Científica, Vol.15 Núm. 1, pp. 17-24, enero-marzo 2011.
ISSN 1665-0654, ESIME Instituto Politécnico Nacional MÉXICO.

Experiments on One-Phase Thermally Stratified Flows in Nuclear Reactor Pipe Lines

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Recibido el 3 de mayo de 2010; aceptado el 28 de noviembre de 2010.

1. Abstract

The one-phase thermal stratified flow phenomenon occurs when two different layers of the same liquid at different temperatures flow separately in horizontal pipes without appreciable mixing. This phenomenon was not considered in the design stage of most of the operating nuclear power plants, but in last two decades it has become apparent due to the temperature monitoring of piping systems. The occurrence of temperature differences of about 200ºC have been found in a narrow band around the hot and cold water interface in components under stratified flows. Loadings due to thermal stratification affected the integrity of safety related piping systems.

This paper presents the results of a range of experiments performed to simulate one phase thermally stratified flows in geometry and flow condition representing a nuclear reactor steam generator injection nozzle. They have 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 0.018 to 0.22, were obtained in different testes by setting injection cold water flow rates and hot water initial temperatures as planned in the test matrix. Results are presented showing the influence of Froude number on the hot and cold water interface position, temperature gradients and striping phenomenon.

Key words: thermal stratification, nuclear reactor, thermal hydraulic.

2. Resumen (Experimentos de simulación de flujo monofásico térmicamente estratificado en la tuberías de los reactores nucleares)

El fenómeno del flujo monofásico térmicamente estratificado ocurre cuando dos camadas de un mismo fluido, a distintas temperaturas, fluyen separadamente en un tubo horizontal, sin mezcla significativa entre ellas. Dicho fenómeno no fue tomado en consideración en la fase del proyecto de gran parte de las centrales nucleares que hoy día están en operación. Sin embargo, en las últimas dos décadas, tal fenómeno ha aparecido frecuentemente en el monitoreo de las temperaturas de los sistemas de canalización. Diferencias de temperatura del orden de los 200ºC han sido observadas en una faja bastante estrecha, en torno de la interface entre las camadas de agua caliente y fría, en componentes sometidos a la estratificación térmica. Las tensiones debido a ese grado de estratificación térmica comprometen la integridad estructural de las tuberías relacionadas con la seguridad de las centrales nucleares.

El presente trabajo presenta algunos resultados en una amplia gama de experimentos simulando el flujo monofásico térmicamente estratificado en una geometría y condiciones de flujo simulando el bocal de inyección del generador de vapor de un reactor nuclear. Tales resultados tienen el objetivo de estudiar las condiciones del flujo y la evolución del proceso de estratificación térmica. El principal parámetro utilizado en la caracterización de los flujos estratificados debido a la diferencia entre las masas específicas es el número de Froude. Distintos números de Froude, entre el 0.018 y el 0.22, fueron obtenidos en distintos experimentos, por el ajuste del flujo de inyección del agua fría y de la temperatura inicial del agua caliente, conforme planeado en la matriz de prueba. Los resultados están presentados aquí y muestran la influencia del número de Froude en la posición de la interface entre las camadas de agua caliente y fría, en los gradientes de temperatura y en el fenómeno de la oscilación de la interface (*striping*).

Palabras clave: estratificación térmica, reactor nuclear.

3. Introduction

The material fatigue of the nuclear power plants piping caused by thermal stratified flows may threaten the integrity of the pipes and limit its lifetime. Single phase thermally stratified flows occur in 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*. [1].

Thermal stratification has been observed in several pressurized water reactor systems for a couple of years and is crucial in the aging management and for the lifetime-extension of nuclear power plants. 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 [2]. Temperature differences of about 200°C can be found in a narrow band around the hot and cold water interface, Schuler and Herter [3].

Bieniusa and Reck [4] describe a methodology to calculate thermal stratification stress intensity with a simplified two-dimensional model. Ross *et al*. [5] examined several technical codes of fatigue analysis. Kim *et al*. [6] investigate some conditions that could influence the thermal stratification mechanisms. Kweon *et al*. [7] studied peak stress intensity due to many loadings including thermal stratification.

