

EXPERIMENTAL METHODOLOGY ON THERMALLY STRATIFIED FLOWS IN NUCLEAR REACTORS PIPING

Hugo Cesar Rezende
Centro de Desenvolvimento da Tecnologia Nuclear - CDTN/CNEN, Caixa Postal 941, 30.161-970 – Belo Horizonte, MG, Brazil, e–mail: hcr@cdtn.br

Ramon Molina Valle
Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais – DEMEC / UFMG, Cidade Universitária, 30.270-901, Belo Horizonte, MG Brazil. e–mail: ramon@vesper.demec.ufmg.br

Abstract. *This paper summarizes the experimental study for thermally stratified one phase flow conditions that is part of an ongoing research project at CDTN / CNEN. The study aims for the investigation of the stratification phenomenon under various operating conditions for nuclear reactors cooling systems piping. It covers simultaneously two objectives: the study of the effects of parameters like pressure, hot and cold water flows and temperature, and the resulting pipe loads. The experimental facility is presented here.*

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

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 situation, 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, 1993):

– 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 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, pressurizer spray lines, charging 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 nozzle in the secondary (Häfner, 1990). Figure 1 shows the primary cooling loop of a pressurized water reactor, with the steam generator, where the water in the primary loop coolant transfer heat to the water in the secondary loop.

To assess the potential for piping damage due to the thermal stratification, it is necessary to determine the transient temperature distributions in the wall of the pipe. This paper summarizes the experimental methodology now in development at Centro de Desenvolvimento da Tecnologia Nuclear – CDTN / CNEN, for the simulation of one phase thermally stratified flow in nuclear reactor piping. It has the objective of studying the flow configurations and understanding the influence of characteristic parameters, such as pressure, injection flow rate and temperature difference, on the evolution of the of thermal stratification process, besides its structural consequences for the piping. The initial experiments will simulate the steam generator nozzle.

2. The proposed experiment

2.1 The experimental facility DTL-ES

The experiment of one phase thermally stratified flow is already being set up in a pre-existent experimental facility in the Thermal-Hydraulic Laboratory of CDTN, the LOCA Tests Device – Separated Effects (DTL–ES), built for the simulation of a Loss of Coolant Accident (LOCA), in a pressurized water reactor (PWR). DTL–ES allows experimental simulation of the two-phase phenomena that occur during a LOCA. The one phase thermally stratified flows experiments used DTL–ES for supplying hot and cold water at high pressure (up to 2 300 kPa). The first experiment to check and adjust the experimental methodology will simulate the steam generator feed water nozzle. It was necessary the inclusion of a new water supplying piping, another pressure tank to simulate the steam generator, an instrumented tube to simulate the steam generator nozzle and a new pressure relive piping system to allow the pressure control in the experimental facility.

