RESULTS OF AN EXPERIMENTAL STUDY FOR THE PREDICTION OF STRATIFIED FLOWS IN NUCLEAR REACTORS PIPING SYSTEM

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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 due to low flow velocities and a great density difference. This condition may lead to considerable top to bottom temperature gradient in the pipe wall and can result in excessive differential expansion from upper to lower parts of the pipe threatening its integrity. The main parameters governing single 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. 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. 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.This paper reports some results of an experimental thermal-hydraulic study for single phase stratified flows, under operating conditions for nuclear reactors cooling piping systems. The experimental facility simulates the steam generator injection nozzle of a pressurized water reactor (PWR). The wall and water temperatures were measured with about 100 thermocouples distributed along the horizontal part of the tube. At the begin of each experiment this test facility was filled and pressurized with hot water and then cold water was injected at low flow rate in one end of the nozzle simulator tube. The simulation was carried out with Froude number close to nuclear reactors operational conditions.*

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

1. INTRODUCTION

Single phase thermally stratified flows may occur in the horizontal piping segment, where two layers of the same liquid with great temperature (and density) differences flow separately at low velocities without appreciable mixing. 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 on the pipe wall, Kim et al. (1993) and Stephens et al. (2003).

Thermal stratification has been observed in several pressurized water reactor systems for a couple of years. Piping Systems affected by stratification 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 the primary and the steam generator feed-water piping in the secondary, Häfner (1990). Temperature differences of about 200 °C can be found in a narrow band around the hot and cold water interface, Schuler and Herter (2004).

The main parameters governing single 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:

$$Fr = \frac{u_0}{\left(gD\,\Delta\rho/\rho_0\right)^{1/2}} \tag{1}$$

where,
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 methodology developed for the simulation of single phase thermally stratified flow, with $Fr \cong 0.026$ to 0.436, in a nuclear reactor steam generator nozzle. The objective was to study the flow configurations and to understand the evolution of the thermal stratification process. Some results of four experiments are also presented.

2. EXPERIMENTAL FACILITY

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

Wall thermocouples were positioned on the wall outside and fluid thermocouples were positioned along the inside wall and along the tube vertical diameter. Measuring cross section A has just three thermocouples, one on the external wall and two in the flow, to determine the time when the cold water reaches this vertical position. The fluid thermocouples positioned along the inside wall have their hot junctions positioned 3 mm away from the wall. For each one of these fluid thermocouples, a wall thermocouple was positioned in the same angular position, measuring external wall temperature, so that the temperature difference across the wall thickness could be obtained. Three probes were positioned along the vertical diameter of the measuring cross sections. Fluid thermocouples were positioned on the probes in measuring sections 1 and 2 at the same height of each thermocouple along the inside wall. Figure 2 shows the Measuring Cross Section 1 thermocouple distributions.

Water temperature was also measured with type K thermocouples in the injection piping. The injection water flow rate was determined by pressure drop measurement through an orifice plate. Finally, the system pressure was measured with a gauge pressure transducer.

Before starting the test, both the pressure vessel 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 to a cold water tank. The test begins by acting on a valve in such a 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 test finishes after a planned time.

