Thermal Fatigue in Horizontal Pipelines Due to Thermal Stratification Phenomenon

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ABSTRACT

This work refers to an experiment to conclude a proposed thesis to study the damages due to thermal fatigue caused by thermal stratification phenomenon in horizontal pipes. The thermal stratification phenomenon must have a special attention, because it happens frequently in conventional and nuclear industrial process. This phenomenon is mainly associated with closed operational circuits where fluid fluxing in low velocities and in different temperatures mixes. When a pipe is subjected to a thermal stratified flow, non-linear longitudinal and circumferential loads appear on it and a thermal stripping in the edge between hot and cold water. In the Nuclear Power Plants (NPP) built up to the 80's, the pipe's calculations were done considering that loads as linear. Consequently, the pipes of some NPP became failing and the first damage informed occurred in Farley 2 in 1988. After that event the Nuclear Regulatory Commission (NRC) published a bulletin recommending evaluations and corrective actions at the NPP pipelines subjected to thermal stratification. In a NPP there are great possibilities of occurrence of thermal stratification at the hot and cold legs, at the pressurizer surge line, at the residual heat removal circuit and at the injection nozzle of the steam generator. The proposed studies constitutes in submitting a pipe at a significant number of thermal stratified experiments aiming to analyse the damages caused to its material, perform fatigue tests in specimens made of the pipe's experimental section and of the virgin pipe and plot both strain versus number of fatigue cycles tests curves (ε-N) to quantify the damage induced in the pipe's material and validate a numerical model that could estimates the damages that may appear in a pipeline subjected to thermal stratification. Study of structural integrity of pipelines subjected to thermal stratification in order to determine the causes of fails is the scope of this work. It could be concluded from this work that the proposed experimental methodology permits correlate the damages caused to the pipeline with the thermal fatigue originated in the thermal stratification phenomenon, and based in the amount of damages caused to the pipeline is possible to estimate the pipeline time life and the results of the numerical simulations are in accordance with the literature.

INTRODUCTION

The thermal stratification is present in horizontal pipes where two flows fluxes at different temperatures and at low velocities [1]. This phenomenon is frequent in NPP, in conventional thermal plants and in many other industrial processes that utilize fluids at the same state and in different states. During the thermal stratification phenomenon abrupt local changes in the fluid temperature occurs and this is harmful to the pipe's material. In this work the influence of thermal stratification of two water flows in the pipe’s material of an experimental section is the subject study.

At the end of the 80's leakage due to through wall cracks in some pipelines of NPP was observed and motivated NRC to publish a bulletin recommending evaluations and corrective actions at the NPP pipelines that could be subjected to thermal stratification [2]. The through wall crack could appear in welded regions and in the base material far away from welded regions. At that time researchers discovered that the cracks were due to fatigue caused by loads conditions related to stratified flow present in that pipelines. The design of the NPP up to the 80's do not considered the non linear effects of the loads imposed on the pipelines due to thermal stratification. Calculations were done considering a linear distribution of temperatures and loads as in the cross section as longitudinally.

In this work the proposition is to study the effects of the thermal fatigue originated in the thermal stratification phenomenon in an experimental section that simulates the injection nozzle of the steam generator of a NPP that runs pressurized water reactor (PWR). During operations with low power, the water flows with low velocities in the injection nozzle in a temperature ranging from 237K 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 circuit the thermal stratification is favoured by the combination of low velocities of the flowing water 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's material, a sufficient number of thermal stratification experiments will be simulated and constant deformation fatigue tests in specimens made of the experimental section pipe's material will be done. Utilizing a virgin portion of the same pipe, 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.

DESCRIPTION OF THE THERMAL STRATIFICATION PHENOMENON

When the thermal stratification phenomenon occurs, the pipe is submitted to loads due to the difference of temperature in its upper and lower regions of the cross section. The upper region of the pipe tends to expands and at the same time its lower region tries to constrain this expansion. This phenomenon of expansion and containment happening simultaneously causes 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 separation interface of the fluids, the lower cold part of the cross section of the pipe stay in tension and its upper hot part become contracted. This phenomenon causes circumferential stresses that may deform the pipe's cross section as can be seen in Figure 2. Another phenomenon that appears during thermal stratification is a significant local variation of temperature in the fluids interface which is known as thermal striping. Thermal striping could cause high cycle thermal fatigue and cracks 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 [3].

