Proceedings of COBEM 2007
19th International Congress of Mechanical Engineering
November 5-9, 2007, Brasília, DF

FINITE ELEMENT COUPLED THERMO-MECHANICAL ANALYSIS OF THERMAL STRATIFICATION OF A NPP STEAM GENERATOR INJECTION NOZZLE

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Abstract. *This work refers to a numerical analysis to study damages due to thermal fatigue caused by thermal stratification in horizontal pipes. When a pipe is subjected to a thermal stratified flow, non-linear longitudinal and circumferential loads and thermal stripping appear. This phenomenon is present in pipelines of Nuclear Power Plants (NPP) and analysis performed up to the 80's considered only linear loads. Consequently, failure was recorded in many pipes of NPP. In this work, a finite element model simulating the AISI 304L stainless steel pipe, part of the injection nozzle of a NPP steam generator, was subjected to the effects of thermo-mechanical loading due to thermal stratification. The model considered specific geometric characteristics in order to obtain Froude numbers ranging from 0.02 to 0.2, the same range of a NPP that runs PWRs (Pressurized Water Reactors). Coupled thermo-mechanical numerical simulations were performed using ANSYS as finite element platform, with temperatures and pressure inputs taken from results of a conducted thermo-hydraulic experiment. Strain fields obtained will be used as first approximation to design an experiment for thermal fatigue evaluation.*

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

1. INTRODUCTION

At the end of the 80's, leakage due to through wall cracks was observed at some pipelines of NPP (Nuclear Power Plants) and motivated NRC (Nuclear Regulatory Commission) to publish a bulletin recommending evaluations and corrective actions at the Nuclear Power Plant (NPP) pipelines subjected to thermal stratification (NRC, 1988). The through wall cracks could appear in both welded regions and in the base material far away from welded regions. At that time researchers found out that the cracks were initiating due to thermal fatigue caused by loading conditions related to stratified flow present in those pipelines. The design of NPPs up to the 80's did 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 not only for the cross section but also longitudinally.

The thermal stratification is present in horizontal pipes where the fluid flow is divided in two low velocity fluxes at different temperatures. This phenomenon is frequent in NPPs, in conventional thermal plants and in many other industrial processes that use refrigerating fluids. These refrigerating fluids could be at the same state or at different states. During the thermal stratification phenomenon, abrupt local changes occur in the fluid temperature and this can be harmful to the pipe's material (Liu and Cranford, 1991).

In this work, strain fields due to thermal stratification are studied through a coupled thermo-mechanical finite element analysis using the code ANSYS as the finite element platform. The selected fluid was water and the simulating component was the injection nozzle of the steam generator of a NPP that runs pressurized water reactor (PWR). This component has a horizontal pipe where thermal stratification was verified. During operations with low power, the water flows with low velocities into this component at temperatures ranging from 273K to 313K. At the same time, there is the hot water flowing from the steam generator at temperature of about 553K and under working pressure of 6.4MPa. Thermal stratification is then favored 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. Results are to be used as first approximation for designing an experiment to access the effects of thermal stratification on the fatigue life of such components.

2. THERMAL STRATIFICATION

When the thermal stratification phenomenon occurs, the horizontal 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 expand and, at the same time, its lower region tries to constrain this expansion (Kim *et al.*, 1993). This phenomenon of expansion and containment happening simultaneously cause longitudinal loads in the pipe that are responsible for bending it as shown in Fig. 1. This effect is commonly called as the banana effect. At the same time, in the separation interface of the fluids, the lower cold part of the cross section stay in tension and the upper hot part become contracted. This phenomenon causes circumferential stresses that may deform the pipe cross-section as can be seen in Fig. 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 flaws in the internal surface of the pipe. The thermal striping phenomenon is characterized by an oscillating frequency and amplitude associated to it as shown in Fig. 3.