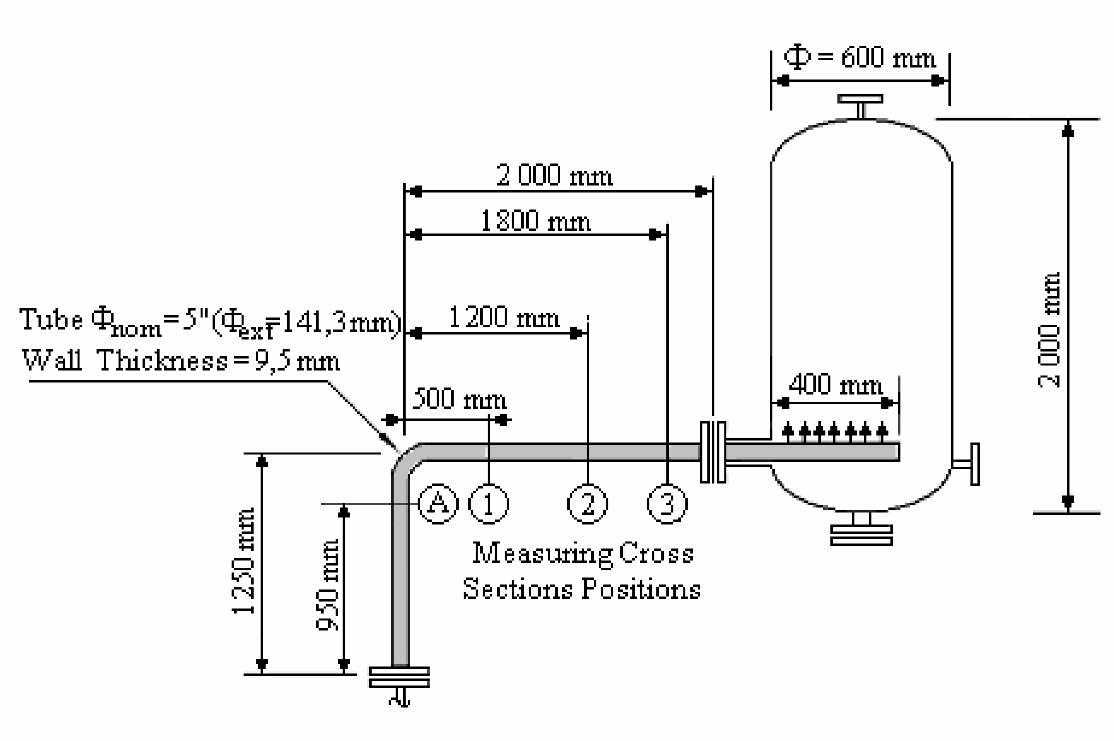

Figure 1. Diagram of the experimental test section and the position of the measuring cross sections 1, 2 and 3.

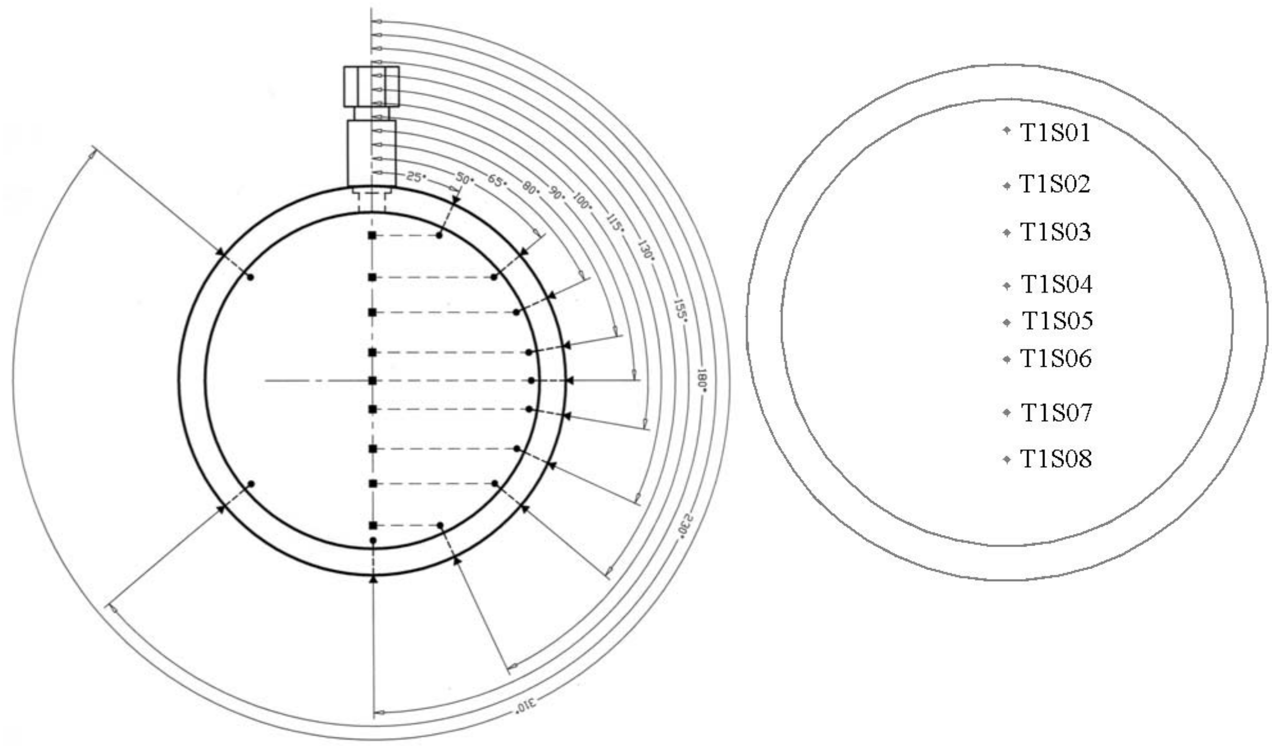

Figure 2. Thermocouple distribution at the measuring cross section I and the identification of the thermocouples positioned along its vertical probe