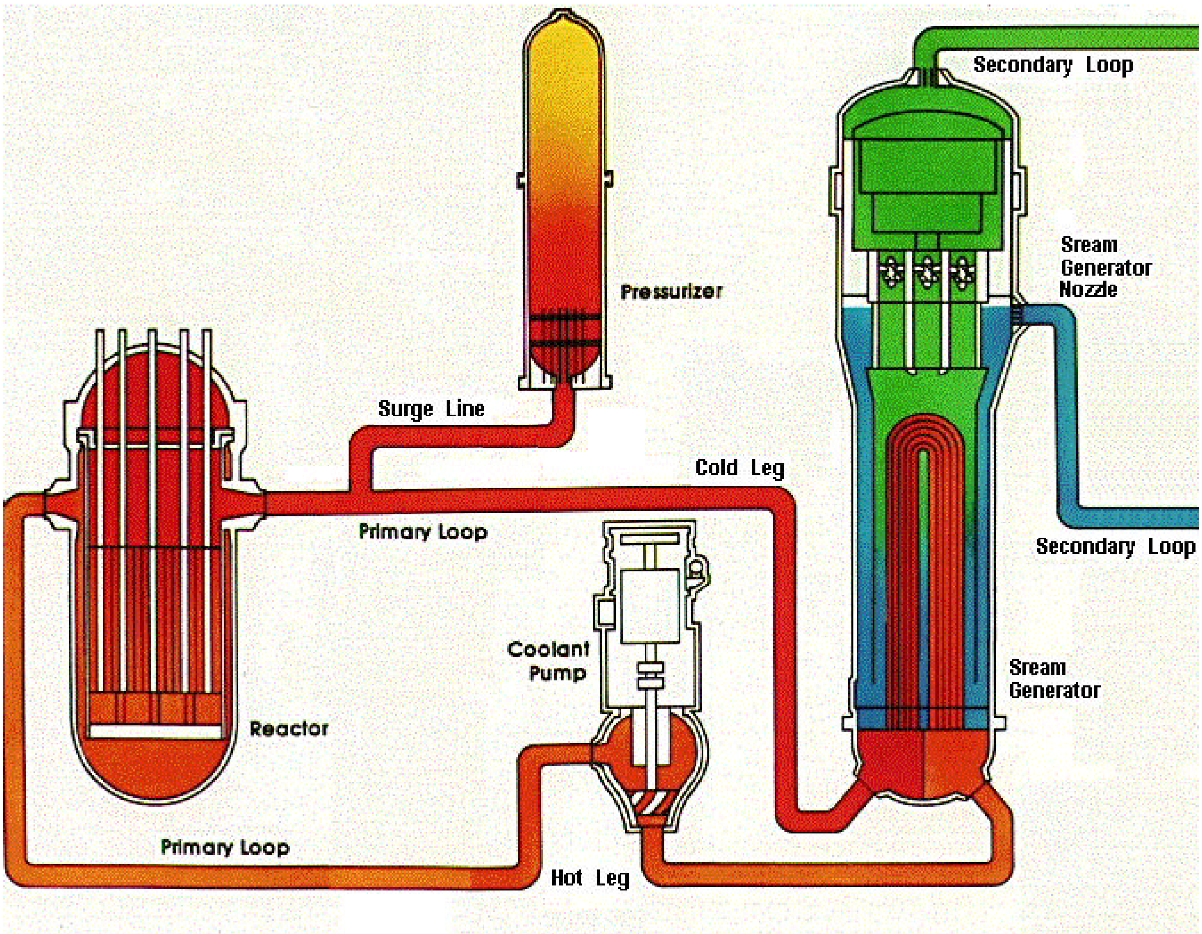


Figure 1. Primary loop of a pressurized water reactor.

2.2. The steam generator nozzle simulation

A schematic diagram of the experimental facility is shown in Figure 2. This facility was project to allow the study of the phenomenon of one phase thermally stratified flows in two different geometry. Initially, it was assembled in the way shown in continuous lines in Figure 2. In this way, that simulated the steam generator feed water nozzle, the pressure tank simulates the steam generator and the instrumented tube simulates the nozzle. Before the starting of the tests, both the tank and the tube will be filled with hot water from tank T10. Soon after, the hot water supply piping will be isolated, by closing the valve V5. Then, the feeding water pump is turned on when the by pass valve V2 is completely opened and the three ways valve V4 deviates the injection flow back to tank T20. The cold water flow rate through the turbine flow meter is set up together with the piping pressure by adjusting valves V1, V2 and V3. The test begins by acting on valve V4 in way the cold water flows in the steam generator nozzle simulator. The system pressure is maintained constant by the upstream pressure control valve (V8) in the drain line, that relieves controlled amount of steam.

One phase thermally stratified flow may occur in the steam generator nozzle when the reactor system undergoes an operational transient. During the start up of the reactor, the secondary loop water inside the steam generator is heated and flows back in the feed water nozzle, because of its thermal expansion. Then, the coolant circulation in the secondary loop begins slowly, and the cold water, at small circulating velocity, meets the heated water in the nozzle and flows in the lower side of the pipe without appreciable mixing, in a stratified way. Therefore, the first phase of the experiments will simulate the evolution of this stratification process along the length of the nozzle. These experiments will reproduce the progress of the cold water layer under the hot water layer during operational transients, particularly the process of start up of the reactor and, possibly, the back flow of hot water from the pressurizer in the nozzle.