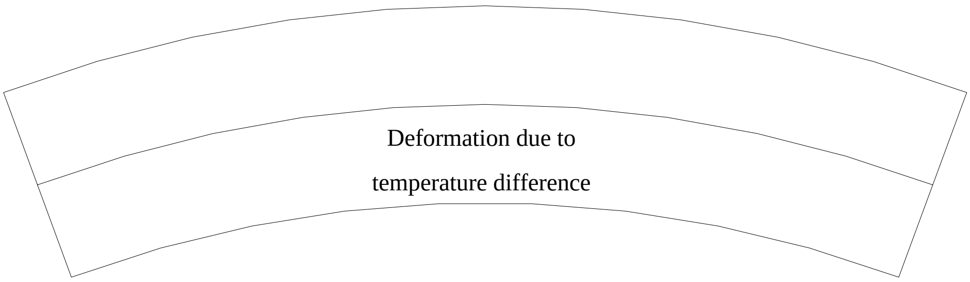

Figure 1. Longitudinal deformation due the difference of cross section temperature

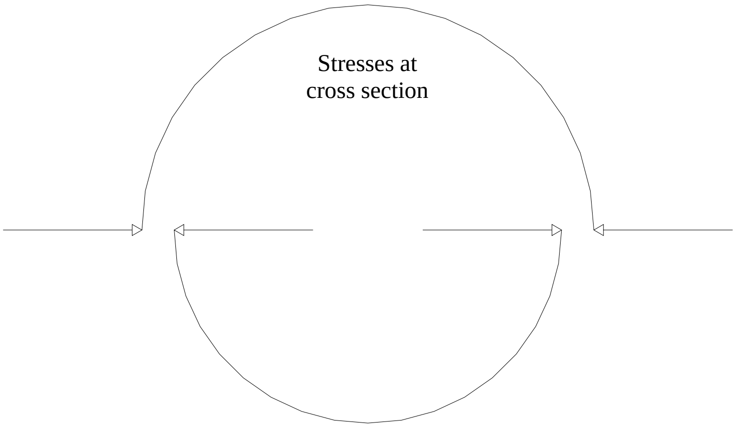

Figure 2. Deformations at the cross section of the pipe

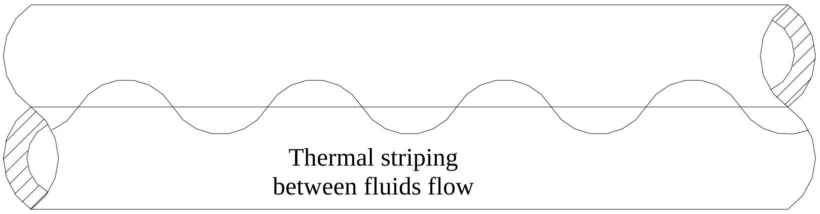

Figure 3. Thermal striping in the fluids interface

Operational characteristics of a PWR reactor includes primary and secondary loops where the same water is submitted to temperature variations what favors the occurrence of thermal stratification during start up, shutdown and power variations of the NPP. Besides these two operational circuits there are others that can be also submitted to thermal stratification. The circuits with great possibility of occurrence of thermal stratification 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: the hot and cold legs, the surge line of the pressurizer and the injection nozzle of the steam generator (Jo *et al.*, 2001). Thermal stratification may also 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 region where cold fluid is, inducing thermal stratification.

3. FINITE ELEMENT STRATEGY

3.1. Model input

An experimental section was designed by Rezende *et al.* (2006) with geometric characteristics adequate to obtain Froude numbers ranging from 0.02 to 0.2. This range of Froude number is similar to the ranges that exist in NPPs that run PWRs. Using this range of Froude number, it is possible to do experiments with a vast proportion of hot and cold fluids and with great gradients of temperatures.