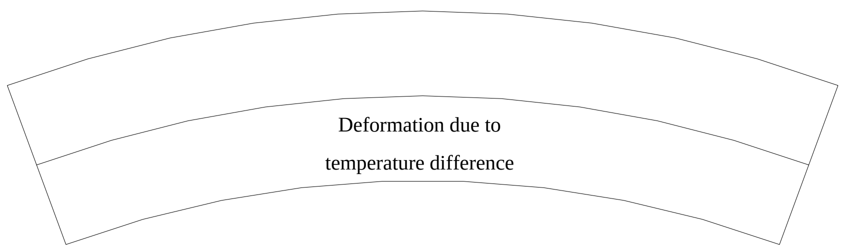

Figure 1 Longitudinal deformation due the difference of cross section temperature

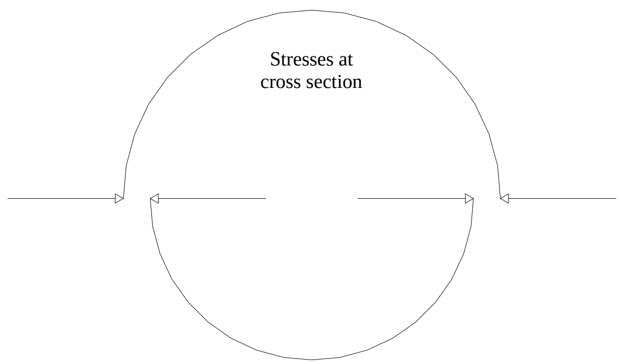

Figure 2 Stresses of the cross section of the pipe

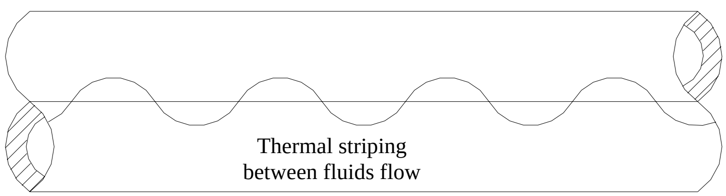

Figure 3 Thermal striping in the fluids interface

Operational characteristics of a PWR reactor includes the primary and the secondary loops where the same water is submitted to temperature variations that favours the occurrence of the thermal stratification phenomenon 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 surge line of the pressurizer and the injection nozzle of the steam generator [4]. 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 [5]. At these points a small amount of fluid leaks through the closing mechanism with low velocities inducing thermal stratification.

THE UTILIZED MODEL AND SIMPLIFICATIONS

The experimental section was made with geometric characteristics in order to obtain Froude numbers ranging from 0.02 to 0.2. This range of Froude number is similar to the range that exists in NPP that runs PWR reactors. 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 will be done do not support pressures above 2.3MPa. This limitation reduces the maximum work temperature of the water. On the other hand, the working temperature of the water in the injection nozzle is 6.4MPa. At the experiments, the maximum working temperature will not reach the steam generator temperature that is around 553K. The cold and hot temperatures of the water are very important for characterizing the thermal stratification phenomenon and they will be measured in different levels along the pipe's inside diameter. The temperatures will be measured circumferentially in the external surface of the pipe in three different positions along the horizontal pipe’s length. With these measured temperature the thermal stratification phenomenon could be identified and a correlation with the pipe’s deformation could be confirmed. The pipe’s deformations will be measured externally in six different circumferential and longitudinal positions. The amplitude of the thermal striping are being measured by a set of five thermocouples with a constant space of 0.002m between each other. The thermal striping frequency is defined as the inverse of the thermocouple time response. Both frequency and amplitude of the thermal striping phenomenon are being measured by the thermo hydraulic studies of the thermal stratification phenomenon in a experimental sections with the same characteristics. Measuring positions are defined and could be seen in Figure 4 as the positions I, II, III, A, B and C. The measured deformations will be utilized as a guide parameter to carry out the fatigue tests in the specimens made of the pipe’s experimental section and the ones made of the virgin material.