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

$$Fr = \frac{u_0}{(gD\Delta\rho/\rho_0)} \qquad (1)$$

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 for the simulation of single phase thermally stratified flow in a nuclear reactor steam generator nozzle, with Froude Number ranging from 0.018 to 0.22, obtained by the cold water injection velocity from 0,0099 to 0,0989 m/s and the hot water temperature from 140°C to 219°C. The objective was to understand the evolution of the thermal stratification process.

4. Experimental facility

The Experimental Facility for Thermal Stratification (ITET) allowed characterizing stratified flow regimes for different piping system and operation conditions. Figure 1 shows a

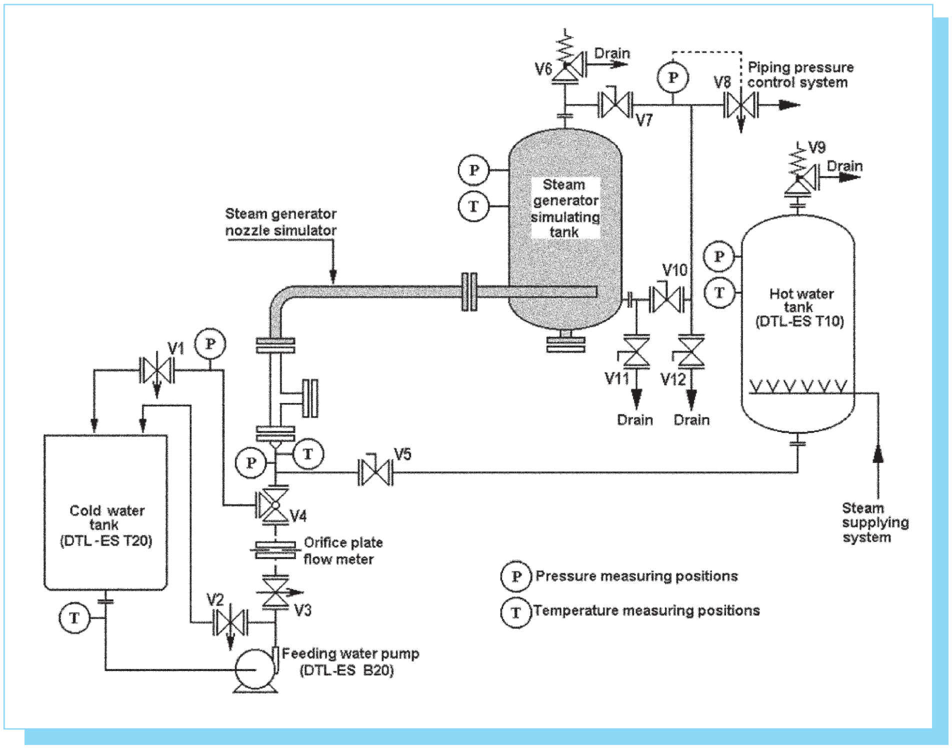

Fig. 1. Diagram of the experimental facility for thermal stratification (ITET).

diagram of the facility with the test section for the simulation of the steam generator injection nozzle in gray. This test section is made up of a pressure vessel simulating the steam generator tank and a tube simulating its injection nozzle. It simulates start up conditions at the injection nozzle.

Before the beginning of each test the whole system is filled with cold water and then it is pressurized and heated by steam. A temperature equalization pump ensures a homogeneous heating of the entire system. After the heating process, the equalization pump is turned off and the equalization lines are isolated. The steam supply is also isolated by closing valve V5. The tests began by acting on valve V4 moving the cold water flows into the nozzle simulator pipe, through its lower end. 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 (V6) and relieve (V8) 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.

Figure 2 detailed the test section. Type K thermocouples, 0.5 mm in diameter, were distributed in four measuring cross sections (1, 2, 3 and A) to measure wall and fluid temperatures. On the measuring cross sections 1, 2 and 3 wall thermocouples were positioned on the wall outside and fluid thermocouples were positioned along the inside wall and along the tube vertical diameter. 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 at the same angular position, measuring external wall temperature. Probes were positioned along the vertical diameter of each measuring cross sections for positioning fluid thermocouples, at the same height of most of the thermocouples along the inside wall. Measuring cross section A has just three thermocouples to determine the time when the cold water reaches their position

