Thermal Fatigue Analysis of a NPP Steam Generator Injection Nozzle Model SubJECTED TO Thermal Stratification

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1 ABSTRACT

This work is related to an experimental thermal stratification study aiming to quantify thermal fatigue damages in the pipe material. Thermal fatigue damages appear as a consequence of non-linear longitudinal and circumferential loads and thermal stripping present in pipes with thermal stratified flows. In this work an experimental section, simulating the injection nozzle of a Nuclear Power Plant (NPP) steam generator, was subjected to the effects of thermal fatigue due to thermal stratification. The experimental section was made of stainless steel pipe type AISI 304L and its geometric characteristics allowed the same range of Froude numbers of a Pressurized Water Reactor (PWR) NPP. Temperatures were measured externally and internally in three positions and deformations just externally in seven positions. Up-and-down fatigue tests were done to assess the amount of damage induced in the material experimental section. Preliminary numerical simulations were done using a coupled analysis in the ANSYS code with temperatures and pressure inputs taken from thermo-hydraulic experimental results. The objectives in this work are quantify the thermal fatigue intensity imposed to the pipe material by thermal stratification experiments, verify the agreement between numerical and experimental thermal stratification results and obtain the material fatigue limit testing specimens made of pipe experimental section and from the virgin pipe.

2 INTRODUCTION

At the end of the 80's leakage due to through wall cracks from some pipelines of NPP was notified. After that the American commission – Nuclear Regulatory Commission (1988) published a bulletin recommending evaluations and corrective actions at the NPP pipelines subjected to thermal stratification. Through wall cracks may appear in welds and in base material. At that time researchers discovered that the cracks were due to thermal fatigue caused by loads conditions related to stratified flow present in that pipelines. The NPP designed up to the 80's do not consider the non-linear effects of the loads imposed to the pipelines due to thermal stratification.

In horizontal pipes where there are two flows fluxing at different temperatures and at low velocities, thermal stratification could be present. This phenomenon is frequent in NPP, in conventional thermal plants and in many other industrial processes that use liquid or gases as refrigerating fluids. The refrigerating fluids could be at the same state or in different states. Accordingly with Liu and Cranford (1991), during thermal stratification phenomenon an abrupt local change in the fluid temperature exists and this is harmful to the pipe's material. The stratification of two water flows, as refrigerator fluid, and its effects in the experimental section pipe material are the subject study in this work.

In PWR NPP during operations with low power, start up, shut down and changing in power, the water with temperature ranging from 273K to 313K, flows with low velocities into the steam generator. At the same time in the injection nozzle there is the hot water from the steam generator at the temperature of about 553K and at the working pressure of 6.4MPa. At this secondary circuit point the thermal stratification is favored by the water low velocities entering the steam generator and by the significant difference of temperature between cold and hot water. The objective here is to study the fatigue damage, due to thermal
stratification phenomenon, in the material of an experimental section that simulates the steam generator injection nozzle of a PWR NPP. In order to study the effects of thermal stratification in the pipe's material, 41 thermal stratification experiments were simulated. After performing thermal stratification experiments the experimental section was dismantled from the experimental circuit, cut and a set of specimens was made from its material. From a virgin portion of the same pipe used to make the experimental section, another set of specimens was made. Both sets of specimens were submitted to the up-and-down fatigue tests and their fatigue limits were determined, Collins (1993). Experimental pressure and temperature were used as loads to simulate numerically stresses and strains in the experimental section.