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

Thermal Fatigue

Thermal fatigue is a fail mode that cause damages in structural parts and may increase them to dangerous conditions. The cause of the damages are the component's internal variations of energy due to multiples thermal cycles or temperature changing associated with the restriction of the part's 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. The thermal fatigue originates basically in the thermal cycling or in periodic temperature changes imposed to the components. The restriction of the part's 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's coefficient of the material’s 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” [6]. 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 too, that is originated in the temperature fluctuations at the interface between the cold and hot fluids, depending on the velocity and the difference of temperature of the flow. Thermal striping cause thermal cycling in the material of the wall pipe and cracks could appear at this site.

EXPERIMENTAL PROCEDURES

The experimental section is made of a stainless steel pipe type AISI 304L in horizontal position, with external diameter of 0.1413m, 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^o elbow. At the end of this elbow there is a small vertical pipe welded on it and at the other end it is welded to a flange that is connected to the laboratory process. Figure 4 depicts the experimental section and the other accessories connected to it. The dimensions and geometry of the experimental section were designed in order to study the thermal stratification phenomenon in the greatest possible extension. Temperatures and deformations of the experimental pipe's section will be measured at six positions along the horizontal pipe that were previously defined. These positions can be seen in Figure 4 and they are marked as A, B, C, I, II and III. At positions I, II and III thermocouples and strain gages will be installed. On the other hand, in positions A, B and C just strain gages will be bonded. Thermocouples are already installed externally in the wall pipe and in probes that penetrates the pipe. Inside the pipe the thermocouples are positioned vertically in different levels along the diameter and at outside the pipe 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 positions of the outside diameter of the pipe in the measuring positions I, II and III. Strain gages are not installed yet and they will be bonded just externally along the horizontal pipe and at the 90^o elbow. Many of them will be positioned in the upper region of the pipe because this is more loaded than the lower region.

Among a set of experiments utilized to study the thermo hydraulic characteristics of the thermal stratification phenomenon, it was defined that the ones with low Froude number are more suitable to study the influence of the thermal stratification in the pipe's material. So, the experiments for this work will be done with Froude numbers up to 0.05, because this is the flow range that produces the most pronounced thermal stratification [7]. A great amount of experiments will be done in the same condition that induces more loads in the pipe.

The frequency of the thermal striping was already measured in a similar experimental section where thermo hydraulic studies of the thermal stratification phenomenon are being done and is detected as being 0.25Hz [8]. For the range of Froude number of 0.02 to 0.2, the maximum frequency and amplitude are 1Hz and 5mm, respectively. It was detected that near the wall pipe and at the half diameter the amplitudes could reach their maximum values [9].