3. RESULTS

Results of six different tests are presented below. Table 1 shows the values of the main parameters for these tests, which were chosen to obtain a wide range of Froude Number. This variation in Froude Number is mainly due to the variation in the flow rate, but also due to the density difference between the cold and hot water. Tests 1, 2, 3 and 4 were carried out with the system pressure at about 21 bar and the hot water temperature at about 220 °C (saturated water temperature). Tests 5 and 6 were carried out with the system pressure at 10.4 bar and the hot water temperature at about 185 °C (saturated water temperature).

Figures 3, 4, 5, 6, 7 and 8 show the results for Tests 1, 2, 3, 4, 5 and 6. The results of each test are presented in four graphics. The first graphic in each figure shows the temperature evolution at the thermocouples on the vertical probe. The second graphic shows the same results for four or five thermocouples, in a time interval chosen for each test, in such way to better show the striping phenomena. However, for Tests 1 and 6, which presents respectively the lowest and the highest Froude Numbers, the results on the second graphics of Fig. 3 and 8 present a lack of definition and the phenomena could not be characterized. This graphics show the temperature evolution at four thermocouples in regions where striping was expected to occur.

Table 1. Parameter values for the tests

Test	Froude Number	Flow rate [kg/s]	Pressure [bar]	Hot water temperature [^{o}C]	Cold water temperature [^{o}C]
1	0.026	0.13	21.1	211	32
2	0.069	0.35	21.1	223	39
3	0.146	0.74	21.3	221	32
4	0.204	1.04	21.3	219	26
5	0.345	1.49	10.4	185	23
6	0.436	1.90	10.4	186	28

The striping phenomena can be seen clearly in the results of Tests 2 to 7. For Test 2, the temperature measurements with thermocouples T1S06 and T1S07 oscillated at same time with the same frequency, characterizing striping. The oscillation frequency was of about 0.4 Hz and it is the striping frequency. As the thermocouples are 14.5 mm from each other in vertical direction, the striping amplitude was equal or higher then it. Test 3 presents a similar result for thermocouples T1S04 and T1S05, with the same frequency. But the first oscillation was also detected by thermocouple T1S06, what means that the striping amplitude was at least 20.2 mm high, the distance between thermocouples T1S04 and T1S06. For Test 4, some oscillations were detected by thermocouples T1S04 and T1S05 at same time, characterizing striping with amplitude of at least 10.1 mm. Thermocouple T1S03 detected some later oscillations. For Test 5, three thermocouples detected oscillations at same time and frequency (thermocouples T1S04, T1S05 and T1S06), characterizing striping with amplitude higher then 34.7 mm, the distance between thermocouples T1S04 and T1S06. Some later oscillations were detected by thermocouples T1S03 and T1S04 together, characterizing striping with amplitude higher then 14.5 mm. Finally, thermocouples T1S02 and T1S03 detected together another period of oscillation, probably more striping, at this time with amplitude higher then 12.8 mm.

The evolution of the temperature differences between neighboring thermocouples were presented in the third graphic of Fig. 3 to 8. The maximal temperature gradient in Test 1 was obtained at about 242 s after the beginning of the test, when the difference between thermocouples T1S06 and T1S07 reached 100 °C. These thermocouples are 14.7 mm far from each other and then the maximal temperature gradient measured on the vertical probe of measuring cross section 1 was 6.8 °C/mm. During Test 2 the maximal temperature gradient measured at this probe was 9.1 °C/mm. It was obtained at about 100 s when the difference between thermocouples T1S07 and T1S08 reached 116 °C. These thermocouples are 12.8 mm far from each other. During Test 3 the maximal temperature gradient measured on the same probe was 11.9 °C/mm, at about 72 s when the difference between thermocouples T1S04 and T1S05 reached 125 °C, for a distance of 10.1 mm. For Test 4 the maximal temperature gradient measured on the probe was obtained at about 79 s when the difference between thermocouples T1S05 and T1S06 reached 150 °C. The thermocouples distance is 10.1 mm and the gradient obtained was 14.9 °C/mm. The maximal temperature gradient in Test 5 was obtained at about 61 s after the beginning of the test, when the difference between thermocouples T1S02 and T1S03 reached 122 °C. These thermocouples are 12.8 mm far from each other and then the maximal temperature gradient measured on the vertical probe of measuring cross section 1 was 9.5 °C/mm. During Test 6 the maximal temperature gradient measured at this probe was 8.8 °C/mm. It was obtained at about 459 s when the difference between thermocouples T1S01 and T1S02 reached 135 °C. These thermocouples are 15.3 mm far from each other.

