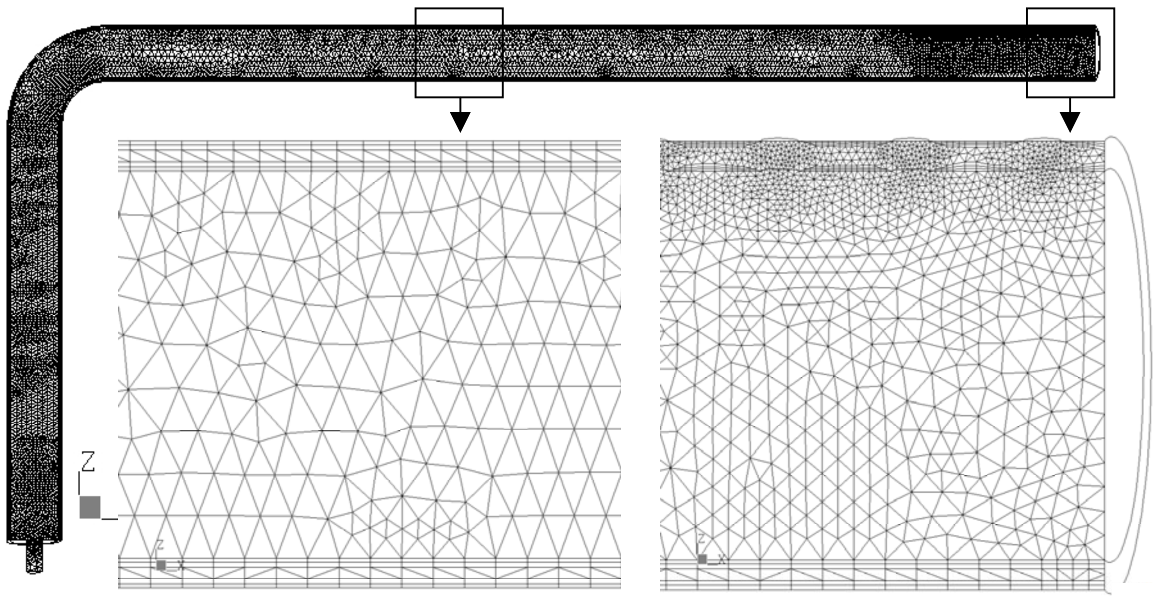

Figure 2. Mesh details in the symmetry plane.