The dashed lines in Figure 2 show the way the same experimental facility can be used for the simulation of the pressurizer surge line. In this way, the pressure tank simulates the pressurizer and the instrumented tube simulates the surge line. Here the tube is filled, initially, with cold water and the one phase stratified flow is obtained by injecting hot water in low velocity, from the pressurizer simulation tank into the surge line simulation tube. In the actual surge lines one phase thermally stratified flow may occur during the pressurization process when heated water flowing in low velocity from the pressurizer meets cold water in the pipe.

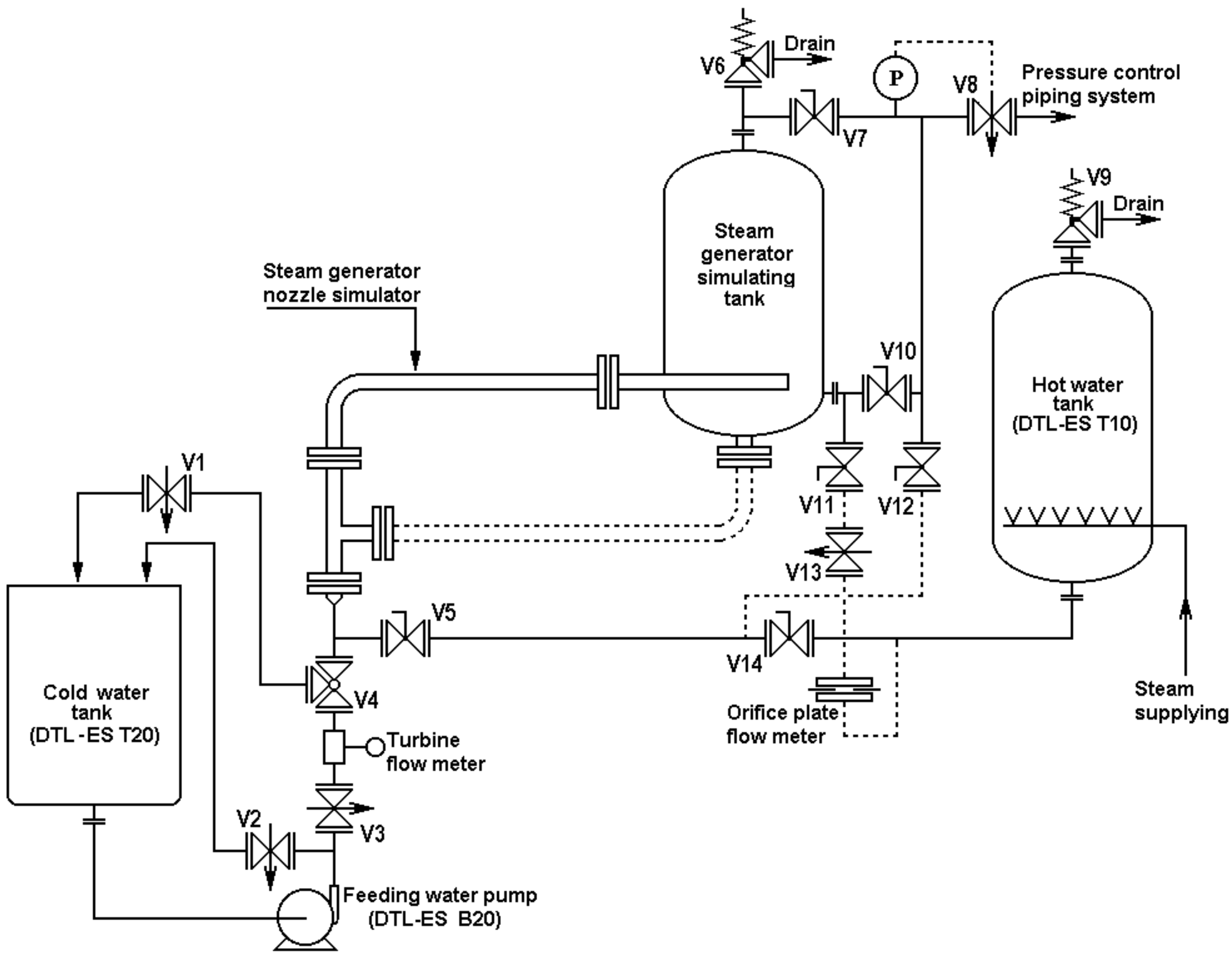


Figure 2. Schematic diagram of the experimental facility.