Table 2 summarizes the tests results on striping and temperature gradient. From Test 1 to Test 5, there is a tendency of reducing the time for occurrence of the maximal temperature gradient by increasing the Froude Number. This tendency changes completely for Test 8, that has the largest Froude Number and a time for occurrence of the maximal temperature gradient much longer then any other test. However, this maximal temperature gradient was detected between thermocouples T1S01 and T1S02, the two highest thermocouples of the probe. It probably means that this gradient occurrence was due to a secondary cold water layer that returns over the first layer from the tube outside end after the cold water reaching it.

The fourth graphics of Fig. 3, to 8 show the evolution of the average temperature obtained from measurements with the upper wall thermocouples of each measuring cross section (T upper). The same graphics show the evolution of the average temperature obtained from measurements with the lower wall thermocouples of each measuring cross section (T lower) and also the evolution of the difference between T upper and T lower (Difference). These differences cause a difference of dilatation between the upper and lower sides of the tube, resulting in great stress in the tube wall. This average temperature difference between the upper and lower tube wall presents a maximal value of about 147 °C for Test 1, 141 °C for Test 2, 149 °C for Test 3, 155 °C for Test 4, 114 °C for Test 5 and 116 °C for Test 6.

Table 2. Striping and maximal gradient detected for the tests

Test	**Froude [*Fr*]**	**Striping**		**Maximal temperature gradient**		
		Position [Between thermocouples]	**Amplitude [mm]**	**Position [Between thermocouples]**	**Gradient [°C/mm]**	**Time [s]**
1	0.026	-	-	T1S06 and T1S07	6.8	242
2	0.069	T1S06 and T1S07	≥ 14.5	T1S07 and T1S08	9.1	100
3	0.146	T1S04 and T1S06	≥ 20.2	T1S04 and T1S05	11.9	72
4	0.204	T1S04 and T1S05	≥ 10.1	T1S05 and T1S06	14.9	79
5	0.345	T1S04 and T1S06 T1S03 and T1S04 T1S02 and T1S03	≥ 34.7 ≥ 14.5 ≥ 12.8	T1S02 and T1S03	9.5	61
6	0.436	-	-	T1S01 and T1S02	8.8	459

