ANALYSIS OF THERMAL FATIGUE DUE TO THERMAL STRATIFICATION IN A NPP STEAM GENERATOR INJECTION NOZZLE

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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. Thermal stratification phenomenon is present in pipelines of Nuclear Power Plants (NPP) and calculations done up to the years 80 just consider linear loads. Consequently, many NPP pipelines became failing. In this work an experimental section, simulating the injection nozzle of a NPP steam generator, is subjected to the effects of thermal fatigue due to thermal stratification. The experimental section is 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 are measured externally and internally in three positions and deformations just externally in seven positions. Inside the pipe thermocouples are positioned vertically along the diameter in different levels. Deformations of the pipe experimental section are utilized as a guide parameter to carry out fatigue tests. 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 stresses and strain parameters to carry out fatigue tests in specimens made of pipe experimental section and in specimens made of the virgin pipe. In this work is possible to conclude that thermal stratification happens in the experimental section and that numerical and experimental results agreed in the pipe region where they are compared and that thermal stratification induces considerable thermal stresses and strains in the experimental section pipe material.*

Keywords*: thermal fatigue, thermal stratification, thermal cycling, injection nozzle, fatigue test*

1. INTRODUCTION

Leakages due to through wall cracks from some pipelines of NPP were first observed at the end of the years 80. This event motivated the United States Nuclear Regulatory Commission (NRC) to publish a bulletin recommending evaluations and corrective actions at the NPP pipelines subjected to thermal stratification (NRC, 1988). The through wall cracks may appear in welds and in the base material far away from welded regions. At that time researchers discovered that the cracks were due to thermal fatigue caused by loads conditions related to stratified flows present in those pipelines. The NPP design up to the years 80 do not considered the non-linear effects of the loads imposed to the pipelines due to thermal stratification. Calculations were done considering just a linear distribution of temperatures and loads in the cross section as well in longitudinal directions.

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

The option here is to study the effects of fatigue due to thermal stratification phenomenon in an experimental section that simulates the steam generator injection nozzle in a PWR NPP. During operations at low power, the water flows at low velocities into the component in study at temperatures ranging from 273K to 313K. At the same time in the injection nozzle there is the hot water from the steam generator at the temperature of about 553K and in the working pressure of 6.4MPa. At this point of the secondary loop the thermal stratification is favored by the water low velocities entering the steam generator and by the significant difference of temperature between the cold and the hot water. In order to study the effects of thermal stratification in the pipe material, sufficient amount of thermal stratification experiments are being simulated and constant deformation fatigue tests in specimens made of the experimental section pipe material will be done. Utilizing a virgin portion of the same pipe that was used to make the experimental section, specimens will be made and submitted to the same constant deformation fatigue tests. The results of these fatigue tests will be used to compare the fatigue life of the pipe submitted to the effects of the thermal stratification and the virgin pipe.

2. THE THERMAL STRATIFICATION PHENOMENON

If there were thermal stratification phenomenon in a pipe, it is submitted to loads due to the difference of temperature in its upper and lower regions. The upper region of the pipe tends to expand and at the same time its lower 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 separation interface 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 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.

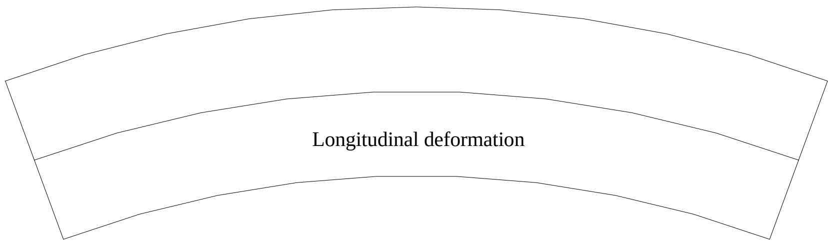

Figure 1 Longitudinal deformation due the difference of cross section temperature

