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Thermal fatigue damage evaluation of a PWR NPP steam generator injection nozzle model subjected to thermal stratification phenomenon

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ABSTRACT

Thermal stratification phenomenon with the same thermodynamic steam generator (SG) injection nozzle parameters was simulated. After 41 experiments, the experimental section was dismantled; cut and specimens were made of its material. Other specimens were made of the preserved pipe material. By comparing their fatigue tests results, the pipe material damage was evaluated. The water temperature layers and also the outside pipe wall temperatures were measured at the same level. Strains outside the pipe in 7 positions were measured. The experimental section develops thermal stratified flows, stresses and strains caused enlargement of material grain size and reduction in fatigue life.

Contents

1. Introduction

Thermal stratification is a thermo-hydraulic phenomenon present in horizontal pipes where there are cold and hot flows at the same time. The difference of temperature between fluid flows must be significant and their velocity must be low in order to characterize the phenomenon. The first problem due to thermal stratification in a Nuclear Power Plant (NPP) component was notified in the end of the 80s. The problem was a leakage due to through wall cracks in some pipelines at the American NPP Farley 2. After that event, a bulletin recommending evaluations and corrective actions at the NPP pipelines subjected to thermal stratification (NRC Bulletin, 1988) was published in the USA by the Nuclear Regulatory Commission (NRC). At that time, it was discovered that the cracks were caused by thermal fatigue loads related to stratified flow present in those pipelines. That problem may have happened because the NPP designed up to the 80s did not consider the non-linear effects of the loads imposed to the pipelines due to thermal stratification.

Thermal stratification is a frequent phenomenon in NPP, in conventional thermal plants and also in many other industrial processes where liquid or gases are refrigerating fluids. The refrigerating fluids could be at the same state or in different ones. According to Liu and Cranford (1991), during the thermal stratification phenomenon, there is an abrupt local change in the fluid

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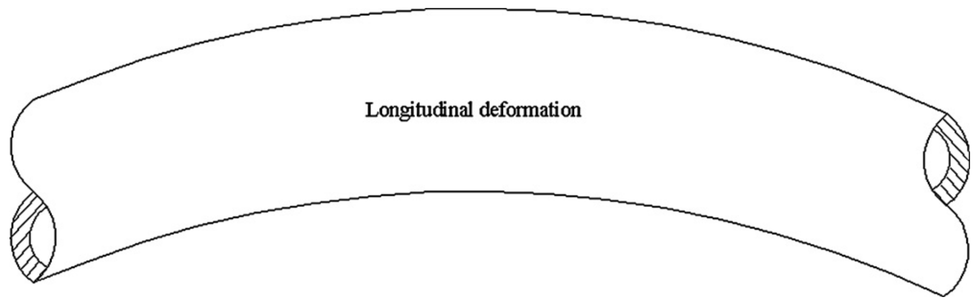


Fig. 1. Longitudinal deformation due to the difference of the cross-section temperature.

temperature and it is harmful to the pipe's material. This work aims at analyzing the stratification of the two water flows, as refrigerating fluid, and its effects in the experimental section pipe material.

The objective here is to study the fatigue damage due to the thermal stratification phenomenon in the material of an experimental section that simulates the SG injection nozzle of a Pressurized Water Reactor (PWR) NPP. In order to study the effects of thermal stratification in the pipe material, 41 thermal stratification experiments were carried out. After that, the experimental section was dismantled from the experimental circuit, cut and specimens were made from its material. Others specimens were made from a virgin portion of the same experimental section pipe. Both sets of specimens were submitted to up-and-down fatigue tests and their fatigue limits were determined (Colins, 1993). Metallographic studies were performed in order to realize what happened in the microstructure of the material.

2. Thermal stratification phenomenon

When the thermal stratification phenomenon is present in a pipe, its upper hot region tends to expand and at the same time its lower cold region tries to constrain this expansion, causing longitudinal loads in the pipe. Those loads are responsible for bending the pipe as shown in Fig. 1 (banana effect). At the same time, in the pipe wall near the fluids edge, the lower part of the cross-section stays in tension and the upper part becomes contracted, causing circumferential stresses that may deform the pipe cross-section. A significant phenomenon of local oscillation in temperature, which