Rezende *et al.* (2006) designed experimental section is schematically shown in Fig. 4. Thermal stratification occurred on the horizontal pipe, which was selected to be modeled using the finite element method in this work. Three measurement positions were established to capture the hot and cold flows of the thermal stratification along the pipe. However, the thermo-hydraulic pressure was limited to 2.3MPa. This limitation reduced the maximum working temperature of the water at the experiment. On the other hand, the working pressure of the water in the injection nozzle of a typical NPP is 6.4MPa. The maximum working temperature was expected to be 373K (100^{o}C) and 553K (280^{o}C) at the steam generator. Temperature profiles were obtained at the three measurement sections (I, II and III) showed in Fig. 4. These three sections were instrumented internally and externally with thermocouples as shown in Figs 5 and 6. Internal thermocouples were used to capture the hot-cold interface of the fluid. External thermocouples were intended to present the actual thermal profile on the pipe material.

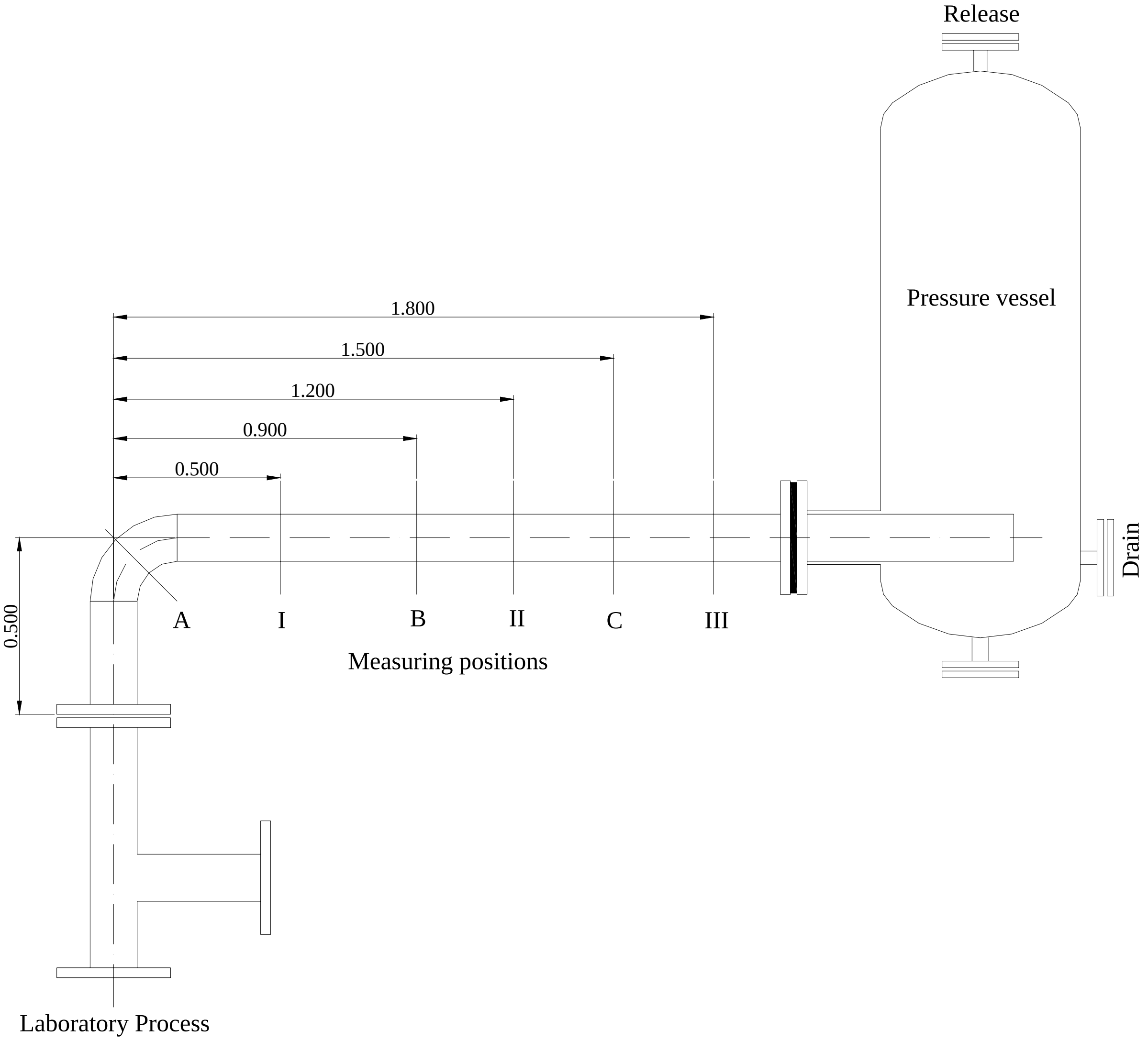

Figure 4. Sketch of the experimental section and its accessories Rezende *et al.* (2006)