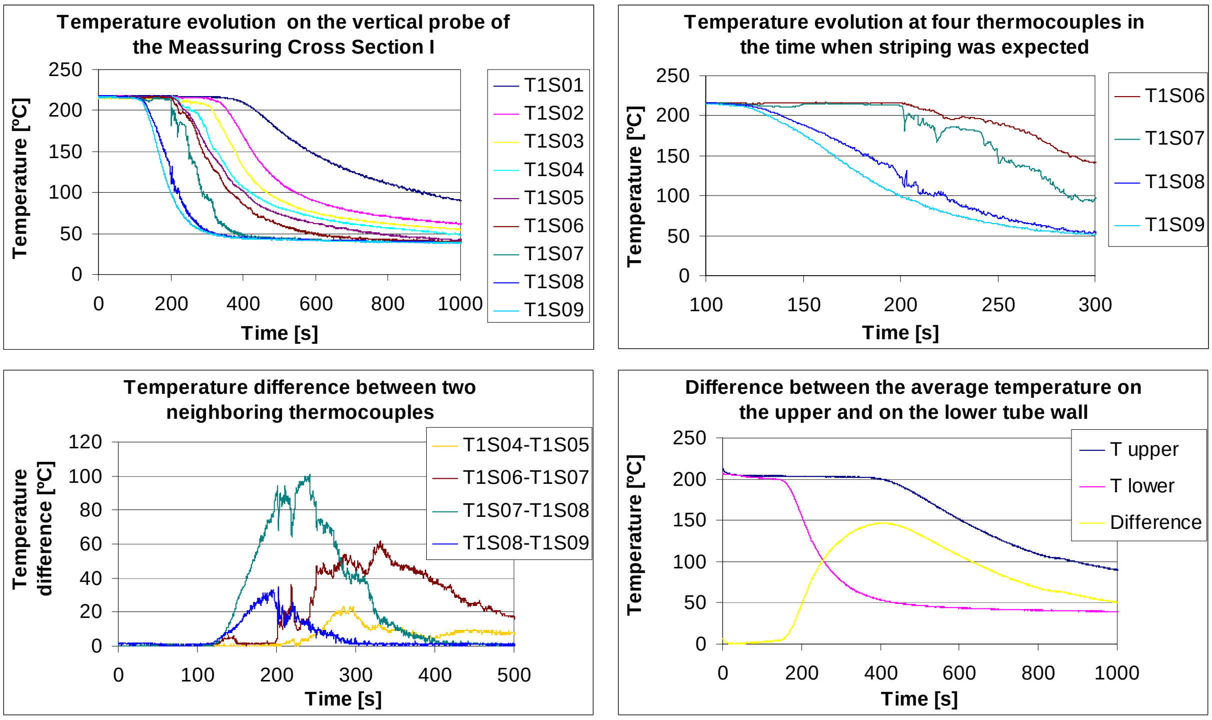

Figure 3. Results of Test 1 (Fr = 0.026)

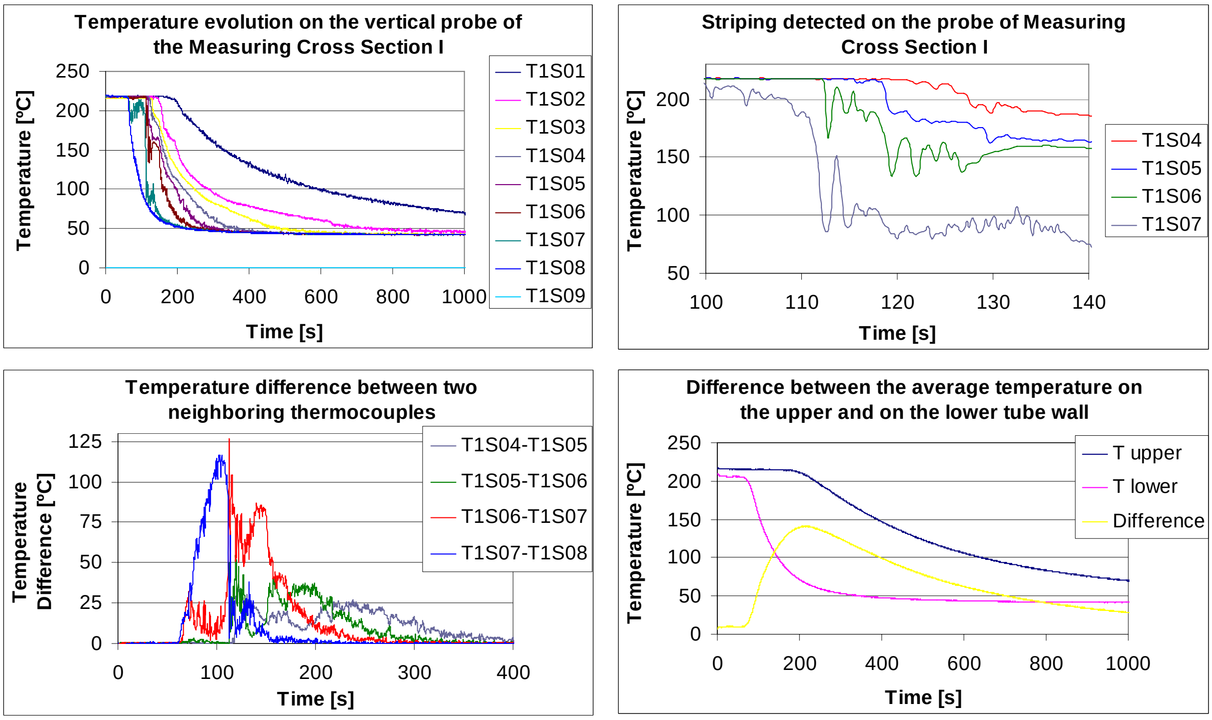

Figure 4. Results of Test 2 (Fr = 0.069)