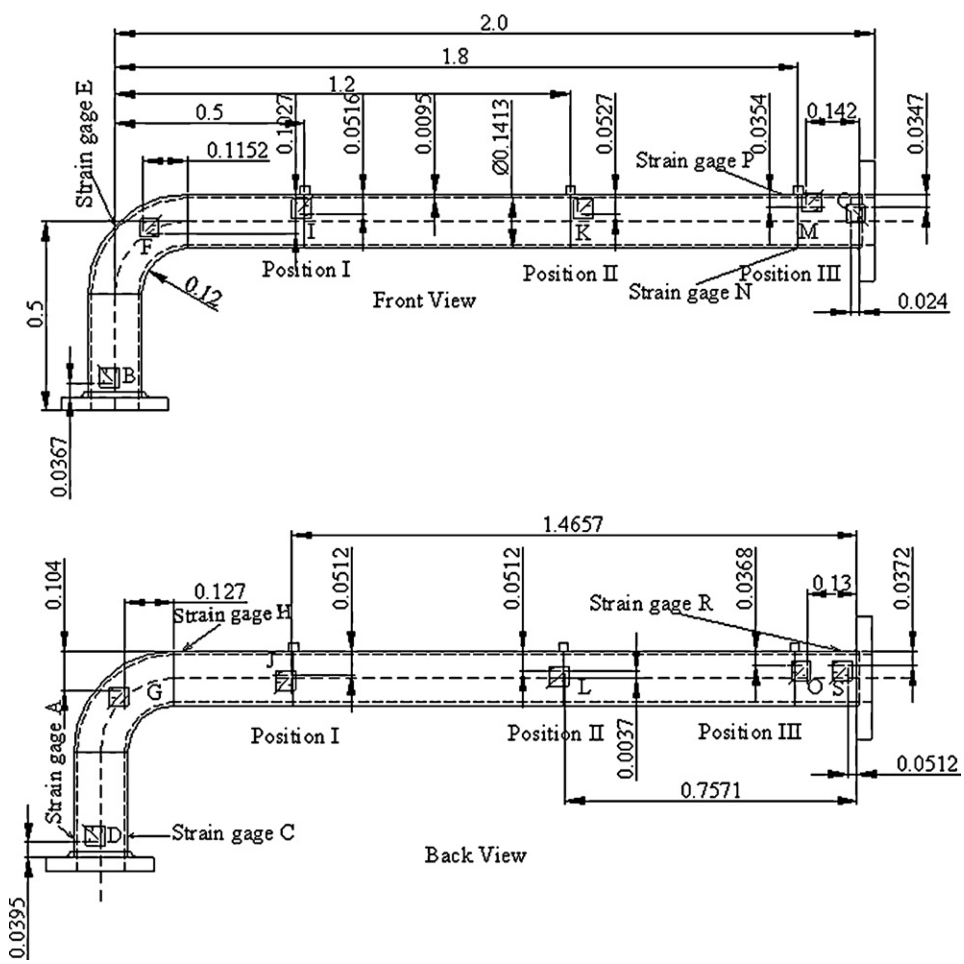


Fig. 2. Strain gages positions in experimental section, front and back view (m).

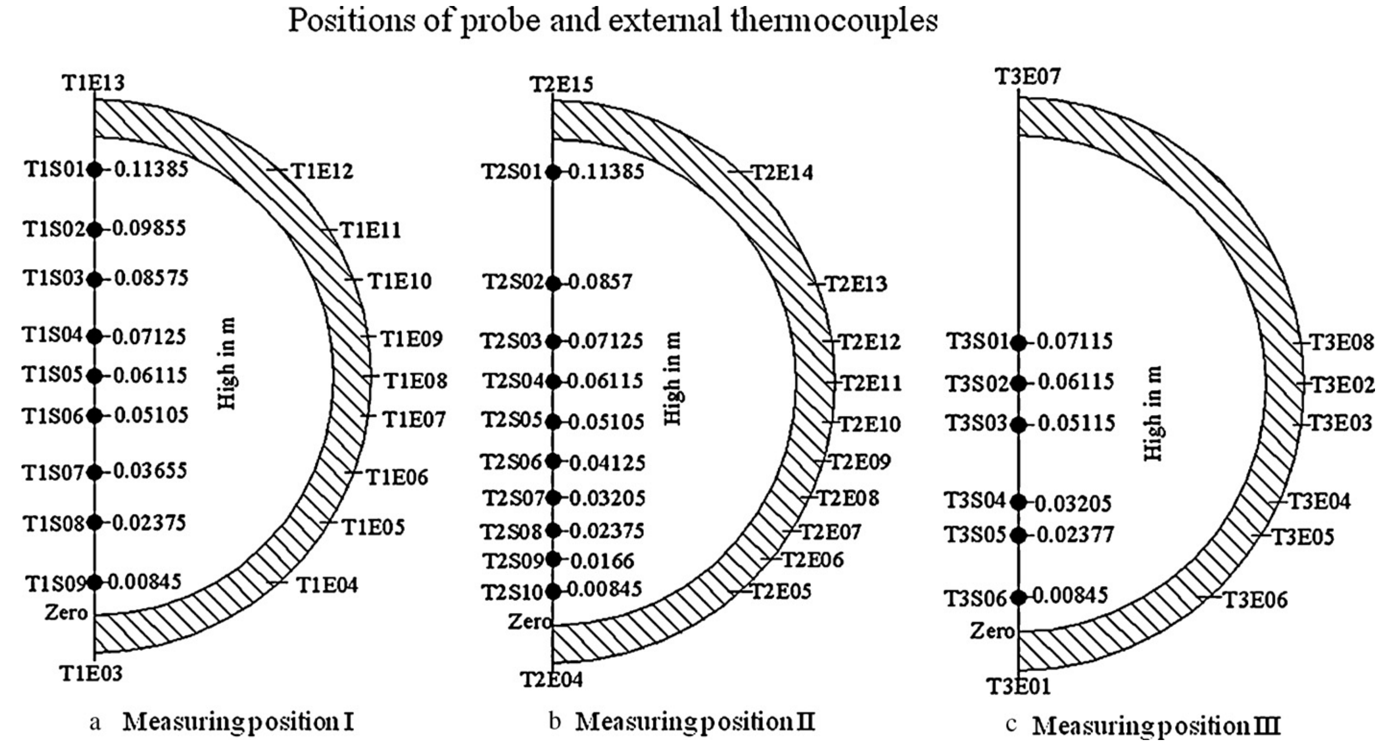


Fig. 3. Internal and external thermocouples of measuring positions I, II and III.

is known as thermal striping, is present during the thermal stratification in the fluids interface. This phenomenon is characterized by an oscillating frequency and also by the amplitude associated to it. Thermal striping may cause high cycle thermal fatigue and flaws may appear in the pipe internal surface.

Operational characteristics of a PWR reactor could favor thermal stratification phenomenon occurrence during start up, shutdown and power variations of the NPP. Some NPP circuits, where there is the possibility of thermal stratification occurrence, are the hot and cold legs, the pressurizer surge line, the emergency cooling lines, the residual heat removal lines, the injection nozzle of the SG and the pressurizer spray lines. Among them, the hot and cold legs, the pressurizer surge line and the SG injection nozzle have a great probability to suffer thermal stratification (Jo et al., 2001). The ther-