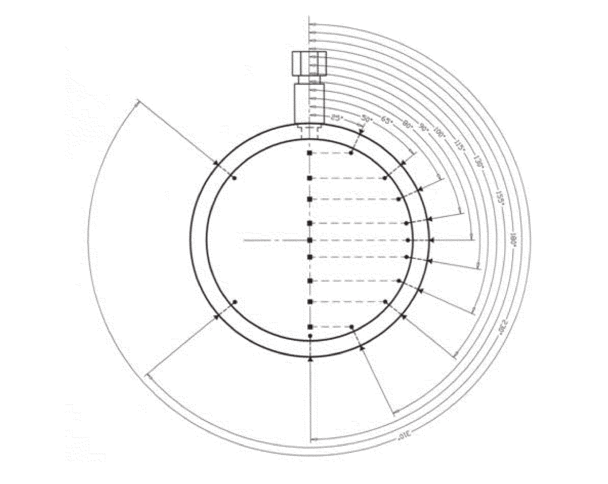

Fig. 3. Thermocouple distribution at the measuring cross section 1.

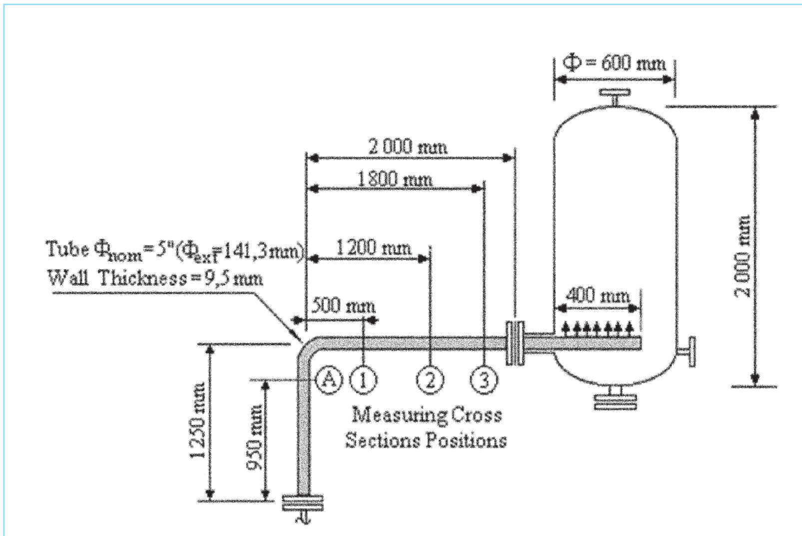

Fig. 2. Experimental test section diagram with the position of the Measuring Cross Sections 1, 2 and 3.

Figures 3, 4 and 5 show, respectively, the thermocouple distribution in the Measuring Cross Sections 1, 2 and 3. The thermocouples positioned on the probes along the vertical diameter were named as TiSjj, where i is the number of the Measuring Cross Section (1, 2 or 3) and jj is the number of the thermocouple position from top to bottom (from 01 to 09 on Measuring Cross Section 1, from 01 to 10 on Measuring Cross Section 2 and from 01 to 06 on Measuring Cross Section 3). Water temperature was also measured with type K thermocouples in the injection piping.

The injection water flow rate was determined by a set of orifice plate and differential

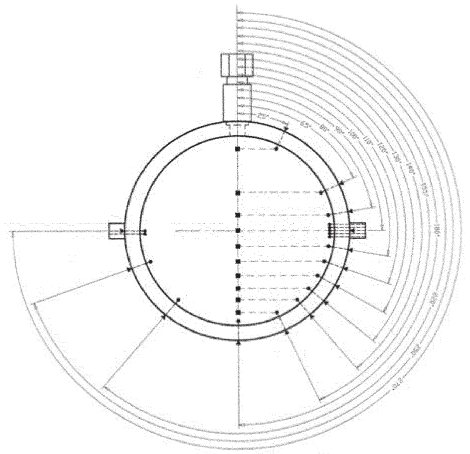

Fig. 4. Thermocouple distribution at the measuring cross section 2.

pressure transducer. The system pressure was measured with a gauge pressure transducer and, finally, the water level in the steam generator simulation tank was also measured with a differential pressure transducer.