3 THERMAL STRATIFICATION PHENOMENON

If there is thermal stratification phenomenon in a pipe, it is submitted to loads due to the difference of temperature in its cross section. The upper hot region of the pipe tends to expand and at the same time its lower cold region tries to constrain this expansion. This phenomenon of expansion and containment happening simultaneously cause longitudinal loads in the pipe that are responsible for bending it as shown in Figure 1 (the banana effect). At the same time in the fluids edge the lower cold part of the cross section stay in tension and its upper hot part become contracted. This phenomenon causes circumferential stresses that may deform the pipe cross-section as can be seen in Figure 2. Another phenomenon that appears during thermal stratification is a significant local oscillation of temperature in the fluids interface, which is known as thermal striping. Thermal striping could cause high cycle thermal fatigue and flaws could appear in the internal surface of the pipe. The thermal striping phenomenon is characterized by an oscillating frequency and by the amplitude associated to it as can be seen in Figure 3.

Figure 1 Longitudinal deformation due the difference of cross section temperature

Figure 2 Deformations at the pipe cross section

Figure 3 Thermal striping in the fluids interface

Operational characteristics of a PWR reactor include primary and secondary closed loops. In both loops the water is submitted to temperature variations that favors thermal stratification phenomenon occurrence
during start up, shutdown and power variations of the NPP. Besides these two operational circuits there are others that can be submitted to the thermal stratification phenomenon. The circuits with great possibility of thermal stratification occurrence are the pressurizer surge line, the emergency cooling lines, the residual heat removal lines, the injection nozzle of the steam generator and the pressurizer spray lines. Three lines among them are more prone in suffering thermal stratification, which are the hot and cold legs, the pressurizer surge line and the steam generator injection nozzle, Jo et al (2001). Thermal stratification may exist in pipelines with stagnant fluid or in pipelines with closed valves where exists cold fluid in one side and hot fluid at the other side of the valve closing mechanism Hytönen (1998). At these points a small amount fluid leaks with low velocities from one pipeline side to the other, inducing thermal stratification.

3.1 The Experimental Section and Simplification

The experimental section is not a steam generation scaled model but it was made with geometric characteristics in order to obtain the same range of injection nozzle Froude number that is from 0.02 to 0.2. Using this range of Froude number is possible to do experiments with a vast proportion of hot and cold fluids and with great gradients of temperatures. The thermo hydraulic laboratory, where the experiments were carried out, does not support pressures above 2.3MPa, which is lower than the injection nozzle pressure of 6.4MPa. This limitation reduces the maximum water working temperature. At the experiments, the maximum working temperature is 490K against 553K at the steam generator. The temperatures are very important for characterizing the thermal stratification phenomenon. Because of that, temperatures are measured along the pipe diameter in different levels and circumferentially at the same three positions in the horizontal pipe. With these measured temperature the thermal stratification phenomenon could be identified and a correlation with the pipe deformation could be confirmed.

Deformations were measured in seven different positions along the experimental section pipe. Rectangular rosettes strain gages bounded externally at the wall pipe measure deformations imposed to the experimental section pipe by thermal stratification. Measuring positions could be seen in Figure 4 and they are named as I, II, III, A, B, C and D.

The fluid used in the experiments was water and in PWR reactor the water used contains boric acid, what alter its chemical and physical properties but this simplification did not invalidate the studies.

3.2 Thermal Fatigue

Thermal fatigue is a fail mode that cause damages in structural parts and may increase them to dangerous conditions. The damages are caused by component internal variations of energy due to multiples thermal cycles or by temperature changing associated with the restriction of the part expansion. Consequences of thermal fatigue in a component part could be geometric deformations or changes in the material properties and because of them cracks could appear. Basically, thermal fatigue is caused by thermal cycling or by periodic temperature changes imposed to the components. Restriction of part expansion may be due to internal and external factors. The external constraints induce alternated loads in the component when it is heated and cooled down. In another way, the internal constraints could 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 could 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”, Merola (1995). A component that will be submitted to thermal fatigue must be designed to prevent unacceptable damages caused by fatigue loads. Thermal fatigue could be related to thermal striping, originated from temperature fluctuations, at the cold and hot fluids interface in a stratified flow. Thermal striping cause thermal cycling in the wall pipe material and cracks could appear at this site.