Figure 3 shows some more details of the experimental facility as built for the steam generator feed water nozzle simulation. The nozzle simulator constitutes of a standard stainless steel tube, 2000 mm length, 141.3 mm outside diameter and 9.5 mm of wall thickness. At one end of the tube there is a welded 90° curve and then more 500 mm of the same tube. At the other end there is a flanged piece of the same tube that penetrates 450 mm inside the steam generator simulator tank. The inner end of this tube is plugged and the water can flow to the tank through 11 holes with 12 mm in diameter at the up side of the tube.

2.3. The measuring instruments distribution

The problem of investigating the thermal stratification in a pipe is very complex since stratification induces local stresses and a pipe curvature, as a result of the non-linearity of the temperature distribution over a cross-section, even in unrestrained pipes. The stresses at a given location in a restrained pipe submitted to stratified flow are therefore a function not only of the local temperature distribution but also of the curvatures induced by the stratification at all other locations. Usually the stratification pattern is variable along the length of the pipe. The local temperature distribution as well as the linear thermal gradient must be obtained from the monitoring sensors. To reach a sufficient accuracy, a minimum of five temperature measurement points per cross section are required and a minimum of three measurement cross section along the length of the instrumented tube must be used. Therefore, six cross sections along the length of the nozzle simulator were chosen for the measuring instruments distribution. These positions, called measuring positions A, B, C, I, II and III, are shown in Figure 3. The measuring positions I, II and III, were instrumented with thermocouples and with strain gauges, the measuring positions B and C just contain strain gauges and the measuring position A contains only one strain gauge rosette and two thermocouples.

2.3.1. Temperature measurements

Fluid and wall temperatures are measured in measuring positions I, II, III and A with K type thermocouples (chromel / alumel), 0.5 mm in diameter. Wall thermocouples were distributed on the wall outside and fluid thermocouples were distributed in two ways: along the inside wall, 3 mm far from it, and along the tube vertical diameter. Figures 4, 5 and 6 show the thermocouples distribution in the measuring positions I, II and III.