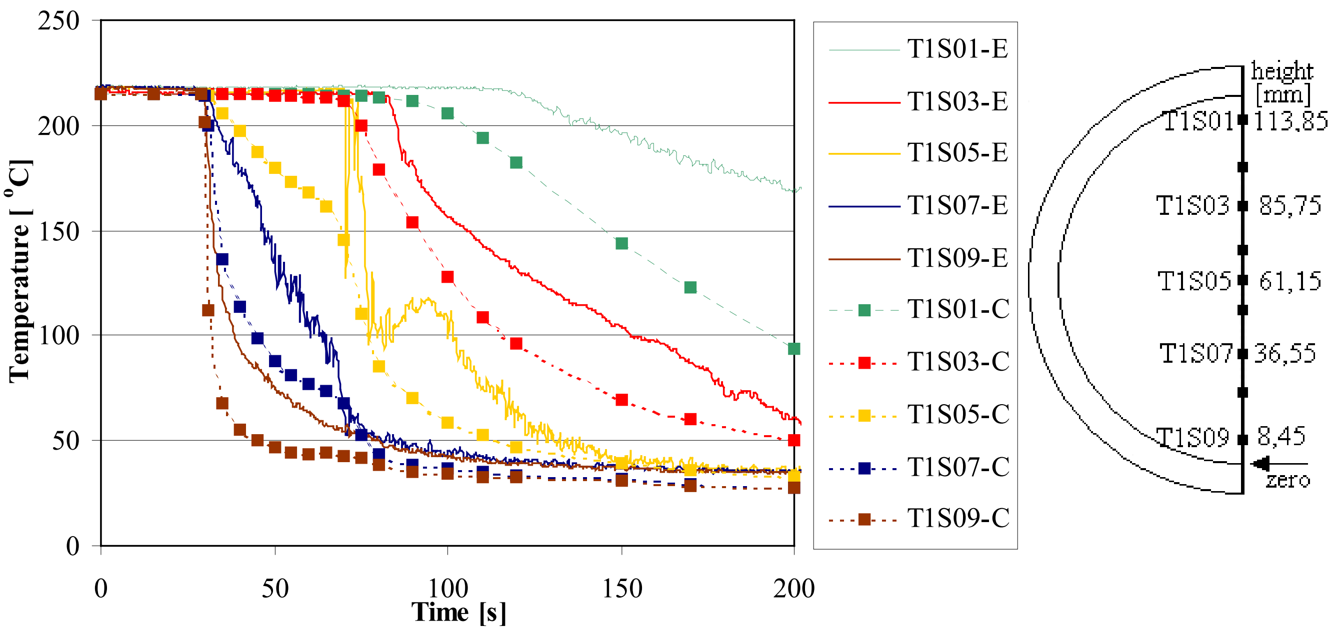

Figure 3. Experimental (E) and calculated (C) results of temperature evolution at the positions of five termocouples on the vertical probe in the Measuring Cross Section 1.

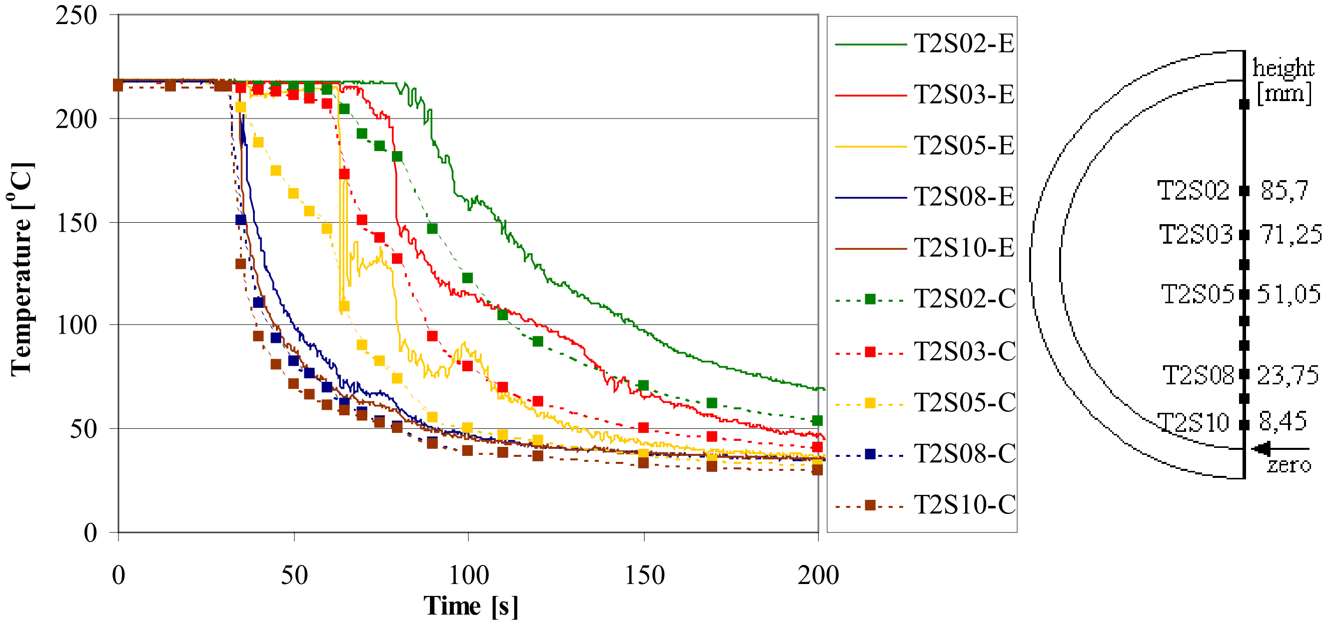

Figure 4. Experimental (E) and calculated (C) results of temperature evolution at the positions of five thermocouples on the vertical probe in the Measuring Cross Section 2.