5. Results

5.1. Temperature difference between two neighbouring thermocouples

Results of two different tests are presented below to illustrate the typical temperature distribution on the vertical probes. Table 1

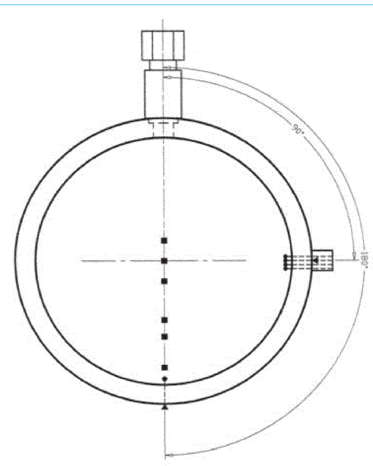

Fig. 5. Thermocouple distribution at the measuring cross section 3.

Table 1. Parameter values for the tests.

Test	Fruode number	Flow rate [kg/s]	Pressure [bar]	Hot water temperature	Cold water temperature
1	0.069	0.35	21.1	223	39
2	0.146	0.74	21.3	221	32

shows the values of the main parameters for these tests, with different Froude Numbers. As both the tests were carried out at pressures close to 21 bar, and hot water temperature close to 220°C, the difference in Froude Number was mainly due to the difference in the flow rate. The pressure value in Table 1 was measured at the steam generator simulating tank and there is a loss of pressure through the exit holes from the tube simulating injection nozzle to this tank.

Figures 6-9 show some results for Tests 1 and 2, two graphics with results of each test. The graphics in figures 6 and 8 show the temperature evolution at the thermocouples on the vertical probe at the Measuring Cross Section 1 respectively for Tests 1 and 2. The graphics in figures 7 and 9 show the evolution of the temperature differences between neighbouring thermocouples also respectively for Tests 1 and 2.

The maximum temperature gradient in Test 1 was obtained at about 104 s after the beginning of the test, when the difference between thermocouples T1S06 and T1S07 reached 126°C. These thermocouples are 9.2 mm far from each other, and the maximum temperature gradient obtained was then 13.7°C/mm. During Test 2 the maximum temperature differences between neighbouring thermocouples was obtained at about 62 s when the difference between thermocouples T1S06 and T1S07

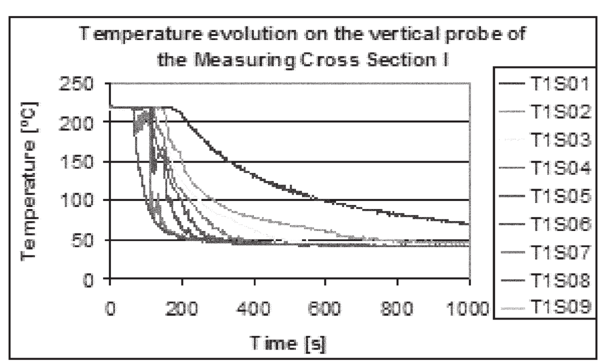

Fig. 6. Results of test 1.

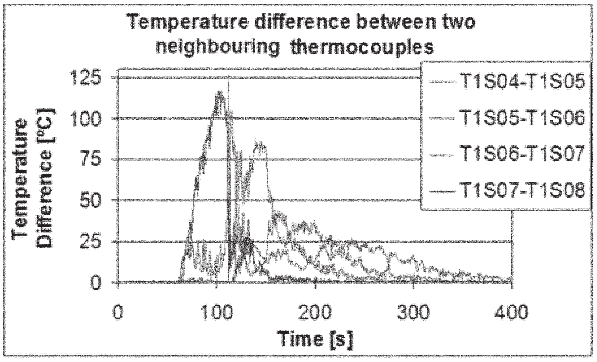

Fig. 7. Results of test 1.

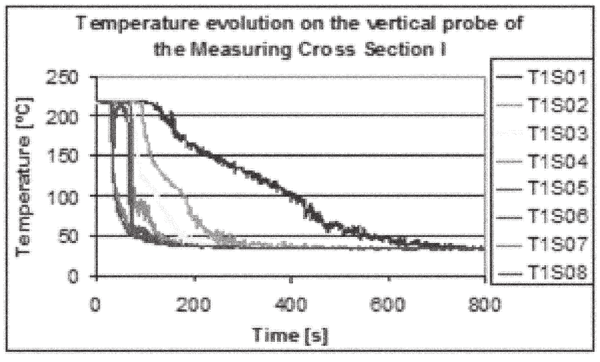

Fig. 8. Results of test 2.