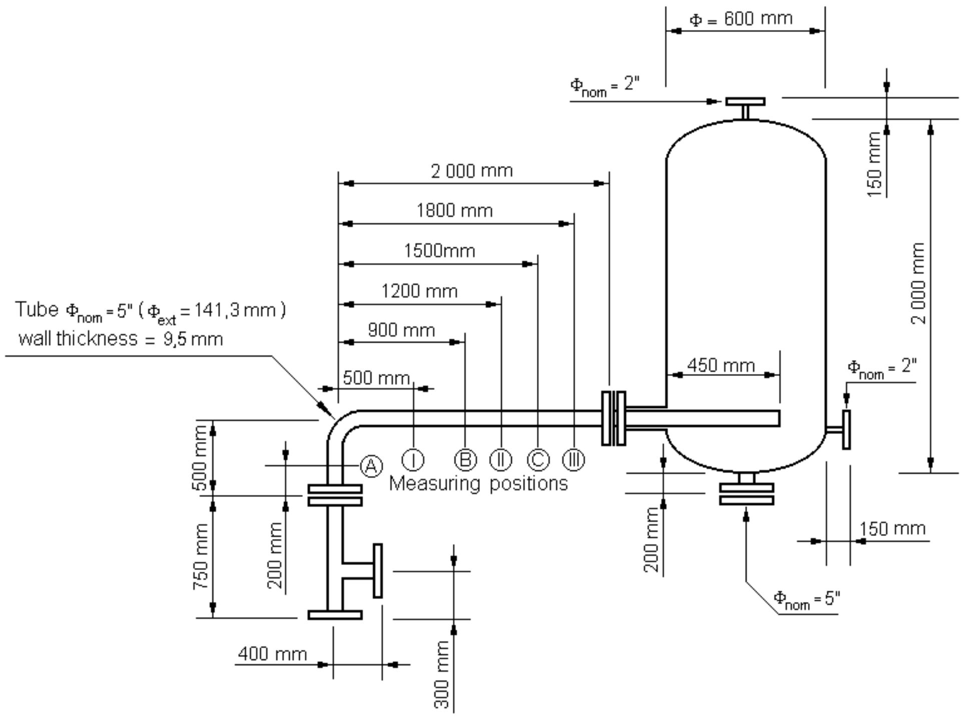
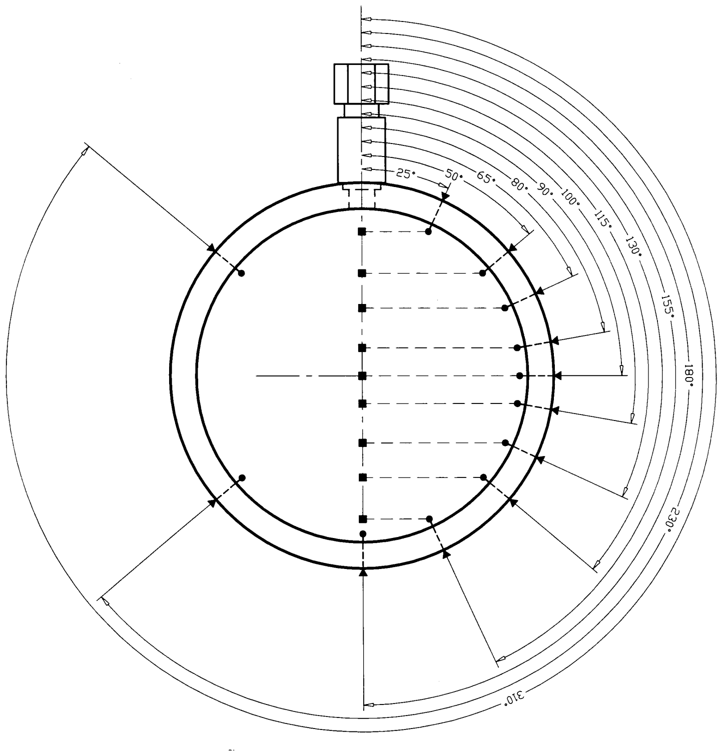


Figure 3. Temperature and strain measuring position at the experimental facility.



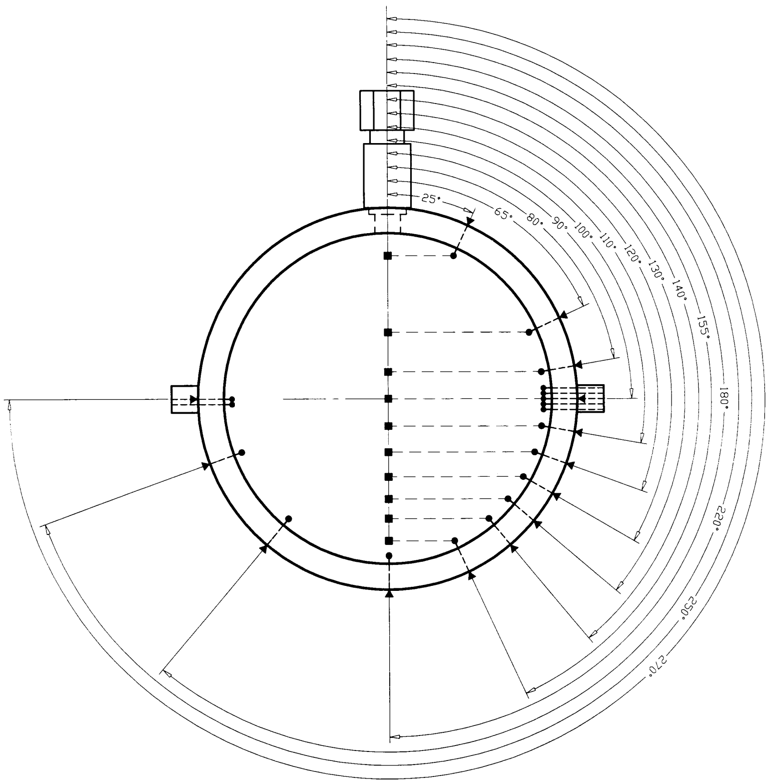
Thermocouples position:

? wall thermocouples

? fluid thermocouples (along the wall)

¦ fluid thermocouples (along the diameter)

Figure 4. Fluid and wall thermocouples distribution in the measuring position I.