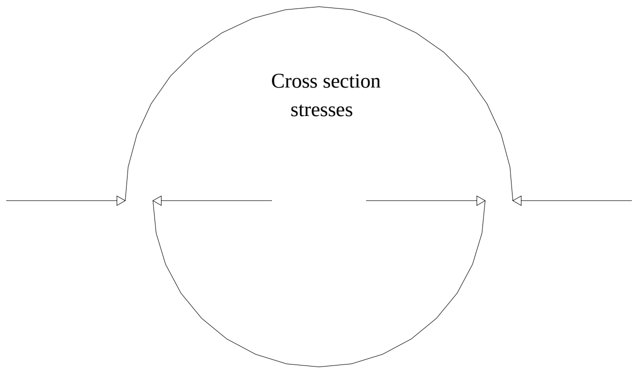

Figure 2 Deformations at the pipe cross section

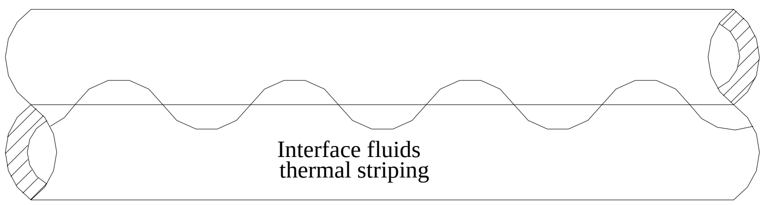

Figure 3 Thermal striping in the fluids interface

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 of hot fluid leaks with low velocities to the pipeline's side with cold fluid, inducing thermal stratification.

2.1 The Experimental Section and Simplifications

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 Froude number. Froude number is the hydraulic parameter commonly used to model thermal stratification phenomenon relating the flow velocity, acceleration due to gravity, difference of fluid density and the pipe internal diameter. The Froude number range of 0.02 to 0.2 is similar to that existing in PWR injection nozzle NPP. 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 are being done, do 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. They are measured inside along the diameter and distributed circumferentially outside in three different positions along the horizontal pipe length. With these measured temperature the thermal stratification phenomenon could be identified and a correlation for the pipe deformation could be confirmed. The pipe deformations are measured by strain gage rosettes positioned circumferentially in seven positions along the horizontal experimental pipe.

Measuring positions are defined and could be seen in Figure 4 as the positions I, II, III, A, B, C and D. The measured deformations will be utilized as a guide parameter to carry out the fatigue tests in the specimens made of the pipe experimental section and the ones made of the virgin material.

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

2.2 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 components internal variations of energy due to multiples thermal cycles or 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 cracks could appear because of them. Basically, thermal fatigue is caused by thermal cycling or by periodic temperature changes imposed to the components. Restriction of 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, what is done by imposing on it a number of fatigue cycles lower than the number of fatigue cycles established by the project calculations. Thermal fatigue could be related to thermal striping that is originated in pipe wall temperature fluctuations at the interface between cold and hot fluids. Thermal striping cause thermal cycling in the pipe wall material and cracks could appear at this site.

3 EXPERIMENTAL PROCEDURES

The experimental section is a horizontal pipe of AISI 304L stainless steel type. The pipe external diameter is 0.1413m, with 0.0095m wall thickness and 2.0m in length. A flange is welded to one end of the pipe and is attached to a pressure vessel that simulates the steam generator and a 90^o elbow at the other end is welded. The lower end of the elbow is welded to a vertical pipe of the same diameter and wall thickness that is connected to the circuit. Figure 4 depicts 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. Temperatures of water and pipe experimental section are measured in three positions. Deformations of the pipe experimental section are measured at seven positions along the horizontal pipe. These positions can be seen in Figure 4 and they are marked as A, B, C, D, I, II and III. At the positions I, II and III thermocouples and strain gages are installed, when in positions A, B, C and D just strain gages are bonded. Thermocouples are installed externally in the wall pipe and in probes that penetrates the pipe. Inside the pipe the thermocouples are positioned vertically along the diameter and outside they are positioned circumferentially at the same height as the inside ones as can be seen in Figure 5. Besides these, two thermocouples are positioned at the lower and at the upper pipe outside diameter at the measuring positions I, II and III. Strain gages are bonded just externally along the horizontal pipe, in the 90^o elbow and near the vertical position end. Many of them are positioned in the thermal stratification region and some of them in the upper region.

Among a set of experiments already done to study the thermo-hydraulic characteristics of the thermal stratification phenomenon, it was defined that the ones with low Froude numbers are more suitable to study thermal stratification influence in the pipe material. So, the experiments in this work are being done with Froude numbers up to 0.05, because this is the flow range that produces the most pronounced thermal stratification. A great amount of experiments are being done in the same condition to induce more loads in the pipe.