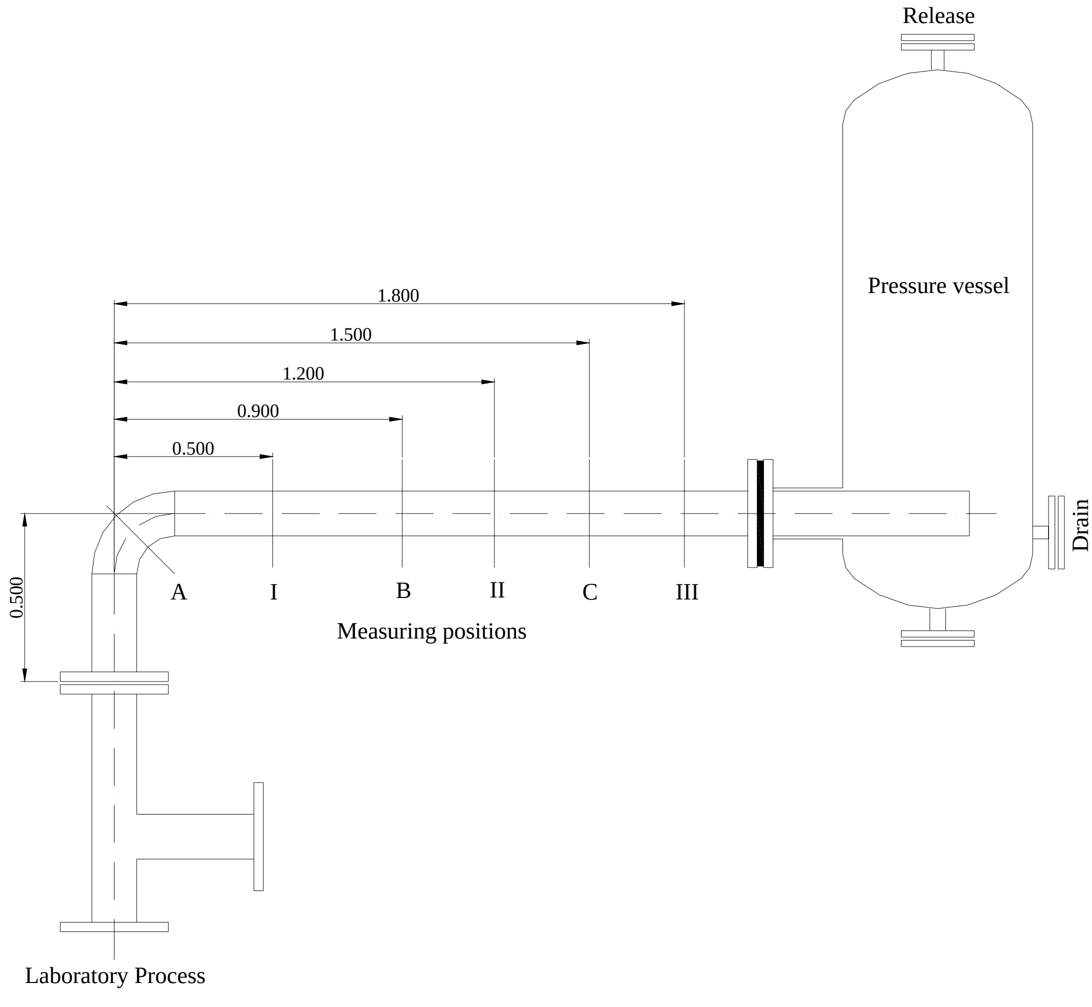

Figure 4 Sketch of the experimental section and its accessories

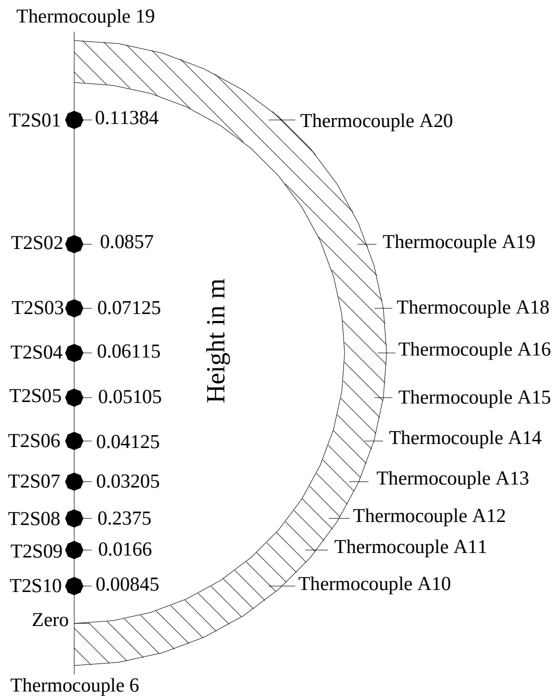

Figure 5 Inside and outside thermocouples of measuring position II

RESULTS TO BE OBTAINED

With the experimental results it will be possible to determine the temperatures of the pipe wall, the temperature distribution in the fluid, the loads and deformations in the pipe of the experimental section. 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 flow velocity of the cold injected water and the difference of temperature between cold and hot water are very important to the experiments because they determine the intensity of the thermal stratification. The external temperature of the pipe wall, which determines its deformation, is related with the fluid temperature. The loads and stresses in the pipe wall are directly related to the deformations of the pipe.