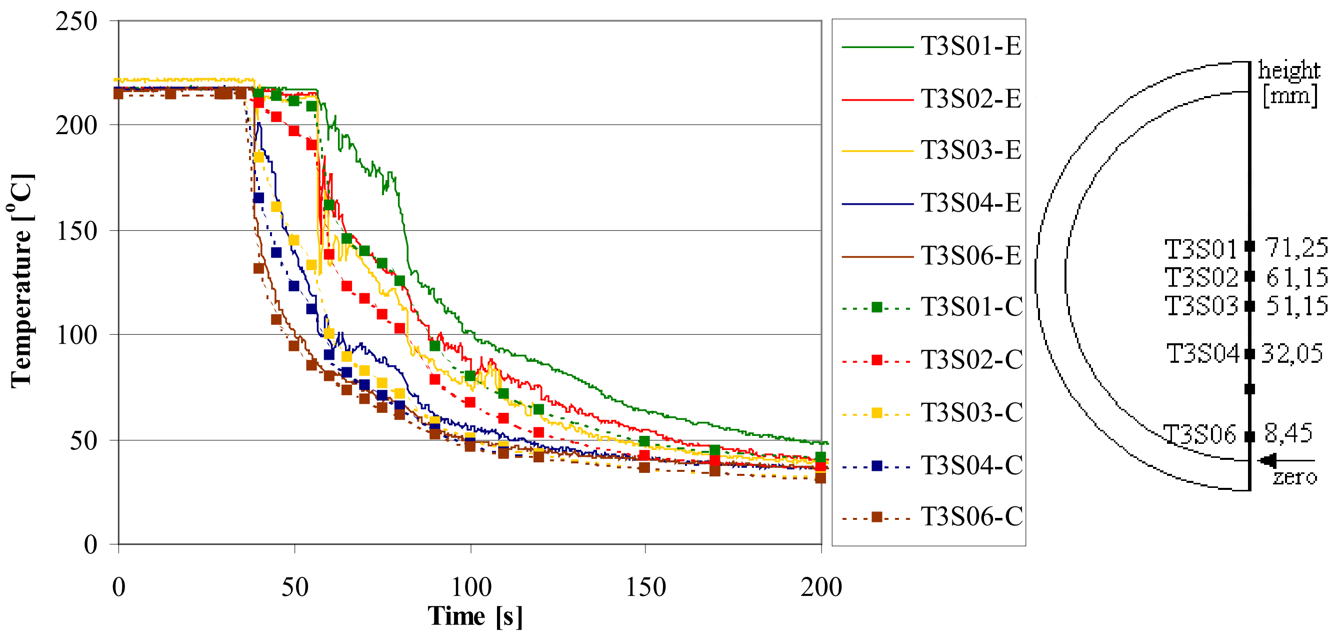

Figure 5. Experimental (E) and calculated (C) results of temperature evolution at the positions of five thermocouples on the vertical probe in the Measuring Cross Section 3.

Figure 7 shows the experimental (E) and numerically calculated (C) temperature evolution on the tube wall outlet surface, at the upper and lower positions of the Measuring Cross Section 2. The difference between these upper and lower experimental temperatures increases up to close to 140 °C, its maximal value, at the time 150 s. Figure 8 presents the temperature distribution, in longitudinal section and in the three Measuring Cross Sections, obtained by numerical method at time 80 s.

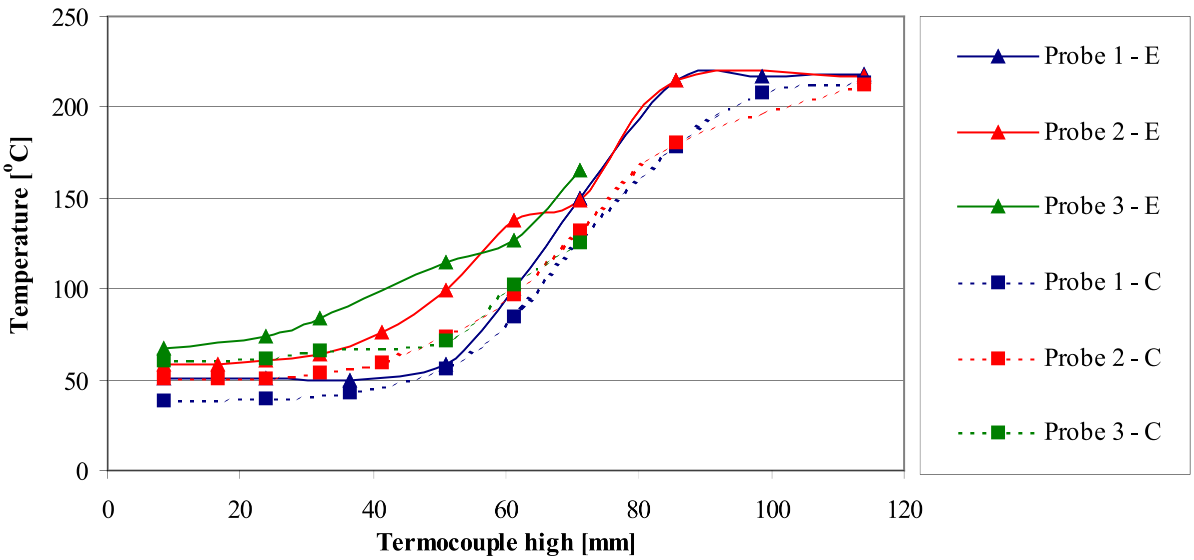

Figure 6. Experimental (E) and calculated (C) temperature distribution along the probes of the three Measuring Cross Sections at time 80 s.