The thermal striping frequency was measured in a similar experimental section where thermo-hydraulic studies of thermal stratification were done and is detected 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).

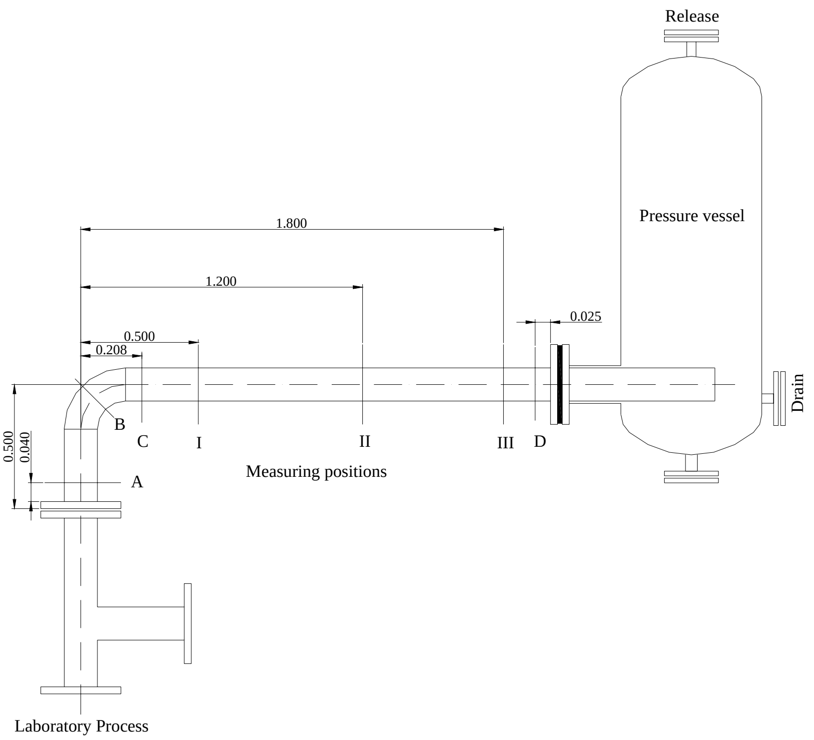

Figure 4 Sketch of the experimental section and its accessories

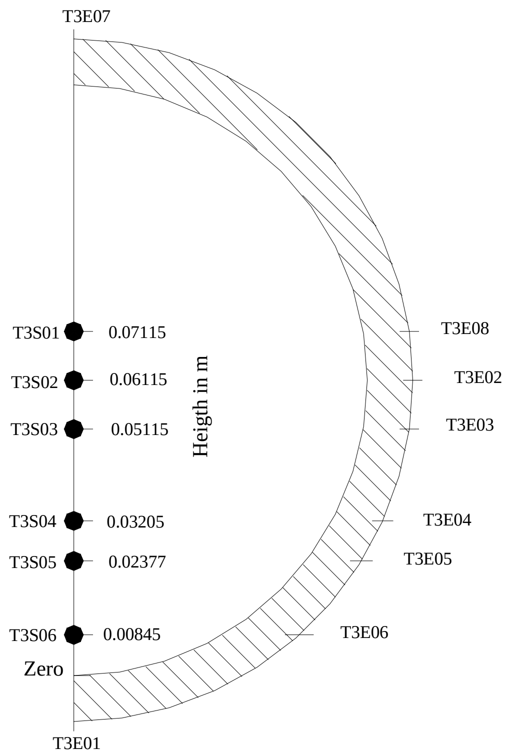

Figure 5 Inside and outside thermocouples of measuring position III

4 RESULTS

Experimental results allowed determining the pipe wall temperatures, the temperature distribution in the fluid, the loads and deformations in the experimental section pipe. The temperature distribution in the fluid that is determined by thermal stratification has a direct relation with the pipe wall temperatures. The injected cold water flow velocity and the temperature difference between cold and hot water are very important to the experiments because they determine the thermal stratification intensity. External pipe wall temperature, which determines its deformation, is related with the fluid temperature distribution and consequently the pipe wall loads 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. Changes in material properties should be considered during transient and static analysis. Experimental results will be used to validate a numerical procedure to help in future thermal stratifications works.