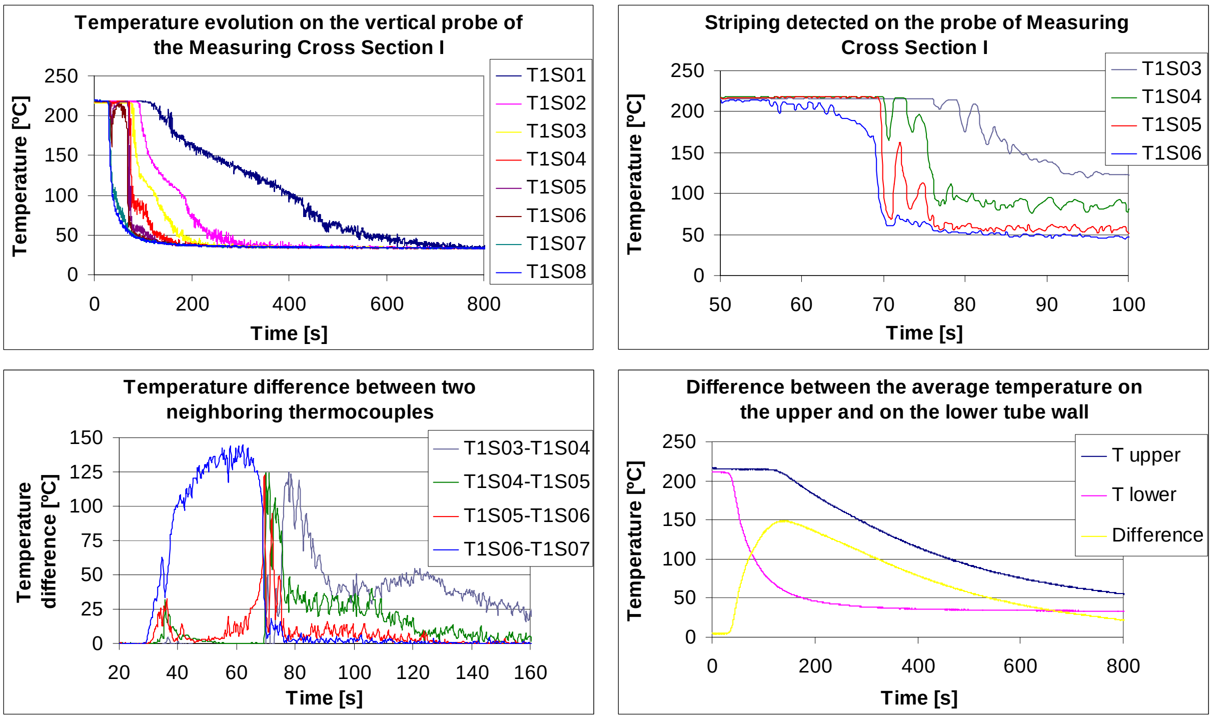

Figure 5. Results of Test 3 (Fr = 0.146)