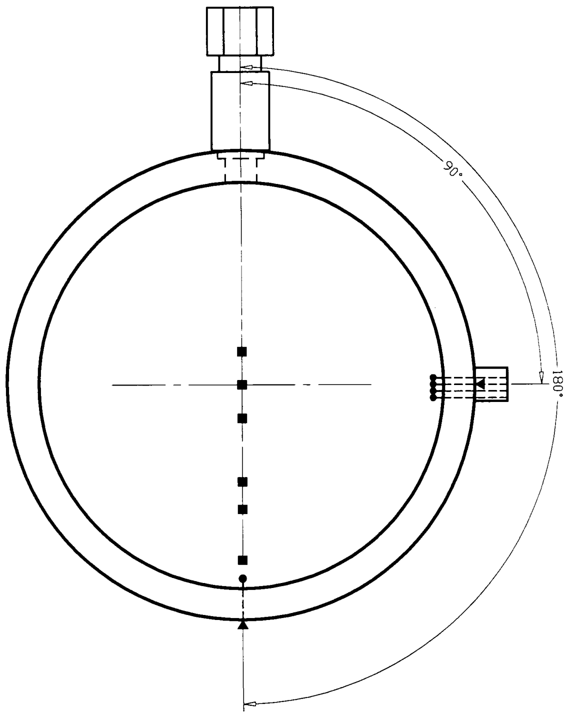
Thermocouples position:

? wall thermocouples

? fluid thermocouples
(along the wall)

¦ fluid thermocouples
(along the diameter)

Figure 5. Fluid and wall thermocouples distribution in the measuring position II.



Thermocouples position:

? wall thermocouples

? fluid thermocouples
(along the wall)

¦ fluid thermocouples
(along the diameter)

Figure 6. Fluid and wall thermocouples distribution in the measuring position III.

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 this fluid thermocouple, another thermocouple was positioned in the same angular position, outside the wall, to measure the external temperature of the wall, so that it is possible to obtain the temperature gradient across the wall thickness. Besides, three removable probes were designed to be stood along the vertical diameter of the cross section, in each one of the measuring positions. These probes have another fluid thermocouple for each thermocouple positioned along the inside wall, at the same height.

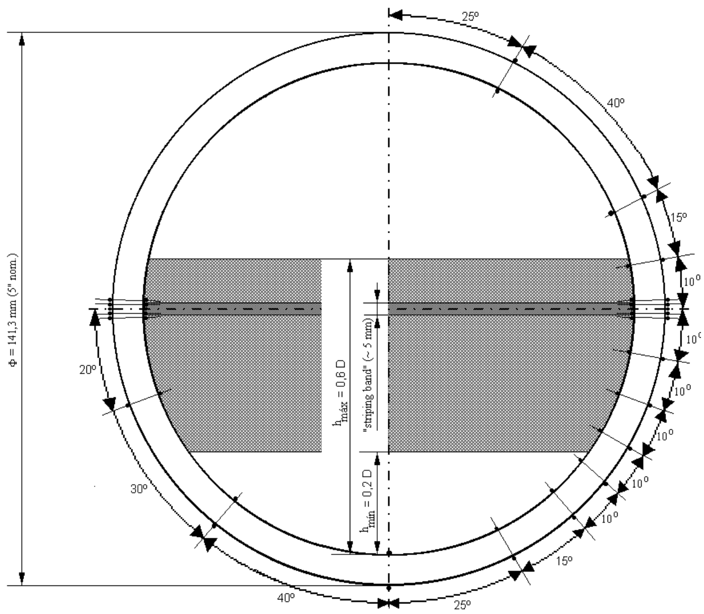


Figure 7. Cross section of measuring position II, with the occurrence area of the interface between the hot and cold water layers and with its oscillation amplitude.