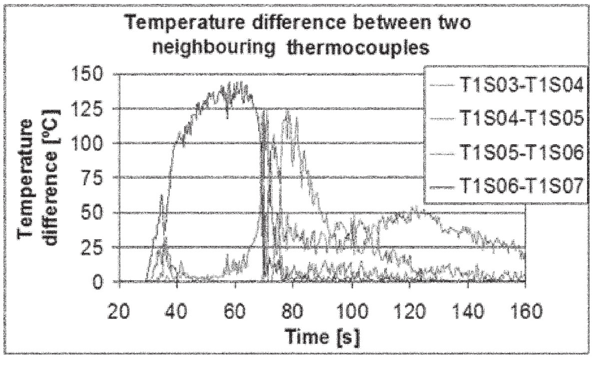

Fig. 9. Results of test 2.

reached 145°C. The maximum temperature gradient was then 15.8°C/mm.

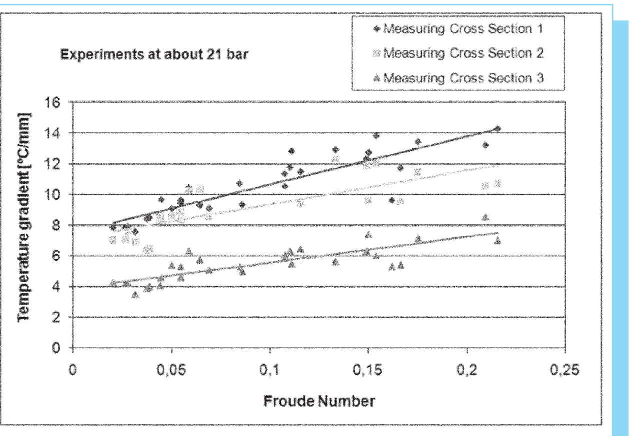

Fig. 10. Maximum measured temperature gradient as a function of Froude Number at each measuring cross section for the tests at 21 bar.

5.2. Temperature gradient as a function of froude number

The test matrix includes tests at two different pressure levels, at about 23 bar gauge (t_{sat} = 220°C) and at about 10.5 bar gauge (t_{sat} = 185°C). The results of these two groups of tests are presented here separately. Tests were done with Froude Number from 0.018 to 0.22. A graphic with the maximum measured temperature gradient at the vertical diameter for each measuring cross section as a function of the Froude Number is shown in Figure 10, for the tests at 21 bar. Figure 11 shows the same for the tests at 10.5 bar.

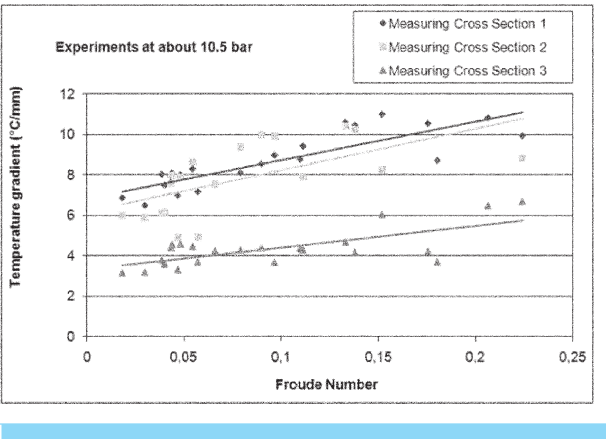

Fig. 11. Maximum measured temperature gradient as a function of Froude Number at each measuring cross section for the tests at 10.5 bar.

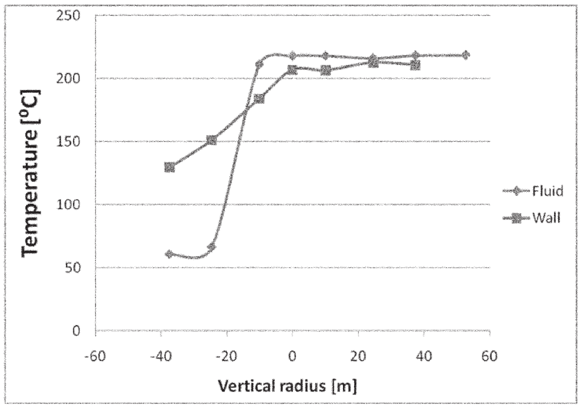

Fig. 12. Vertical temperature distribution at time 60 s of Test 2 at Measuring Cross Section 1.