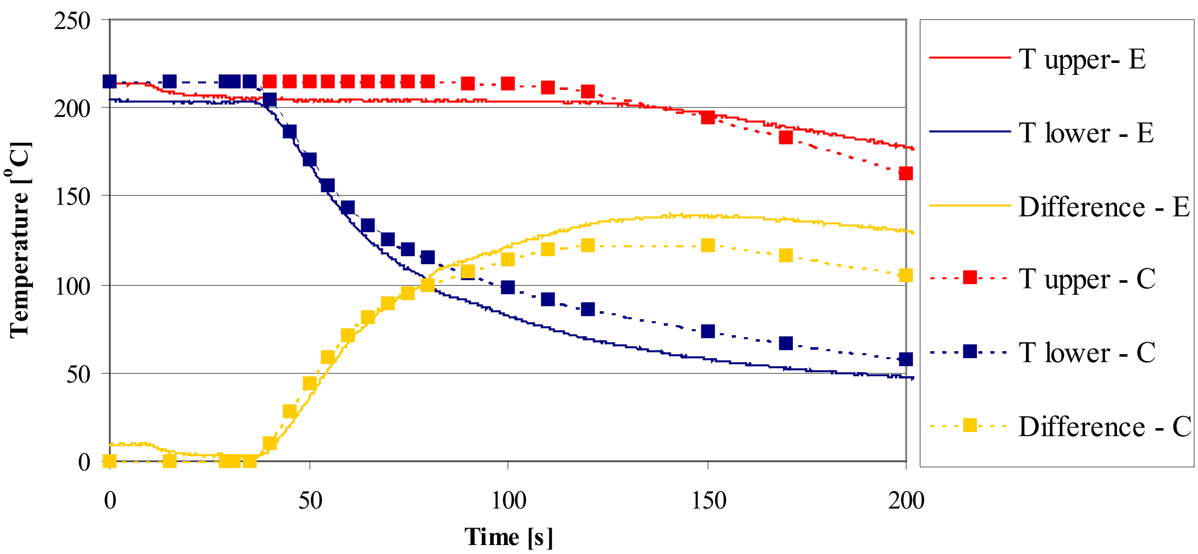

Figure 7. Experimental (E) and calculated (C) temperature evolution at the upper and lower positions on the outlet wall in Measuring Cross Section 2 and their difference.

One of the most important effects that can occur during the thermal stratification process is the striping, the temperature oscillation of the interface between the hot and cold water layers. This oscillation presents a maximum frequency of about 1 Hz, Ensel et al. (1995). For this reason the experiments data were collected in a higher frequency (3 Hz). This effect was detected during the experimental simulation at a frequency of about 0.5 Hz, as can be seen in Fig. 9 that presents the thermal evolution of the temperatures on the probe of the Measuring Cross Section 2, from time 60 s to 90 s, at five thermocouples positions. Figure 10 repeats temperature evolution at thermocouple T2S04 together with thermocouples T2I02 and T2I15 which are positioned at its same high but 3 mm close to the pipe wall, respectively in left and right sides of the cross section.