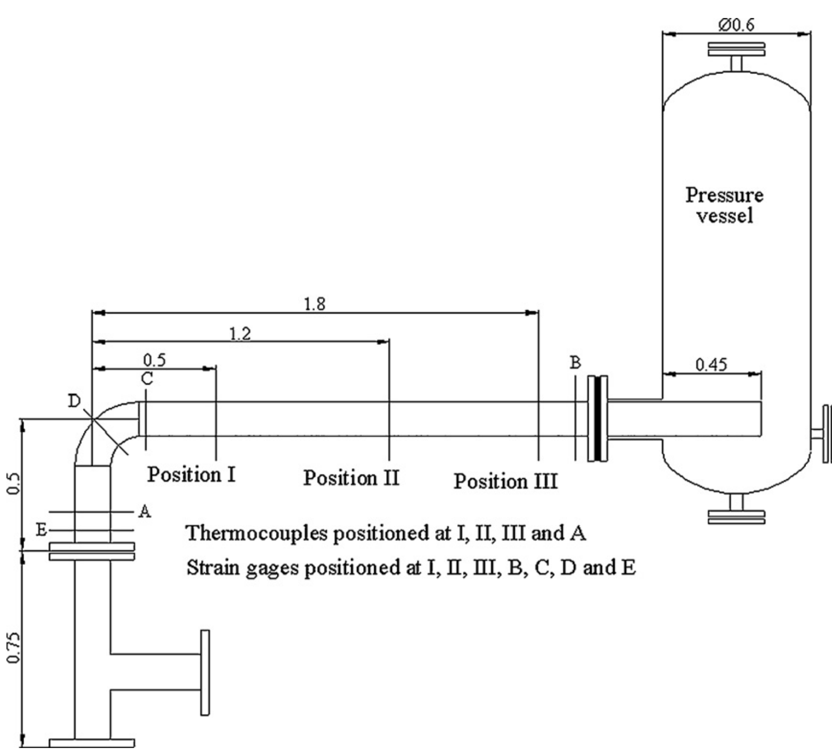


Fig. 4. Experimental section sketch and its accessories (m).

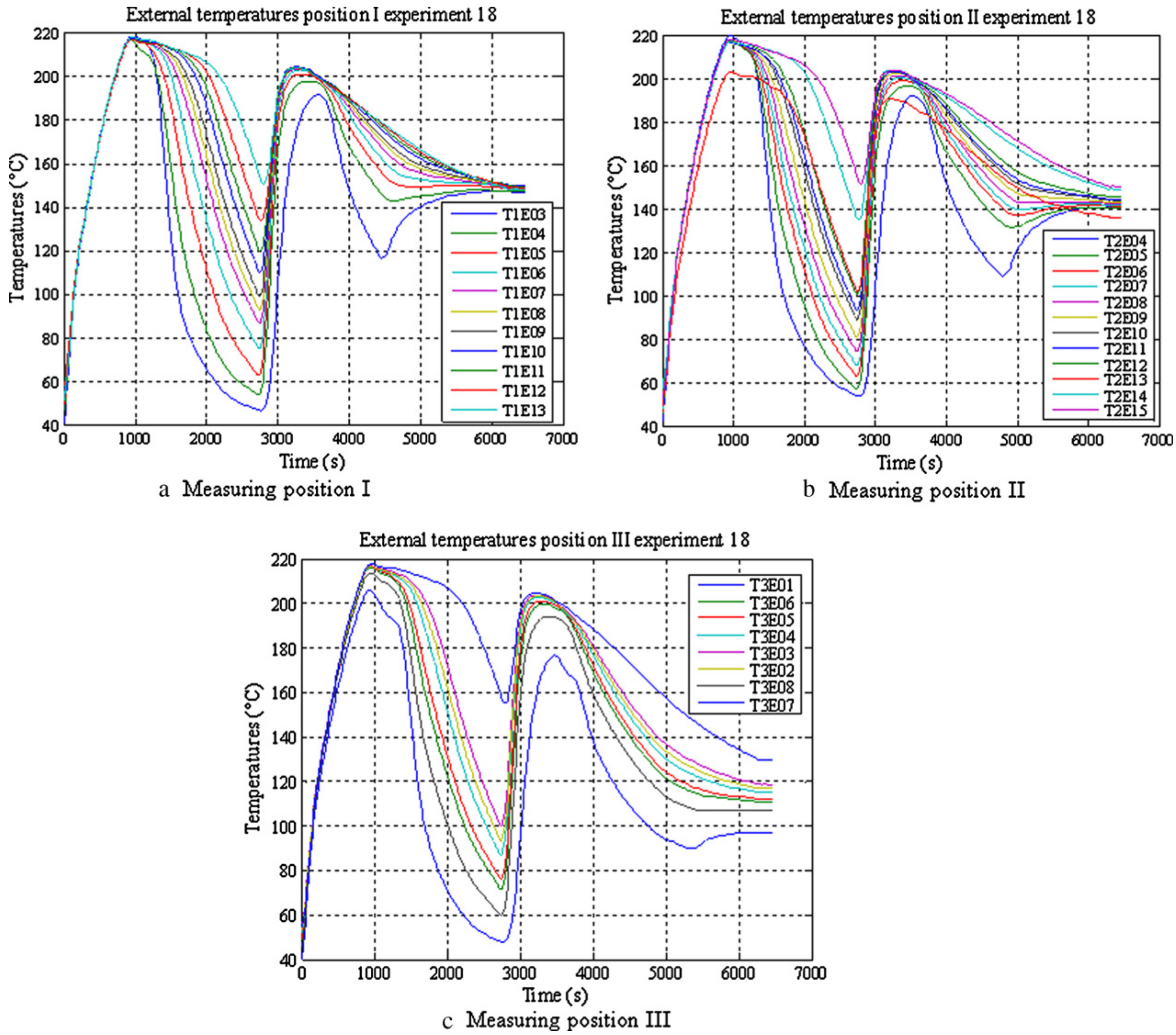


Fig. 5. Pipe wall temperature gradient in positions I, II and III.