One important effect that can occur during the thermal stratification process is the striping, the oscillation of the interface between the hot and cold water layers. This oscillation presents a maximum frequency of about 1 Hz (Enzel, 1995), and its amplitude was estimated, using the methodology described by Uhlmann (1991), to position thermocouples in the best way in order to obtain a good measuring of the striping. The maximum amplitude estimated for all the planned test matrix was of about 5 mm, and it should occur when the interface were close to the medium height of the tube. Then, the striping only will be measured when the interface between the hot and cold water layers occurs in this medium height of the tube. Detecting the phenomenon in many different possible heights is subject to technical difficulties. Therefore, five fluid thermocouples were positioned close to the wall in the medium height in measuring positions II and III, 2 mm distant from each other. It is not probable that striping occurs in measuring position I where it is difficult to obtain stable laminate flow, necessary condition to the occurrence of the phenomenon. Figure 7 shows a drawing cross section of the measuring position II. The area in clear gray is the area where the interface between the hot and cold water layers will probably occur. The dark gray strip represents the oscillation amplitude when the interface occurs in the medium height of the tube.

Finally, another pair of thermocouples, internal and external, was positioned in the measuring position A (Figure 3) with the main objective of detecting the time when the injected cold water reaches their position.

2.3.2. Strain and stress measurements

Measurements of strain and stress will be made in the outside wall of the feed water nozzle simulator tube, to detect the causes of fatigue problems due to thermal stratification. To measure this strain in three directions 3-element rosette type strain gauges were used, bonded with special adhesives to the external wall of the tube. The strain gauges were distributed in the measuring positions in the following way:

1º) four 3-element rosette type strain gauges in the measuring position I,: the first rosette positioned in the lower side of the tube (in a 180° angle with the vertical probe positioning hole); the second rosette positioned in a 205° angle (vertically symmetrical to the thermocouple in the 155°angle); the third rosette positioned in a 245° angle (vertically symmetrical to the thermocouple in the 115° angle); and, finally, the fourth rosette positioned in a 295° angle (vertically symmetrical to the thermocouple in the 65° angle).

2º) four 3-element rosette type strain gauges in the measuring position II, the first rosette positioned in the upper side of the tube (in a 0° angle with the vertical probe positioning hole); the second rosette positioned in the lower side of the tube (in a 180° angle); the third rosette positioned in a 205°angle (vertically symmetrical to the thermocouple in the 155°angle); and, finally, the fourth rosette positioned in a 335° angle (vertically symmetrical to the thermocouple in the 25° angle).

3º) five 3-element rosette type strain gauges in the measuring position III, the first rosette positioned in the lower side of the tube (in a 180° angle with the vertical probe positioning hole) and the others positioned in the angles 230°, 260° , 270° and 280°.

4º) four 3-element rosette type strain gauges in the measuring position B and other four in the measuring position C, positioned in 0°, 90°, 180° and 270° angles.

5º) one 3-element rosette type strain gauge in the measuring position A, positioned just above the pair of thermocouples (wall / fluid), that were positioned in this measuring position.

2.3.3. Other measurements

Besides the measurements that will be done in nozzle simulator tube, described in sections 2.3.1 and 2.3.2, the following measurements will be made along the experimental facility piping system:

– cold water injection flow rate with a turbine type flowmeter;

– water temperature in the hot and cold water tanks, in the injection piping and in the steam generator simulator tank, with four K type thermocouples (chromel / alumel) 0.5 mm in diameter;

– pressure in the steam generator simulator tank and in the cold water injection piping with a gauge pressure transducer;

– level in the cold water tank with a differential pressure transducer.

3. Methodology of analysis

One phase thermally stratified flow is a transient process, and all measured values need be registered along the time duration of any test. Even the system pressure, the hot water temperature and the injection cold water temperature and flow rate, supposed fixed parameters, need to be registered during full test, because of the possibility of occurring some difference between real and planned parameters. These parameters are called the entrance parameters, since they were planned for each test in the tests matrix. Other parameters that will be registered are wall and fluid temperature and strain along the nozzle simulator. They are called variable parameters. Curves with the time evolution of these variable parameters will be obtained. These curves will be presented as function of the injection velocity and temperature difference between the injected cold water and the hot water. The temperature distribution in the fluid should be correlated to the temperature distribution in the wall. Then, this wall temperature distribution should be correlated to the measured values of strain and stress in the tube.