4 EXPERIMENTAL PROCEDURES

The experimental section is a horizontal pipe made of stainless steel type AISI 304L. The pipe external diameter is 0.1413m, with wall thickness of 0.0095m and 2.0m in length. In one end the pipe is welded to a flange that is attached to a pressure vessel that simulates the steam generator and at the other end it is welded to a 90° elbow. At the end of this elbow there is a 0.5m vertical pipe welded on it. At the other vertical pipe end a flange is welded to connect the experimental section to laboratory process. Figure 4 is a draft of the experimental section and the other accessories connected to it. Dimensions and geometry of the experimental section were designed in order to study the thermal stratification phenomenon in the most possible extension.
The measuring positions can be seen in Figure 4 and they were marked as A, B, C, D, I, II and III. At the positions I, II and III thermocouples and strain gages were installed, when in positions A, B, C and D just strain gages were bonded. Thermocouples were installed externally in the wall pipe and in probes that penetrates the pipe. Inside the pipe the thermocouples were positioned vertically along the diameter and outside they were positioned circumferentially at the same height as the inside ones as can be seen in Figure 5. Besides these, two thermocouples were positioned at the lower and at the upper pipe outside diameter at the measuring positions I, II and III. Strain gages were bonded just externally along the horizontal pipe, in the 90° elbow and near the vertical end position. At position I there were 9 inside and 11 external thermocouples, at position II there were 10 inside and 12 external thermocouples and at position III there were 6 inside and 8 external thermocouples. At position A there were 4 rosettes strain gauges, at position B 3 of them, at positions C just one rosette, at position D 3 rosettes, at positions I and II, 2 rosettes and at position III, 4 rosettes. Rosettes were named with capital letters starting with A and ending with S.

The thermal striping frequency was measured in a similar experimental section where thermal stratification thermo hydraulic studies were done. Thermo hydraulic experiments detected thermal striping frequency as being 0.25Hz, Rezende et al (2006). Thermal stratification with flow conditions that produces Froude numbers in the range of 0.02 and 0.2 has maximum frequency of 1Hz and amplitude of 5mm. It was detected that near the wall pipe and at the half diameter the amplitudes could reach their maximum values, Ensel et al (1995). The experiments in this work were done with Froude numbers around 0.05.

In order to start each thermal stratification experiment, steam was injected into the experimental section until temperature and pressure reach the set point. Injection of cold water flowing slowly into the section was the next experiment step. Cold water injection lasts for about 30 minutes or until cold water could be supplied. The next step was release the experimental circuit pressure. Signals from all experimental steps were collected into two systems, one for temperatures, pressure, levels, flow and other for strains and experimental section length changing.

![Figure 4 Experimental section sketch and its accessories](image-url)
Figure 5 Inside and outside thermocouples of measuring position I

5 RESULTS

5.1 Thermal Stratification

The thermal stratification experimental results allowed determine the temperatures distributions in the pipe wall and in fluid, the loads and deformations in the experimental section pipe. The temperature distribution in the fluid that is determined by the thermal stratification has a direct relation with the temperatures in the pipe wall. The external pipe wall temperature, which determines its deformation, is related with the fluid temperature and as a consequence the loads and stresses in the pipe wall are directly related to the pipe deformations.

The response analysis of the pipe experimental section could be done by classical engineering methods or by finite elements methods. Variations in material properties should be considered during transient and static analysis.