After a great number of thermal stratification experiments, specimens from the pipe thermal stratification and from a preserved portion of this pipe will be made and subjected to fatigue tests with constant deformation. Results of the fatigue tests will be utilized to plot the ε-N curves of the virgin pipe material and of the pipe experimental sections material. These curves could be compared to know the mechanical characteristics of the virgin steel and the steel that suffers thermal loads due to thermal stratification. By knowing the amount of damage induced in the pipe material, the lifetime of pipelines subjected to thermal stratifications phenomenon could be estimate.

A correlation between the surface temperature of the pipe experimental section and the water temperature could be done. This correlation is very important because in many situations the only information one could take is the external temperature of the pipe and knowing the external temperature it could be possible to infers the fluid conditions

4.1 Numerical Simulations

Preliminaries stress and strain simulations of the thermal stratification section are already done. Simulations were carried out using a coupled analysis in the ANSYS code (ANSYS, 2004) with ten nodes tetrahedral element Solid98. Temperatures and pressure inputs for the numerical analysis were taken from thermo-hydraulic experimental results. The temperature load was imposed to pipe section as a smooth transition between the cold and hot temperatures. It was done gradually using 18 loads steps to apply temperatures and pressure to the experimental section that was sliced horizontally in 7 volumes and vertically in 11 volumes, as can be seen in Figure 6. The experimental section was insulated and a reference temperature of 300K was considered in numerical simulations. Inside temperatures from thermo-hydraulic experiments were imposed to each volume as determined by the water temperatures measured by the probes inserted in measuring positions I, II and III (Rezende et al., 2006).

Two results of the major load step simulation are shown in Figures 7 and 8. The von Mises stresses could be seen in Figure 7 and in Figure 8 the von Mises strains. Position III outside experimental temperatures, the nearest temperature measuring position from strain gages at position D can be seen Figure 9. In this Figure it is possible to confirm that thermal stratification is present as thermocouples indicate different temperatures when cold water enters the experimental section. It happened at a time around 1200s and after this time the temperatures decrease until approximately 2500s. After 2500s temperatures increase again reaching values lower than the first ones and another thermal stratification happens. This phenomenon matches the experimental depressurization, when hot water from the pressure vessel flows into experimental section where there is cold water.

Figure 10 depicts the calculated maximum principal stresses and Figure 11 the maximum experimental strains from a rosette strain gage bonded at half pipe diameter at position D. As can be seen from Figures 7, 8, 10 and 11, there is an agreement between simulated and measured results. Major experimental calculated stress is approximately 210MPa and the simulated stresses at the strain gage S position are in the range of 148MPa to 295MPa, as can be seen in Figure 7. The major measured strain is approximately 0.00105μm/m and the simulated strains at the strain gage position vary from 0.000889μm/m to 0.001759μm/m, as can be seen in Figure 8. Compared stresses and strains are around the half pipe diameter in position D from Figure 4. As can be observed, the changes in stresses and strains are similar to the changes in temperatures. When temperature increases or decreases stresses and strains show the same behavior. Table 1 shows the experimental stresses at the seven positions along experimental section. It can be seen that for the same position, stresses are different depending on the position where the strain gage is positioned in the experimental section.

Table 1 Maximum von Mises stresses on the different sections at time 900sec

Position	Stress (MPa)
A	150
B	140/175/240
C	160
I	180/215
II	170
III	150/350
D	210