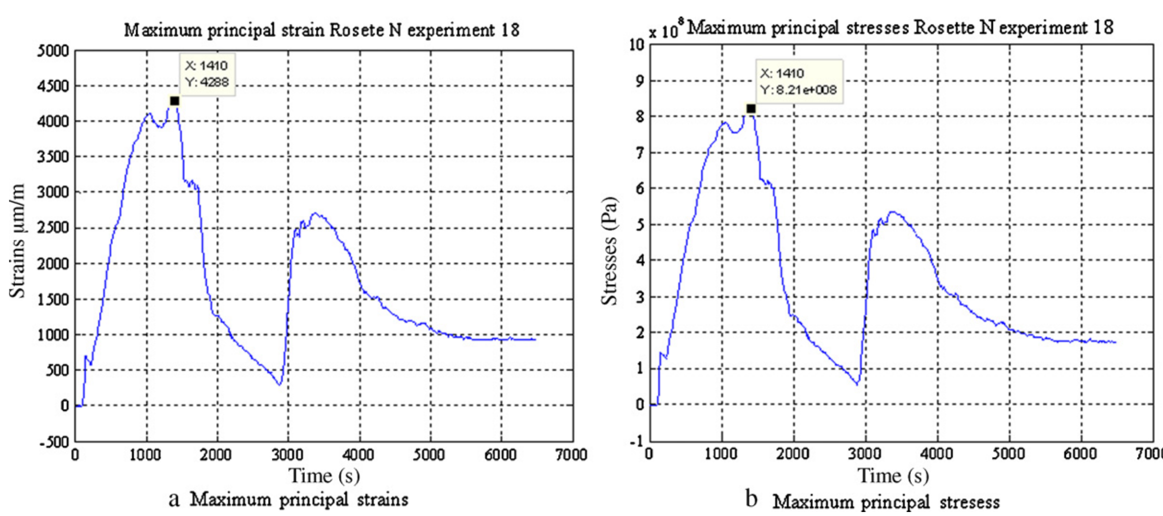


Fig. 6. Maximum strains and stresses in rosette N for experiment 18.

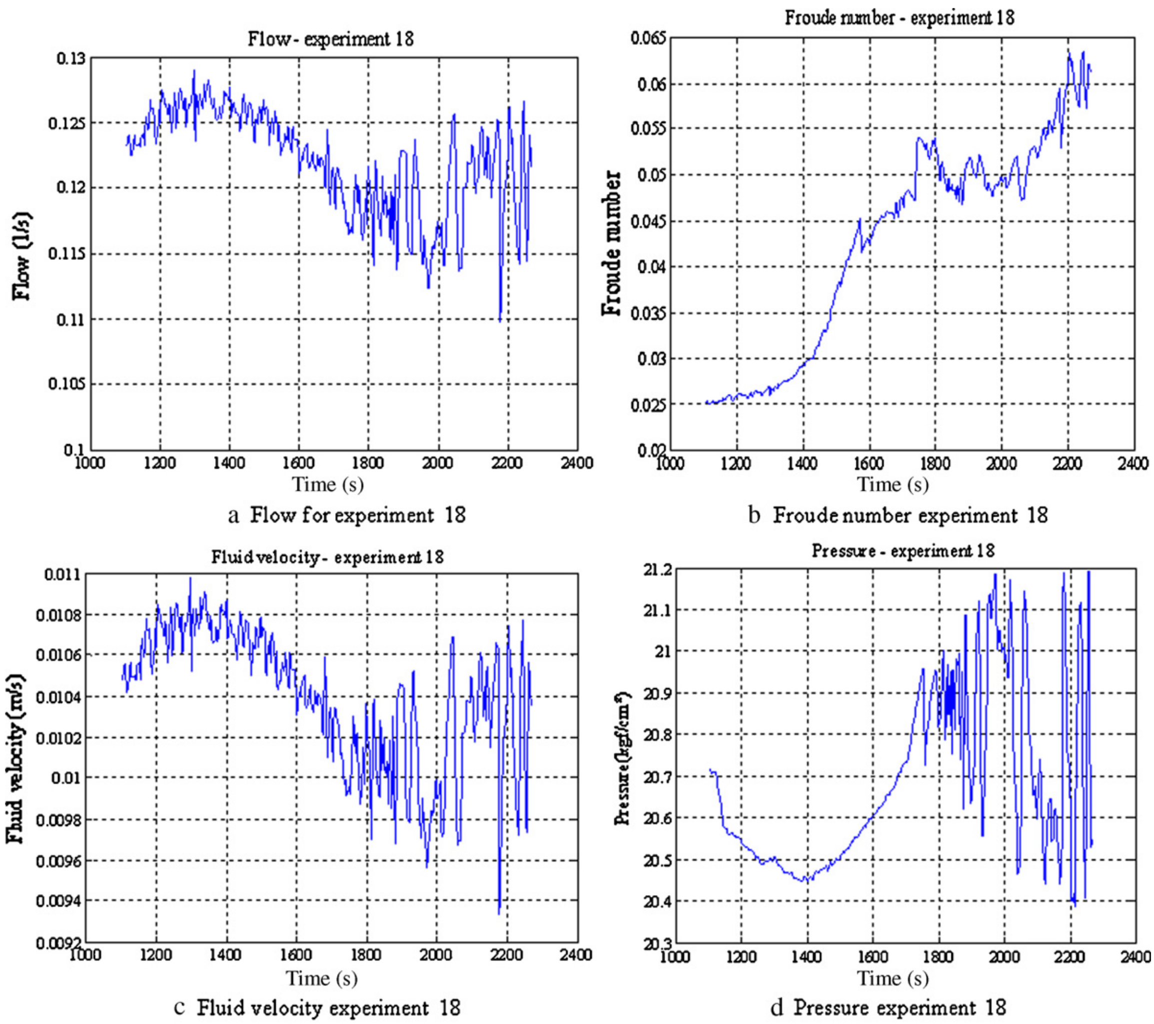


Fig. 7. Thermo hydraulic parameters of cold water during thermal stratification.

mal stratification may be present in pipelines with stagnant fluid or in pipelines with closed valves where there is cold fluid in one side and hot fluid in the other side of the valve closing mechanism (Hytönen, 1998). In such points, a small amount of fluid leaks with low velocities from one pipeline side to the other, inducing thermal stratification.