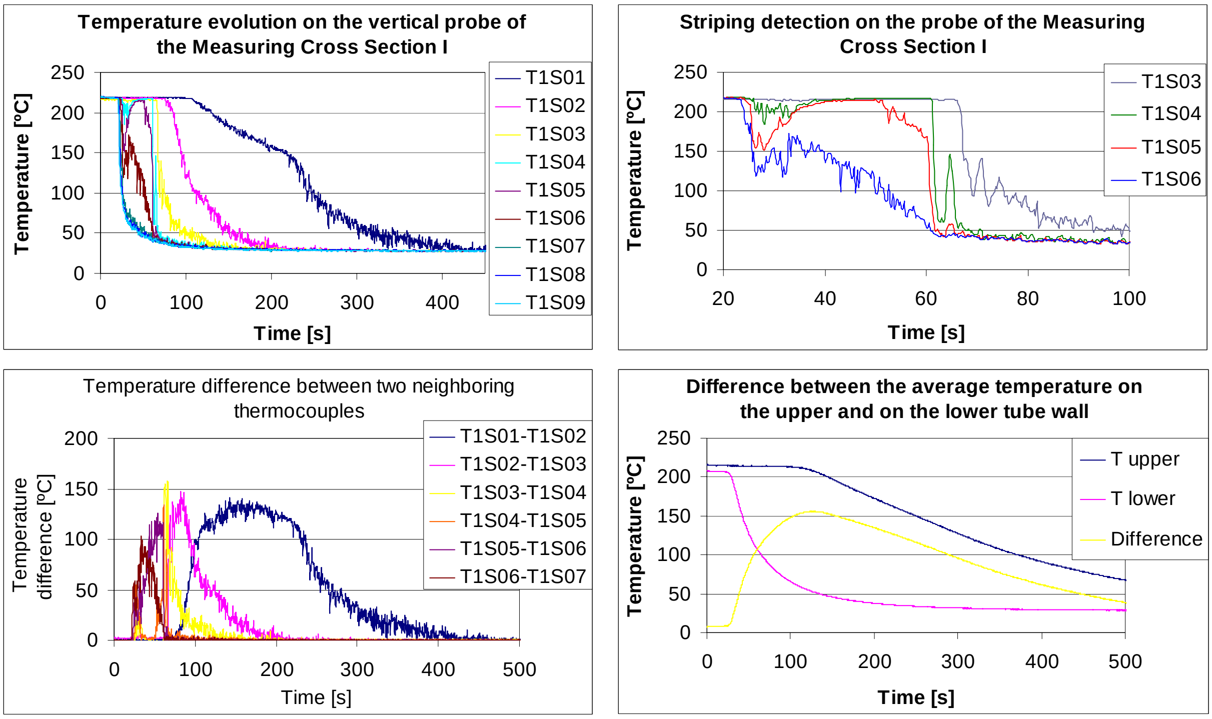

Figure 6. Results of Test 4 (Fr = 0.204)

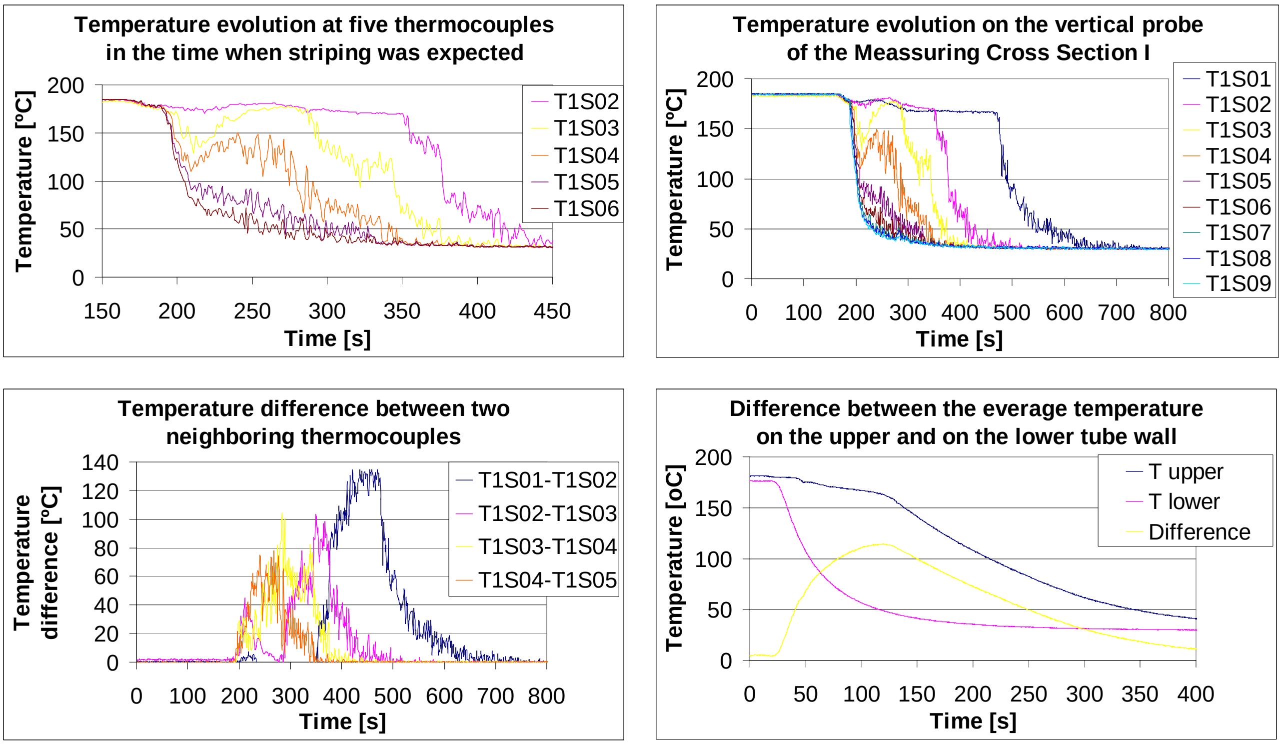

Figure 7. Results of Test 5 (*Fr* = 0.345)