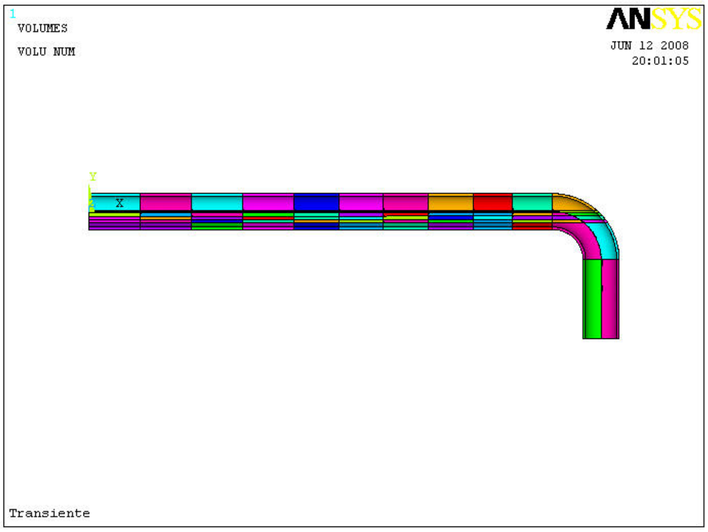

Figure 6 ANSYS model of the pipe experimental section

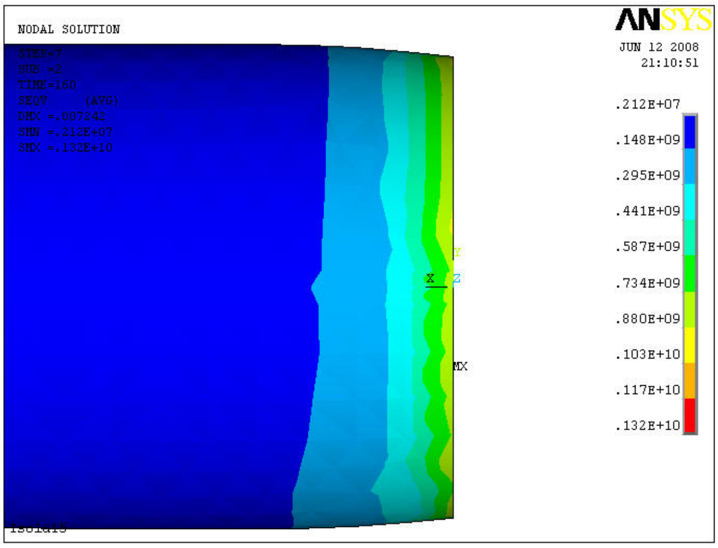

Figure 7 Detail of von Mises stresses at position D

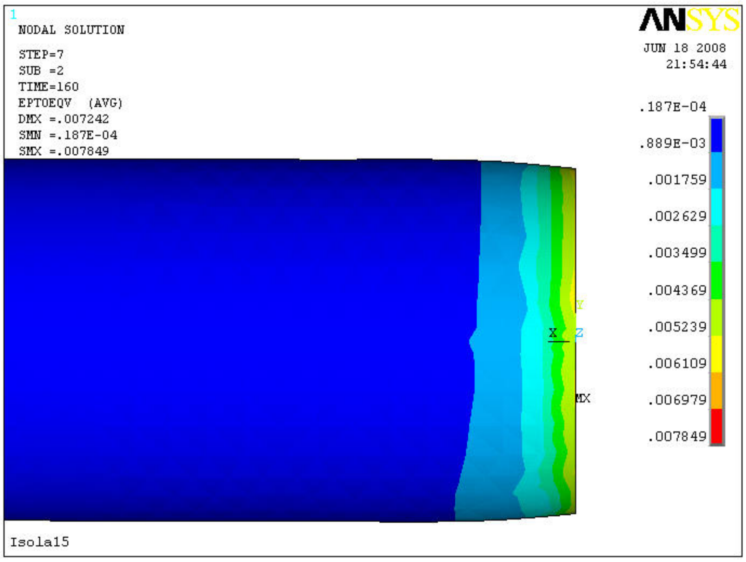

Figure 8 Detail of von Mises strains at position D

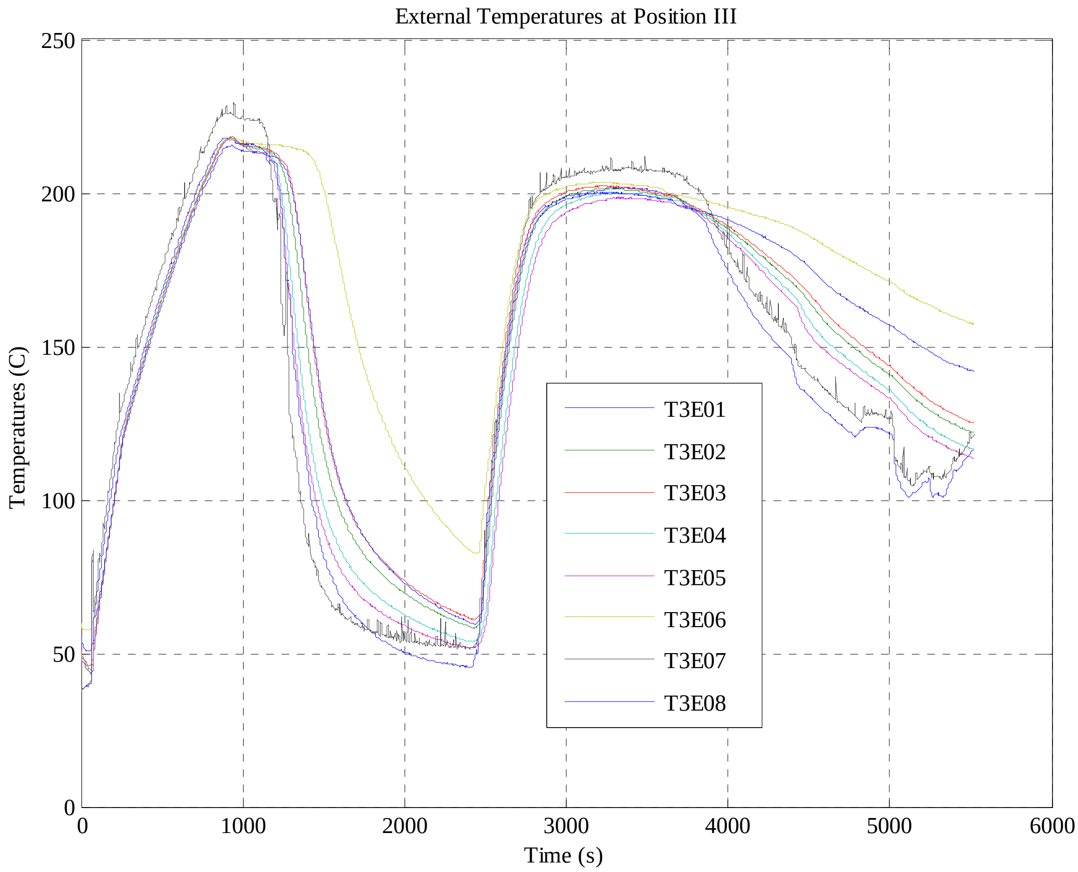

Figure 9 External temperatures of section III