5.3. Temperature distribution on the outside wall

The abrupt vertical temperature change close to the interface between the cold and the hot water is not reproduced on the piping wall, due to the heat conductivity of the metallic wall, as can be seen in Figure 12. However, there were observed great top to bottom temperature gradients that are enough to threaten the piping structural integrity. Figure 12 compares the temperature distribution in the fluid along the vertical diameter probe with the temperature distribution along the piping wall, at time 62 s of Test 2, at measuring cross section 1. The maximum temperature gradient for Test 2 was obtained at this time (15.8 C/mm), when the difference between thermocouples T1S06 and T1S07 reached 145°C.

In dealing with top to bottom temperature differences, top temperatures for Measuring Cross Sections 1 and 2 were considered as the average temperature measured with the thermocouples at the top region, the top quarter of the pipe wall on Figures 13 and 14, and bottom temperatures were considered as the average temperature measured with the thermocouples at the bottom region, the bottom quarter of the pipe wall on Figures 13 and 14. Measuring Cross Sections 3 was not considered because there is no thermocouple at its top region.

The evolution of the top to bottom temperature difference for Test 1 is shown in Figure 15 for Measuring Cross Section 1 and in Figure 16 for Measuring Cross Section 2. The maximal temperature differences were 124°C for Measuring Cross Section 1, obtained at 94 s, and 147°C for Measuring Cross Section 2, obtained at 140 s. There was not notice any clear dependence of top to bottom temperature difference with the Froude Number in the range of the experiments.

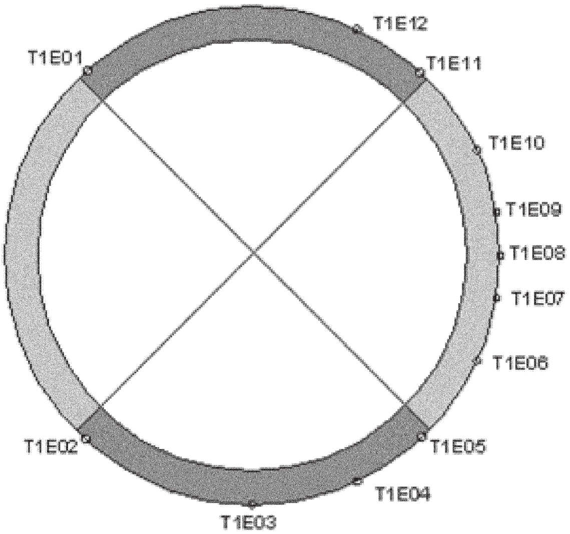

Fig. 13. Measuring Cross Sections 1 with thermocouples and top region and bottom region in dark.

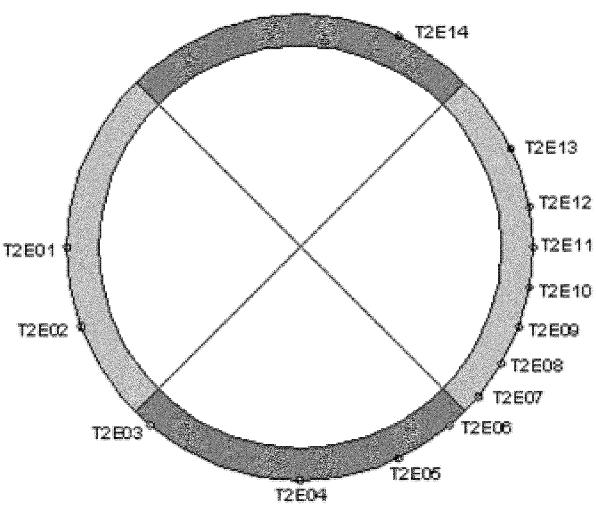

Fig. 14. Measuring Cross Sections 2 with thermocouples and top region and bottom region in dark.