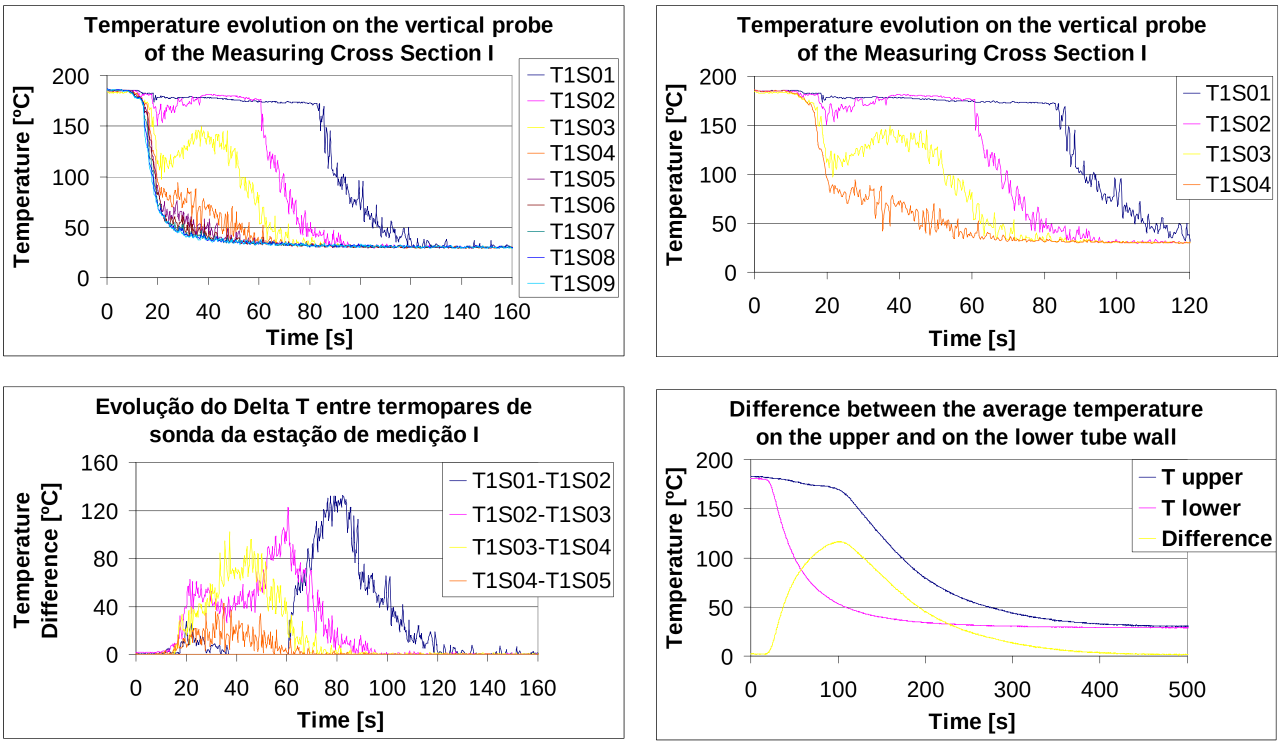

Figure 8. Results of Test 6 (*Fr* = 0.436)

4. CONCLUSIONS

The single phase thermal stratification was simulated experimentally in a piping system similar to the steam generator injection nozzle of a Pressurized Water Reactor (PWR). The test facility was filled and pressurized with hot water and then cold water was injected at low flow rate at one end of the nozzle simulator tube. The simulation was carried out with Froude number close to a nuclear reactor operation (*Fr* from 0.026 to 0.436). The wall and water temperatures were measured with about 100 thermocouples distributed along the horizontal part of the tube. Results of three tests were presented. High temperature gradients around the interface between the hot and cold water layer were obtained in all the tests, characterizing thermal stratification. The maximal temperature gradient obtained in the water was 14.9 °C/mm and was detected in a vertical probe during the test with Froud number of 0,204. The striping phenomenon, the oscillation of the hot and cold interface, was detected during four tests.

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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