Figure 4 Experimental section assembled in the experimental circuit
In Figure 4 the experimental section could be seen in the experimental circuit. The position I 4th July 2008 external experimental temperatures can be seen in Figure 5. As can be seen in the figure, the wall pipe was under stratified temperature, during the cold water injection. In Figure 5, when all the thermocouples were showing increasing temperature, corresponds to the steam injection experimental step. After the stratification the temperature increases again, corresponding to the depressurizing experimental step. After that second increasing in temperature another stratification is formed during the depressurizing process. Figure 6 depicts the 4th July 2008 experimental thermo hydraulic parameters. In Figure 6a the flow in l/s (1e⁻³ m³/s) could be seen, in Figure 6b the Froude number and in Figure 6c the fluid velocity. The Froude number changes from at about 0.025 to around 0.061 from the beginning to end of the experiment. Changes in fluid velocity and flow are more significant in amplitude at the end of the experiment. Such changes could be caused by changes in pressure during the cold water injection. Figure 7 shows the 1st October 2008 experimental thermal stratification along the inside pipe cross section at positions I, II and III. In Figure 7a could be seen that the stratification in position I changes from around 50°C (323K) to 215°C (488K) in about 0.02m of the pipe diameter. In Figure 7b the same change in temperature happens in about 0.04m. In position III, temperature increases continuously as can be seen in Figure 7c and the increase in temperature follows a parabolic law.
5.2 Fatigue Tests

After 41 thermal stratification experiments, specimens from the thermal stratification section pipe material and from a preserved portion of this pipe were made and subjected to fatigue tests. The up-ad-down method was used to determine the mean fatigue limits and the 95% confidence limit of both sets of specimens. Figure 8 shows the up-and-down fatigue tests results to virgin material and in Figure 9 the section material results. A comparison between these results is shown in Figure 10 and a reduction in the fatigue limit of experimental section material could be noticed. The reduction in section material fatigue limit is 6.9% for the mean, 10.8% for the lower and 2.9% for the upper. In Figures 8 and 9 “O” mark stands for censoring at $2\times 10^6$ cycles and the “x” mark stands for fail.

![Figure 7](image1.png)
![Figure 8](image2.png)
![Figure 9](image3.png)
5.3 Numerical Simulations

Some stress and strain simulations of the thermal stratification section were already done. Simulations were carried out using a coupled analysis in the ANSYS code with ten nodes tetrahedral element Solid98. Outside temperatures, inside pressure and thermal insulation inputs for the numerical analysis were taken from 29th May 2008 thermal stratification experimental results. The loads were imposed to experimental section in 65 steps, each one taken from experimental results for every 10°C (10K) in change. In order to impose the loads to the experimental section, it was sliced horizontally in 6 planes and vertically in 10 planes, as can be seen in Figure 11.

The temperatures, pressure and insulation were informed to each volume, in an amount of 79, for the 65 load steps. A reference temperature of 300K was considered in numerical simulations. A von Mises stress...
simulation result for the load step 37 could be seen in Figure 12. The simulated and experimental results and a comparison of them are shown in Table 1. Some simulated results are very different from the experimental ones and some of them agreed satisfactorily. The rosettes F, M, N and R experimental results could be considered in good agreement with the simulations results in their positions. For rosettes B, E, H and I the experimental and simulated results agreement is poor. During simulations, mean values of material mechanical properties were considered for all load steps. These contribute to the experimental and simulated results disagreement. Another point is that just the maximum mean stresses are compared and they could happen in different load step rather than in load step 37.

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<tr>
<th>Rosette</th>
<th>Experiment</th>
<th>Experiment</th>
<th>Simulated</th>
<th>Variation %</th>
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6 CONCLUSION

An experimental study proposition to correlate the effects of the thermal fatigue, due to thermal stratification, and the damages caused to pipelines is presented in this work. Thermal stratification transients with the same injection nozzle Froude number range could be simulated in the designed experimental section. The thermal stratification is nonlinear at the pipe cross section.

Up-and-down fatigue tests done in the virgin and in the experimental section material determined that the thermal stratification phenomenon reduces the material fatigue limit. The mean fatigue limit reduces 6.9%, the lower 10.8% and the upper reduces 2.9%.

A numerical procedure was developed to simulate the experimental section response under thermal stratification. Simulated and experimental results agreed satisfactorily in some experimental section regions.
7 REFERENCES