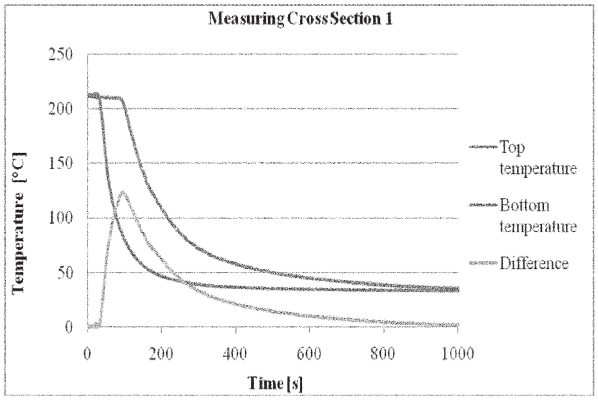

Fig. 15. Temperature evolution on Measuring Cross Section 1 for Test 2.

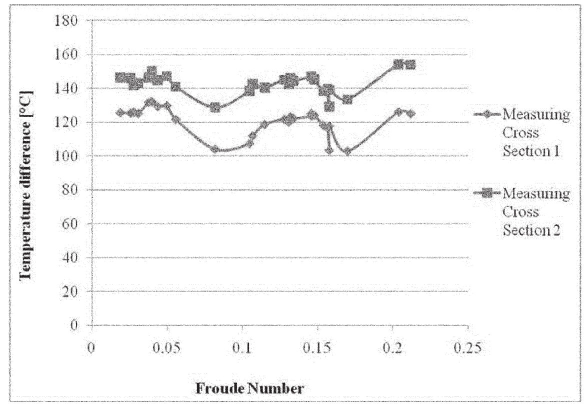

Fig. 17. Top to bottom temperature difference as a function of Froude Number.

Figure 18 shows this top to bottom temperature difference for 27 tests ranging from 0.019 to 0.212 Froude Number. These tests were carried out with the system pressure at about 21 bar, corresponding to a hot water temperature close to 220°C (saturated water temperature). Another consideration was the lasting time for a high temperature difference. It was considerate arbitrarily that temperature difference over 80°C was high enough for threatening structural integrity of the piping. Silva [8] observed grain enlargement at this condition. Figure 17 presents the lasting time of top to bottom temperature difference over 80°C as a function of Froude Number. A great dependence of the lasting time with the Froude Number was observed only for Fr = 0.05.

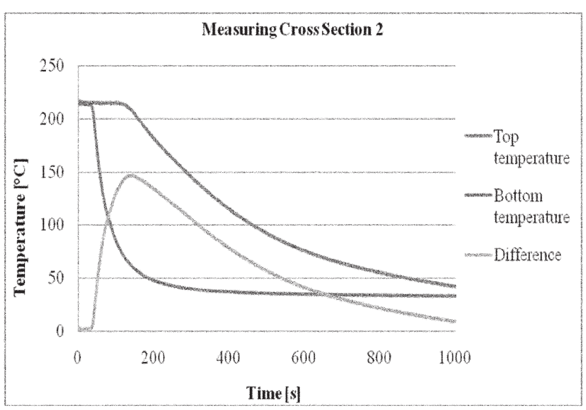

Fig. 16. Temperature evolution on Measuring Cross Section 2 for Test 2.

6. Conclusion

The one 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 0.018 to 0.22). The wall and water temperatures were measured with about 100 thermocouples distributed along the horizontal part of the tube. Temperature gradients up to 14°C/mm were obtained in a narrow band around the interface between

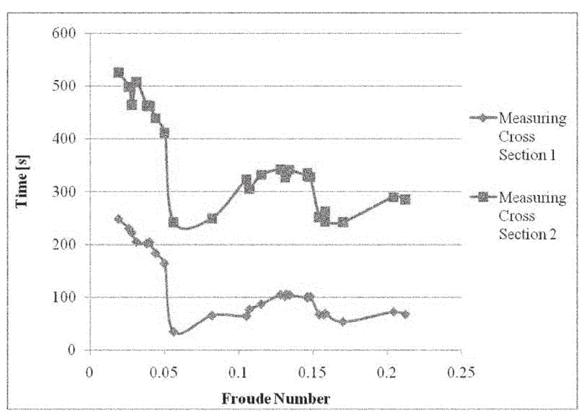

Fig. 18. Lasting time of top to bottom temperature difference over 80ºC as a function of Froude Number.

the hot and cold water layer, characterizing thermal stratification. Results are presented showing the measured vertical temperature gradient in the fluid and in the piping wall as a function of the Froude Number.

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