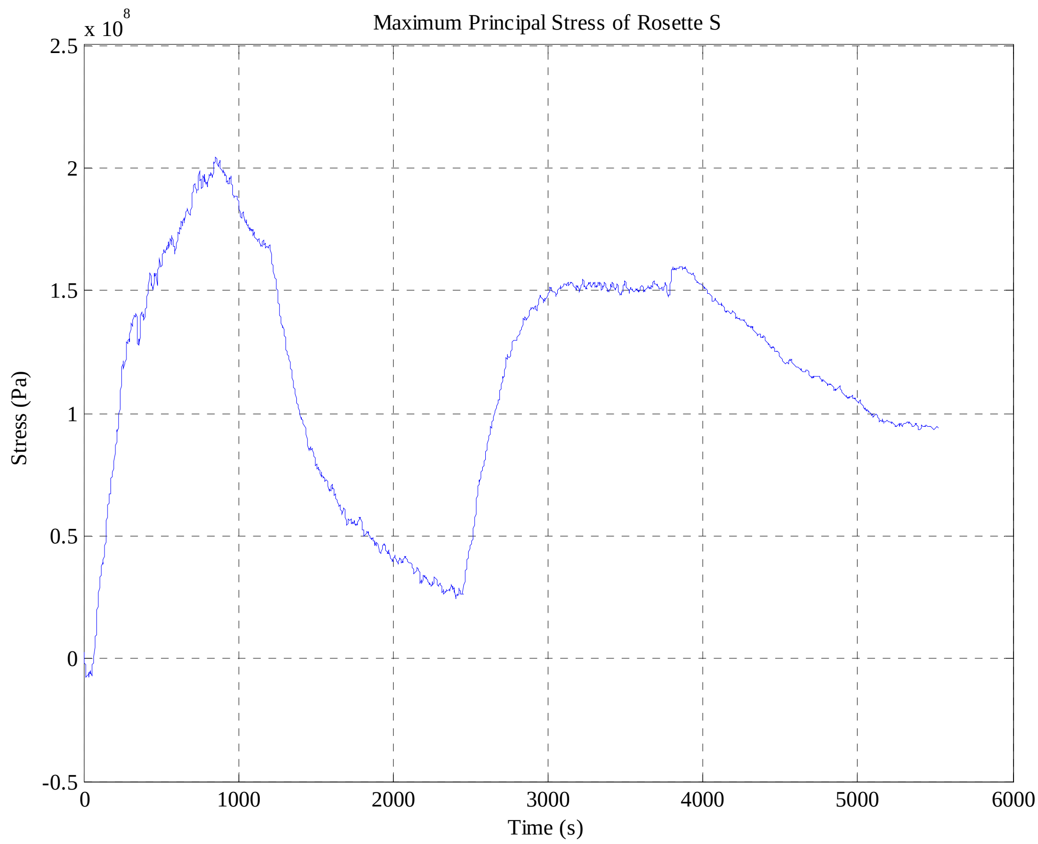

Figure 10 Stresses at position D

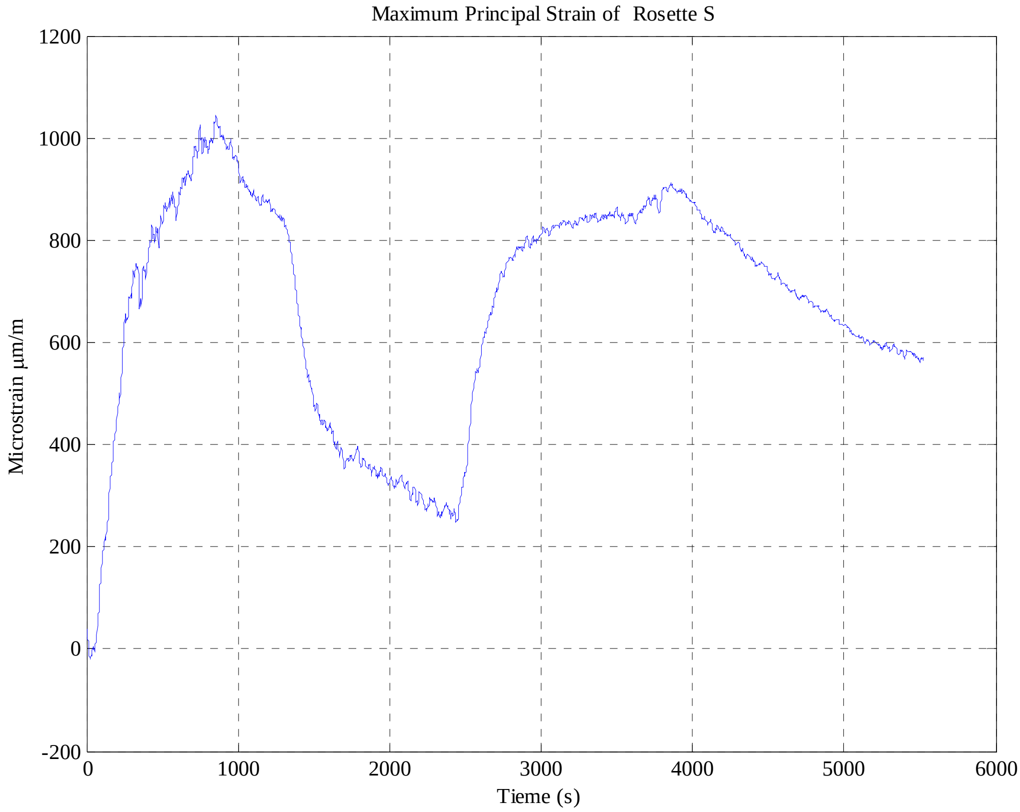

Figure 11 Strains measured at position D

5 CONCLUSIONS

An experimental study proposition to correlate the effects of thermal fatigue, due to thermal stratification, and the damages caused to pipelines is presented in this work. The proposed experimental section is capable to simulate the thermal stratification transients that occur in the steam generator injection nozzle. Experimental and simulated stress and strain at a same pipe position are in agreement. Measured stresses along the experimental section presented non linear behavior.

6 AKNOLEGEMENTS

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