After a great number of thermal stratification experiments, specimens made of the pipe's thermal stratification and made of a preserved portion of this pipe will be 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's material and of the pipe's material of the experimental section. These curves could be compared to know the mechanical characteristics of the virgin steel and of the steel that suffers thermal loads due to thermal stratification. Knowing the amount of damage induced in the pipe's material it could be possible to estimate the life time of the pipelines subjected to thermal stratifications phenomenon.

A correlation between the surface temperature of the pipe's thermal stratification 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

NUMERICAL SIMULATIONS

Preliminaries stress and strain simulations of the thermal stratification section are already done. The simulations were carried out using a coupled analysis in the ANSYS code. In the simulations it was used the element SOLID98 which is a tetrahedron 10 nodes element. This element supports structural, thermal, magnetic and electric loads in its nodes what is ideal to carry out the simulation. The ANSYS free meshing of the experimental section with an element edge of 25mm create 12,234 elements and 23,997 nodes. In a couple analysis all loads are applied simultaneously, temperatures and pressure in the case. Temperatures and pressure inputs for the analyses were taken from the thermo hydraulic experimental results. The temperature load was imposed to pipe's thermal stratification section as a step load without smooth transition between the cold and hot temperatures, what that really exists in a narrow strip along the pipe length. The cold and hot temperatures imposed to the experimental section as loads is 316K and 482K, respectively and the pressure is 2MPa. The edge between hot and cold parts of the pipe, as can be seen in Figure 6, was determined by the temperature water measured by the probes inserted in the pipe at the measuring positions I, II and III [8]. Young modulus of the experimental section material's utilized in the simulations were E_1 = 178.41GPa and E_2 = 189.90GPa for hot and cold regions, respectively [10]. Thermal expansion coefficient, thermal conduction coefficient and Poison modulus are k = 16.67W/mK, α = 18.4e-6/K and ν = 0.29, respectively [11]. The model from ANSYS code of the pipe's experimental section is depicted in Figure 6 and the mesh could be seen in Figure 7. Two simulation results using the ANSYS code are shown in Figure 8 and 9. The von Mises deformations could be seen in Figure 8 and in Figure 9 the von Mises stress.