3. The experimental

The experimental section is an "L" shaped pipe made of stainless steel AISI 304L, with external diameter of 0.1413 m, wall thickness of 0.0095 m and 2.0 m in length as shown in the front view of Fig. 2. Thermocouples were brazed externally at measuring positions I, II and III, as illustrated in Fig. 3. Thermocouples levels in positions I, II and III are shown in Fig. 3(a), (b) and (c), respectively (da Silva, 2009). Strains were measured in positions I, II, III, B, C, D and E in the experimental section with rectangular rosettes strain gages bonded externally. Strain gauges positions for the experimental section are shown in front and back view of Fig. 2. Fig. 4 shows the sites of the measuring positions I, II, III, B, C, D and E and the pressure vessel that simulates the steam generator. Table 1 shows the amount of thermocouples and rosettes in the experimental section.

The experimental section is not a SG injection nozzle scaled model, but the same range of SG injection nozzle Froude number was reached. The range of Froude number in a SG injection nozzle is from 0.02 to 0.2. The experiments in this work were carried out with Froude numbers around 0.05. Due to laboratory limitations, the experiments were carried out in a maximum pressure of 2.3 MPa, which is lower than the SG injection nozzle pressure of 6.4 MPa. Pressure limitations reduced the maximum working temperature of the water to 490 K against 553 K at the SG.

Strains were measured in seven positions in the experimental section with rectangular rosettes strain gages bonded externally. Strain gauges positions for the experimental section front view are shown in Fig. 2. The measuring positions I, II, III, A, B, C and D are shown in Fig. 4.

The thermal striping frequency, with the same thermo-hydraulic parameters, was measured in a similar experimental section and it was found to be 0.25 Hz (Rezende et al., 2006). Ther-

Table 1
Thermocouples and rosettes distribution in experimental section.

Position	Thermocouples (number)		Rosettes
	Inside	Outside	
I	9	11	2
II	10	12	2
III	6	8	4
A	2		
B			3
C			1
D			3
E			4

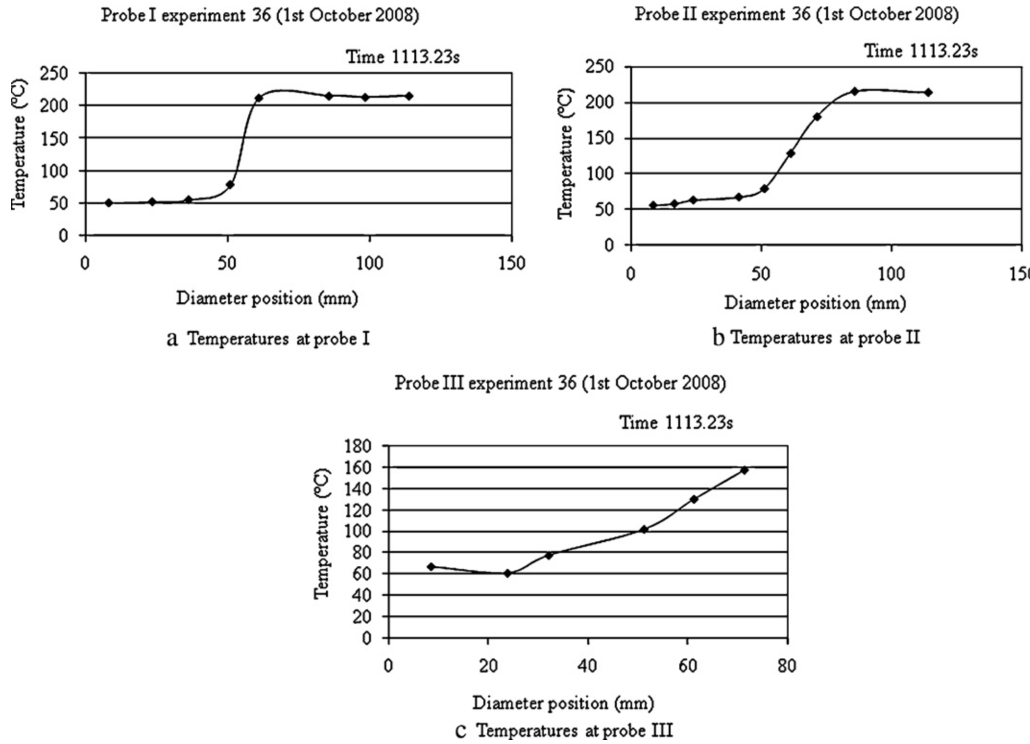


Fig. 8. Temperatures along the internal diameter in positions I, II and III.

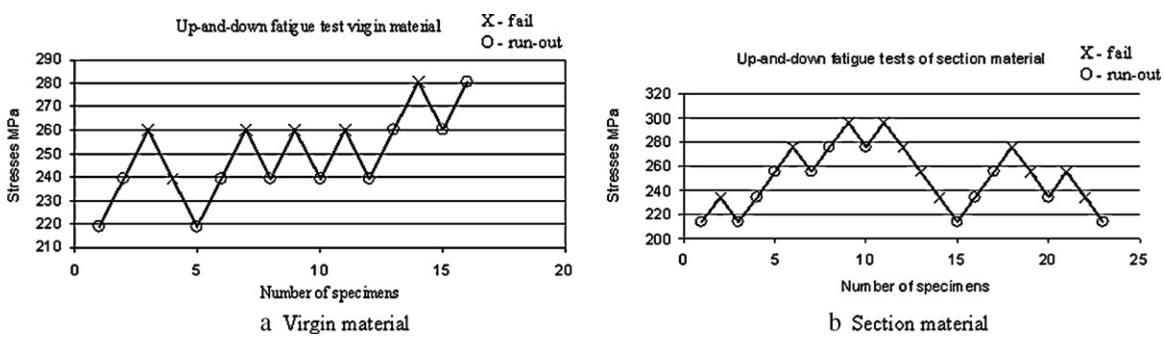


Fig. 9. Virgin and experimental section material up-and-down test.

mal stratification with Froude numbers in the range of 0.02–0.2 has maximum frequency of 1 Hz and amplitude of 5 mm. Close to the pipe wall and at the half diameter, the amplitudes could reach their maximum values (Merola, 1995).