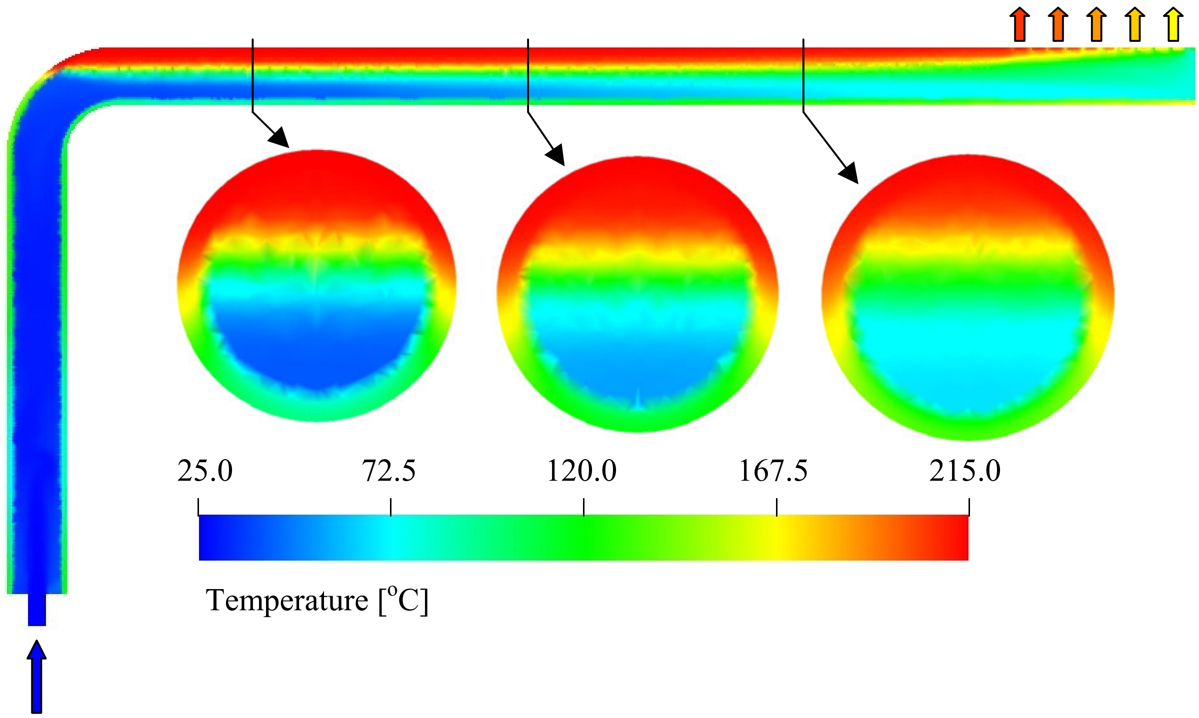

Figure 8. Temperature distribution calculated with CFX in longitudinal section and in the three Measuring Cross Sections, at time 80 s.