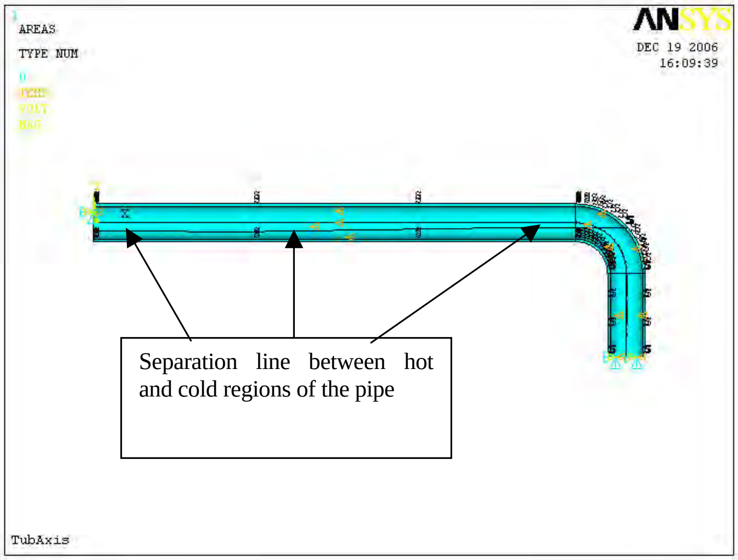

Figure 6 ANSYS model of the pipe's experimental section

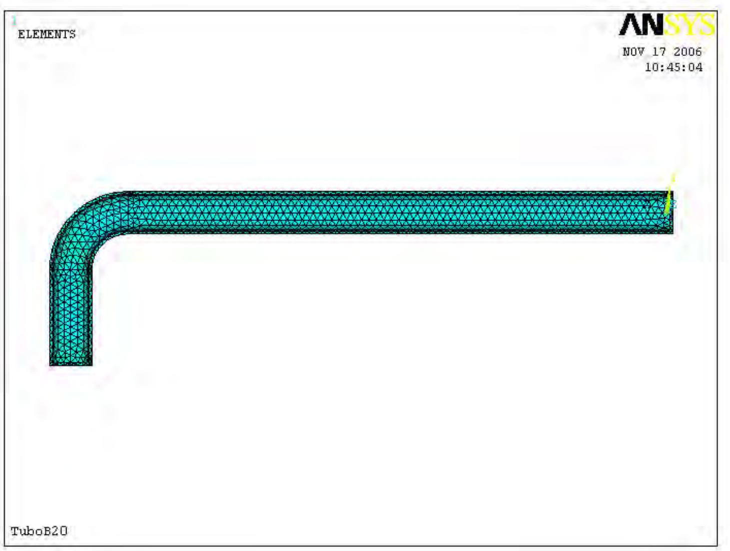

Figure 7 Meshed experimental section

Figure 8 von Mises deformation of the pipe's experimental section

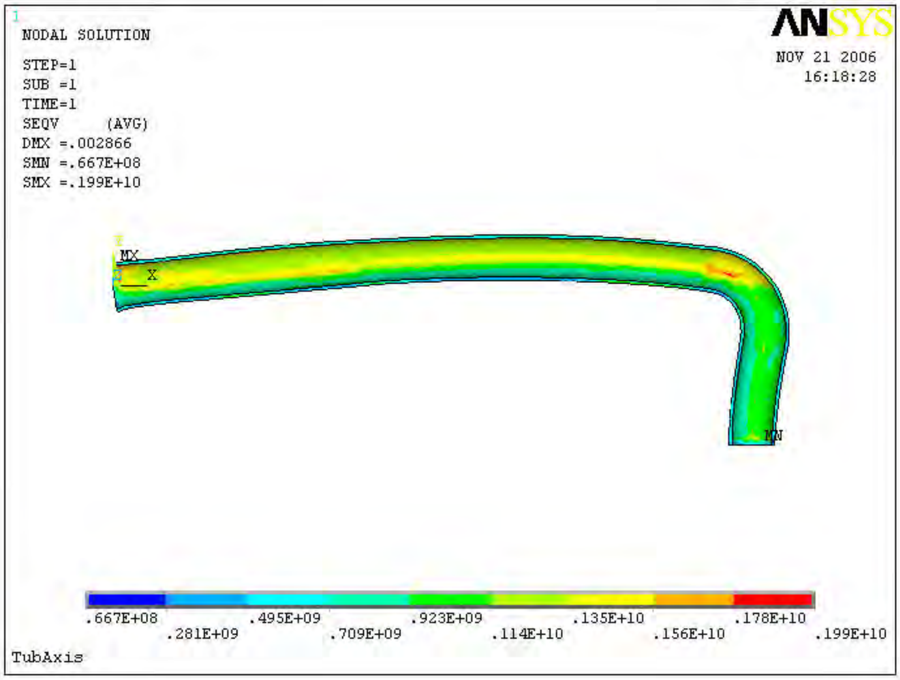

Figure 9 von Mises stress in the pipe's experimental section

The simulations results are in conformity with the specialized literature. Strains are around $\Delta\varepsilon = \beta\Delta T$, where $\Delta\varepsilon$ is the strain variation, β is the material's thermal coefficient of expansion and ΔT is the temperature variation. Considering the conditions of the experimental sections the $\Delta\varepsilon$ value is $\Delta\varepsilon$ = 8,4e-6*(482-316) = 0,0031m. Stresses are around

$\Delta\sigma = \frac{E\beta\Delta T}{1-\upsilon}$, where $\Delta\sigma$ is the stress variation, E is the Young modulus, β is the material's thermal expansion coefficient, ΔT is the temperature variation and ν is Poison modulus [12]. The stresses for the case is $\Delta\sigma$ = 184,16e9*18,4e-6*(482-316)/(1-0,29) = 0,8036Gpa, considering the mean Young modulus.

CONCLUSIONS

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. An estimated life time of pipelines submitted to thermal stratification, based in the amount of damages caused to the material's pipelines could be determined. The proposed experimental section is capable to simulate the transients that occur in the nozzle injection of the steam generator. The fatigue tests will permit to plot ε-N curves and characterize the pipe's material. The experimental results will be used to validate a numerical model. Results of the numerical simulations are in accordance with results found in the literature.

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