4. Thermal fatigue

Thermal fatigue is a damage process of the structural components produced by cyclic thermal loads. Under cyclic thermal loads, a component can suffer unacceptable geometric deformations and changes in its material properties. Cracks may appear in the component as a consequence of constraint and cyclic thermal loads. Restriction of a component expansion may be related to both internal and external factors. External restrictions induce alternated loads in the component when it is heated and cooled down. The internal restrictions can be originated from temperature gradient, material anisotropy and from different expansion coefficients of the material grains of adjacent phases. A possible definition of thermal fatigue can be: "thermal fatigue is a gradual degradation and eventual break of a material by alternated heating and cooling processes with partial or total constraint of the thermal expansion" (Ensel et al., 1995). Thermal fatigue can be related to thermal striping, originated from temperature fluctuations in the cold and hot fluids interface in a stratified flow. Thermal cycles imposed to the pipe wall material can be the reason for the appearance of cracks in such area.

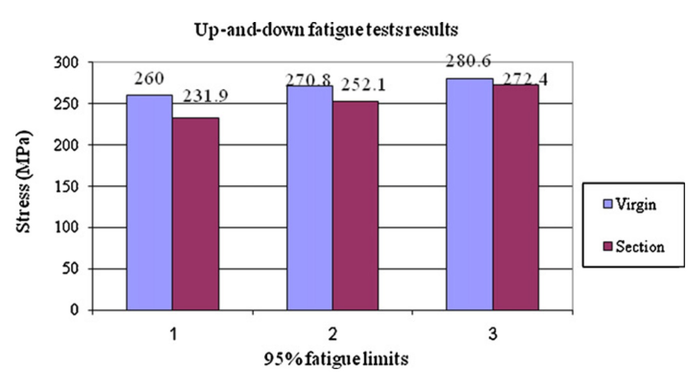


Fig. 10. Comparison of the results.

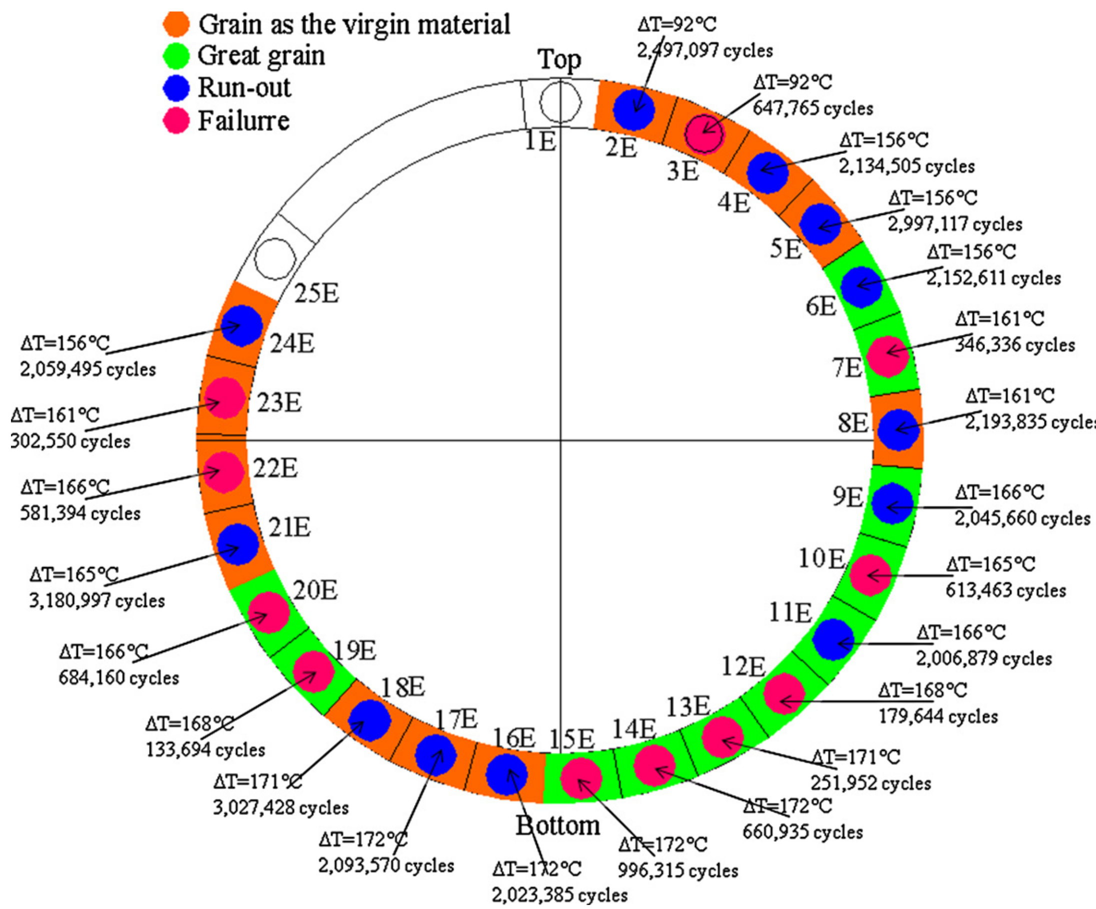


Fig. 11. Specimens positions in the cross-section pipe.