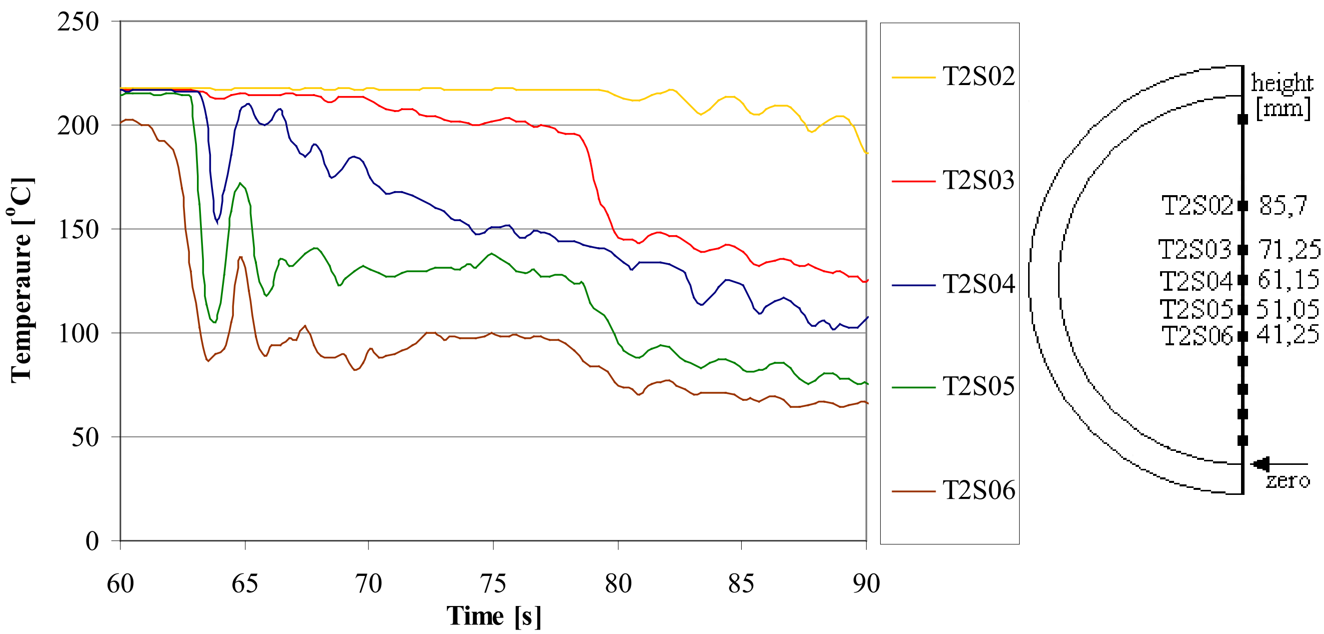

Figure 9. Experimental results showing stripping in the central region of the vertical probe of Measuring Cross Section 2.

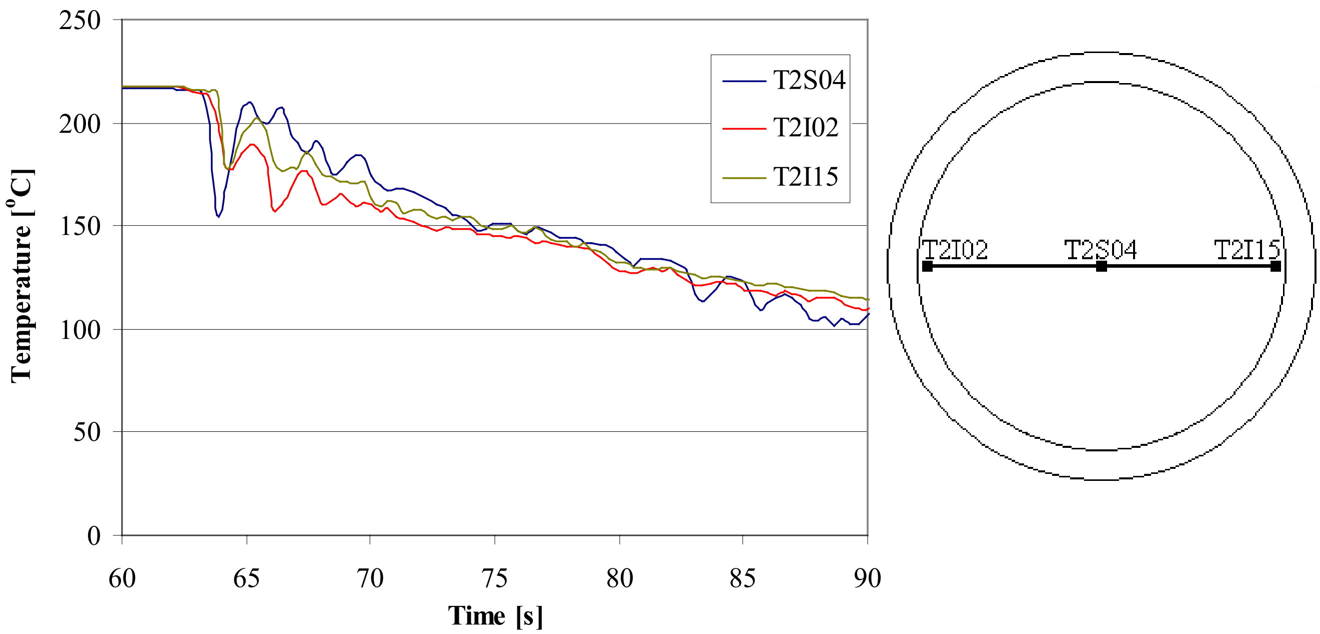

Figure 10. Stripping close to the walls (T2I02 and T2I15) and at the center (T2S04) of Measuring Cross Section 2.

5. Conclusion

The one phase thermal stratification was simulated numerically and experimentally in a piping similar to the steam generator injection nozzle at the secondary loop of a Pressurized Water Reactor (*PWR*). The simulation was carried out with a Froude number close to nuclear reactors operation ($Fr \cong 0.1$) and it was obtained a temperature gradient of about 150 °C in a narrow band around the hot and cold water interface, representing about 1/3 of the pipe diameter. These results characterize thermal stratification.

Though the numerical and experimental conditions were not exactly the same, the results present good agreements. It confirms the numerical methodology as a good additional tool for predicting the thermal stratification behavior and planning experiments.

The experimental thermocouple distribution together with the data collecting frequency was enough to detect stripping, the oscillation of the interface between cold and hot water layers. This phenomenon is one of the most important concerning thermal stratification structural damage.

6. References

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