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:

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

where:

U_0 is the medium 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; and,

ρ_0 is the density of the cold water, in [kg/m^3].

Another dimensionless parameter frequently used in governing equations of stratified flows is the dimensionless time, or Strouchal number, given by:

$$Ho = \frac{U_0 \cdot \tau}{D} ,$$

where:

τ is the time, in [s].

Therefore, these dimensionless numbers will be used for similarity in dimensional analysis. The range of Froude number found in nuclear reactors operational conditions at the steam generator nozzle vary from Fr = 0.02 to Fr = 0.2. This was the range used for planning the tests matrix. In this range, results with different behaviors, with both normal mixing and absence of mixing will probably be obtained. Tests with small Froude number should present no mixing, what means high stratification level, with laminate flow in very defined layers. In opposite, tests with large Froude numbers should result in larger mixing, due to turbulence in the interface between the cold and hot water. The results will present also a great difference in the temperature distribution, both in vertical and longitudinal directions. The position of maximum temperature gradient and its magnitude depend significantly on Froude number.

4. Conclusion

The mixing of flows with different physical parameters (temperature, density, state) in nuclear reactors components is a very complicated and up to date problem from theoretical and practical points of view. Theoretical importance of this question is learning the mathematical description of the physical phenomena. Practical importance of mixing process' studying is the analysis of its influence on equipment integrity subject to these processes in operational conditions. An experimental methodology is under development at CDTN / CNEN to model one phase thermally stratified flows in nuclear reactor piping systems. The first experimental investigation will simulate the steam generator feed water nozzle. The potential damage induced by thermal stratification in this feed water system is considered an important question in steam generator life management.

The flow rate of injected water and the temperature difference between hot and cold water have a great influence on the degree of thermal stratification with different temperature gradients both in transversal and longitudinal directions. These gradients may be also time-dependent. The behavior of stratified flows is governed by two dimensionless parameters:

Froude number, $Fr = \frac{U_0}{(gD\,\Delta\rho/\rho_0)^{1/2}}$, that depends on the injected water velocity, U_0, and on the dimensionless density difference $\Delta\rho/\rho$, and

Strouchal number, $Ho = \frac{U_0 \cdot \tau}{D}$, the dimensionless time.

The Froude number's maximal variation in these planned experiments may be reached by varying the injected water flow rate (velocity), because of the limitation on pressure (2 300 kPa) of CDTN facility, that reduces the possibility of varying the density difference. By a previous analysis, it was determined that the facility will permit to vary the Froude number from 0.02 to 0.2, corresponding to the range of Froude number variation on a pressurized water reactor steam generator feed water nozzle. This range will permit to obtain results with different mixing scenarios, from no mixing, that corresponds to high stratification level, with lower Froude numbers, until large mixing, with higher Froude numbers.

5. References

Kim, J. H.; Roidt, R. M.; Deardorff, A. F., 1993, "Thermal stratification and reactor piping integrity. Nuclear Engineering and Design", v. 139, P. 83 - 95.

Häfner, W., 1990, "Thermische Schichit-Versuche im horizontalen Rohr. Kernforschungszentrum Karlsruhe GmbH", Karlsruhe, April, 238 p. (Technischer Fachberichit Nr. 92 - 89).

Ensel, C.; Glues, A.; Barthez, M.,. 1995, "Stress analysis of a 900 MW pressurizer surge line including stratification effect". Nuclear Engineering and Design, v. 153,. P. 197 - 203.

Uhlmann, D.; Diem, H.; Hunger, H., 1991, "Untersuchung zum zyklischen Rißwachstum eines Umfangsrisses in einem geraden Rohrabschnitt DN 425 bei langsam wechselnder Biegelast und periodisch wiederholter thermischer Schichtung. Kernforschungszentrum Karlsruhe", Karlsruhe, Germany, 15. Statusbericht PHDR, 04. Dezember. P. 371 - 408.