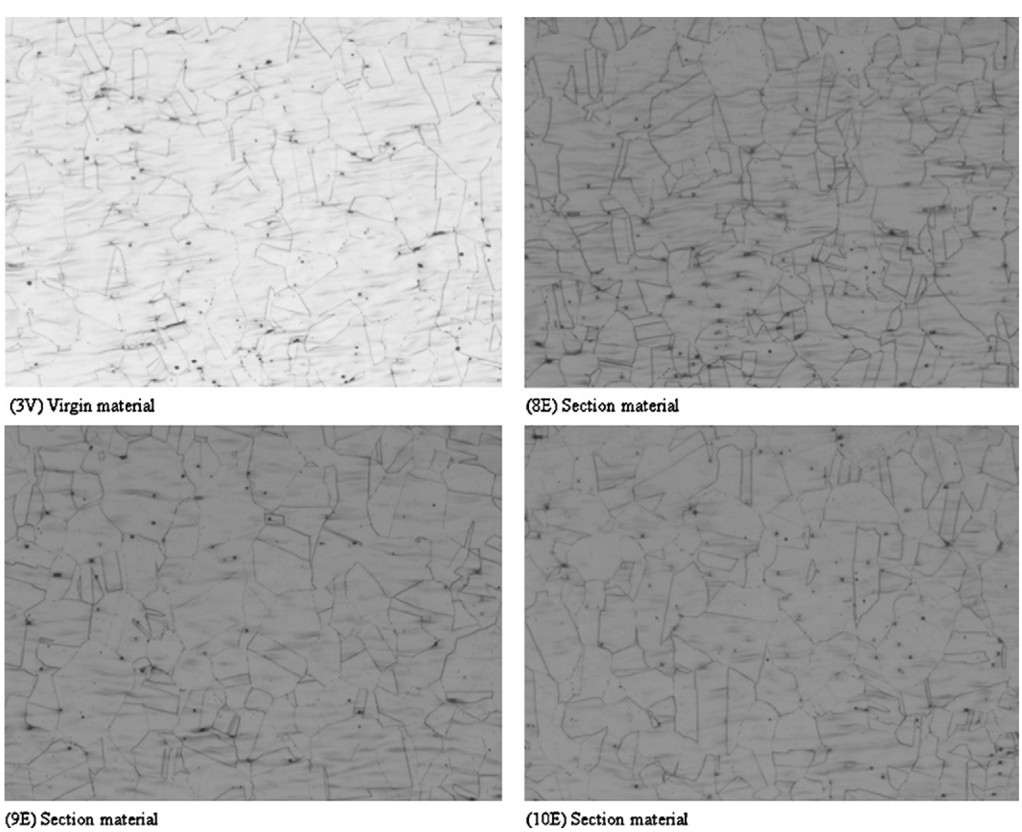
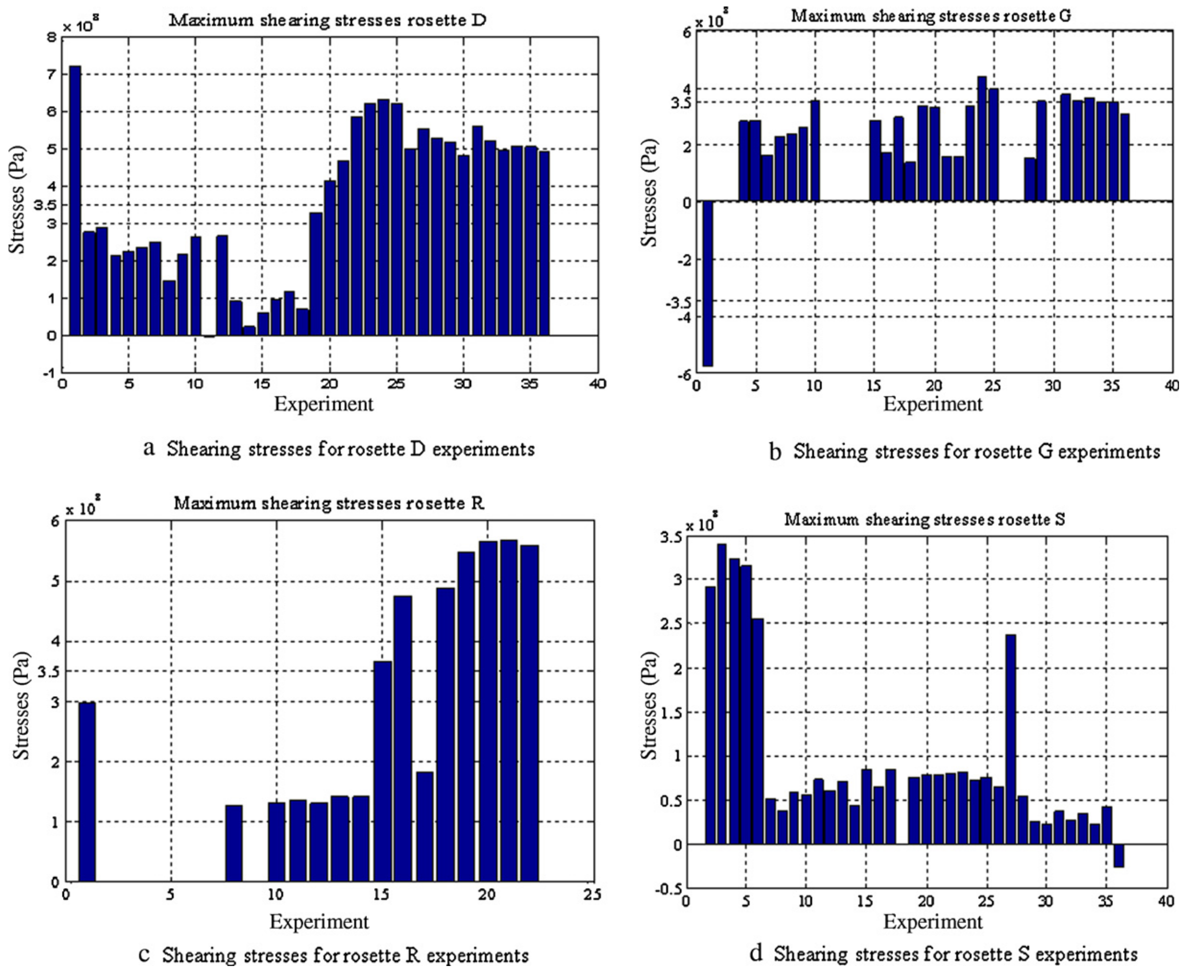


Fig. 12. Metallographic study of specimens 3V, 8E, 9E and 10E.



a Shearing stresses for rosette D experiments

b Shearing stresses for rosette G experiments

c Shearing stresses for rosette R experiments

d Shearing stresses for rosette S experiments

Fig. 13. Maximum shearing stresses of rosettes D, G, R and S.

5. Results and discussion

5.1. Thermal stratification

The thermal stratification experimental results allowed to determine the temperatures distributions in the pipe wall and in the fluid, the loads and deformations in the experimental section pipe. The temperature distribution in the fluid was directly related with the temperatures in the pipe wall and with its deformation and, consequently, with the loads and stresses.

The external experimental temperatures in positions I, II and III for the experiment 18 can be seen in Fig. 5(a), (b) and (c), respectively. Experiment 18 was carried out on 4th July 2008. As it is shown, the pipe wall was under a gradient of temperature during the cold water injection.

Maximum strains measured at the strain gage rosette N for the thermal stratification experiment 18 are shown in Fig. 6(a) and the maximum stresses caused by them are shown in Fig. 6(b).

Fig. 7 depicts the experimental results of the thermo hydraulic parameters for the experiment 18. Fig. 7(a) shows the flow curve; Fig. 7(b), the Froude number; Fig. 7(c), the fluid velocity; Fig. 7(d), the changes in pressure. The Froude number varies from about 0.025 to around 0.061 since the beginning until the end of the experiment. Variations in fluid velocity and flow are more significant in the end of the experiment. Such variations may have been caused by changes in pressure during the cold water injection, as shown in Fig. 7(d). Fig. 8 shows the experimental thermal stratification results of experiment 36 along the inside pipe cross-section in positions I, II and III. Experiment 36 was carried out on 1st October 2008. Fig. 8(a) shows the stratification in position I, which ranges from around 50 °C (323 K) to 215 °C (488 K) at about 0.02 m. In position II, with the same change in temperature, the stratification happens at about 0.04 m as shown in Fig. 8(b). In position III, temperature increases continuously as Fig. 8(c) shows.

5.2. Fatigue tests

After the 41 thermal stratification experiments, specimens from the experimental section pipe material and from a preserved portion of this pipe were made and subjected to fatigue tests. The up-and-down method was used to determine the mean fatigue limits and the 95% confidence limit of both sets of specimens.

Fig. 9(a) shows the virgin material up-and-down fatigue tests results and Fig. 9(b), the results for the section material (da Silva et al., 2009). Run-out was reached at 2 million fatigue cycles. A comparison between these results is shown in Fig. 10 and a reduction in the fatigue limit of the experimental section material can be noticed. The reduction in the section material for the mean fatigue limit, in comparison with the virgin material, is 6.9%. The lower fatigue limit reduced 10.8% and the upper 2.9% (da Silva et al., 2009).

5.3. Metallographic analysis

Before cutting specimens in the pipe wall experimental section, the slice cut from it was mapped and numbered in order to know where each specimen came from. Fig. 11 depicts how the experimental pipe cross-section slice was mapped. In Fig. 11, the temperature difference of the cross-section regions and the number of fatigue cycles of each specimen can be seen. It is also shown in Fig. 11, the specimens that had an increase in grain size, when compared with the grain size of the virgin material (da Silva, 2009).

Fig. 12 shows the metallographic study of the specimens 3V, 8E, 9E and 10E. The specimen 3V was taken from the virgin material and the specimens 8E, 9E and 10E were taken from the experimental section. Comparing the grain size, it is noticed that the specimen 8E did not show significant alteration, while specimens 9E and 10E had their grain size increased (da Silva, 2009). The comparisons were done considering the specimen 3V grain size as a standard. Fig. 11 shows that most specimens below the horizontal center line, 9 out of 14, had an increase in the grain size. In addition, 8 specimens out of 11, that had the grain size increased, failed in the fatigue test.

5.4. Load evaluation

The loads imposed to the experimental section were evaluated using the maximum shearing stress criteria. The experimental section pipe material had ductile properties, what makes the maximum shearing stress criteria appropriate to the evaluation (Boresi and Sidebottom, 1985).

The shearing stress of the material experimental section was determined experimentally and it was found to be 350 MPa (da Silva, 2009). It can be noticed from the experimental data that some thermal stratification experiments imposed loads on the experimental section above the determined shearing stress value. Very few rosettes showed maximum shearing stress equal to the material shearing stress and the major amount of the experimental maximum shearing stresses was under this value.

Fig. 13(a–d) shows the maximum shearing stresses for rosettes D, G, R and S, respectively. Rosette D registered 18 loads above the material shearing stress; rosette G, 8; rosette R, 7; rosette S, none. Rosette G registered one load equal to the material shearing stress. Among the loads registered by rosette G, the greatest of them is in compression.

6. Conclusions

An experimental study proposition to correlate the effects of the thermal fatigue due to thermal stratification and the damages caused to pipelines was presented in this work. Thermal stratification transients with the same injection nozzle Froude number range were simulated in a designed experimental section. The thermal stratification is nonlinear in the pipe cross-section. Results of up-and-down fatigue tests carried out in specimens made of the virgin material and in the specimens made of the experimental section material confirmed that the thermal stratification phenomenon reduces the material fatigue limit. The mean fatigue limit reduced 6.9%, the lower reduced 10.8% and the upper reduced 2.9%, in comparison with the virgin material. Material fatigue life reduction can be associated with an increase in the material grain size and with the gradient of temperature the material was subjected. Enlargement in the material grain size can be related to the difference of temperature and loads imposed to the experimental section. The major amount of specimens from the lower pipe cross-section region had its grain size enlarged in comparison with the virgin material. The specimens above the upper pipe cross-section region did not have its grain size altered significantly. The majority of specimens with their grain size enlarged failed during fatigue tests. A significant amount of stresses imposed to the experimental section by the thermal stratification experiments were above its material shearing stress.

Disclosures

All the authors of this paper disclose any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations. All the authors of this paper disclose any conflict of interest including employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

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