Rezende *et al.* (2006) also measured the frequency of the thermal striping as 0.25Hz for their experiment. 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 5. Internal and external thermocouples of measuring position I Rezende *et al.* (2006)

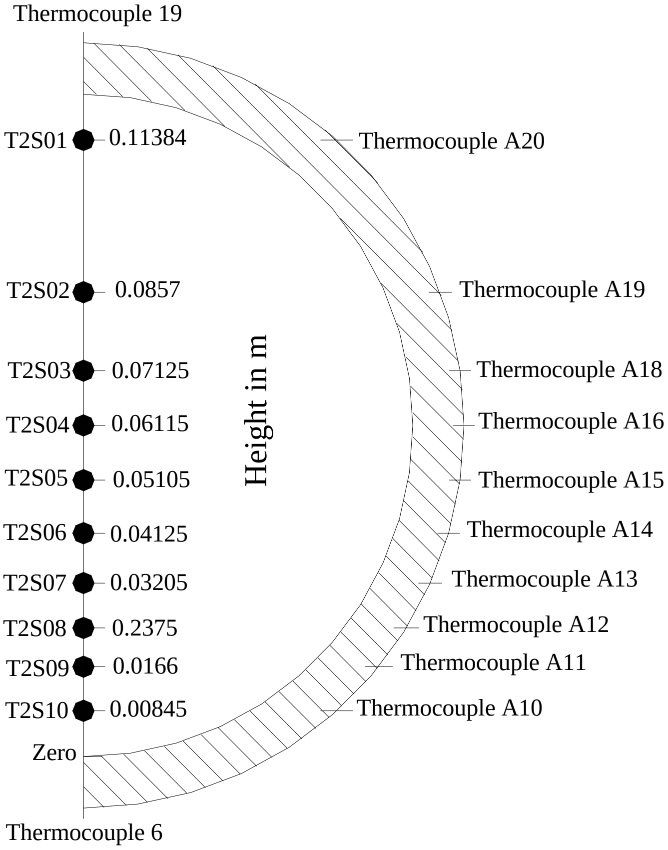

Figure 6. Internal and external thermocouples of measuring position II Rezende *et al.* (2006)

3.2. Model material, geometry, loading and boundary conditions

According to Fig. 4, the experimental section was modeled as a horizontal AISI 304L stainless steel pipe, with mechanical and physical properties shown in Tab. 1 (ASME, 1998). The pipe had external diameter of 0.1413m, wall thickness of 0.0095m and 2.0m length. It was connected in one end at the steam generator and in the other end to a 90^o knee section connected to a small vertical pipe. Therefore, the simulation domain consisted to the horizontal pipe, where the thermal stratification occurred, the 90^o knee section and the small vertical pipe. The code ANSYS was used as the finite element platform. For more accurate results, three-dimensional 10-node SOLID98 tetrahedral elements were selected to mesh the domain. Mesh was generated for element size of 25mm, resulting in a 12,234 elements and 23,997 nodes model. The finite element mesh is presented on Fig. 7.

Table 1. Mechanical and physical properties of AISI 304L steel (ASME, 1998).

Property	Symbol	Value	Unit
Young’s Modulus (cold – 316K)	E_{cold}	189.9	GPa
Young’s Modulus (hot – 482K)	E_{hot}	178.41	GPa
Poisson’s Ratio	ν	0.29	–
Thermal Conduction Coefficient	K	16.67	W/mK
Thermal Expansion Coefficient	β	$18.4\text{x}10^{-6}$	/K

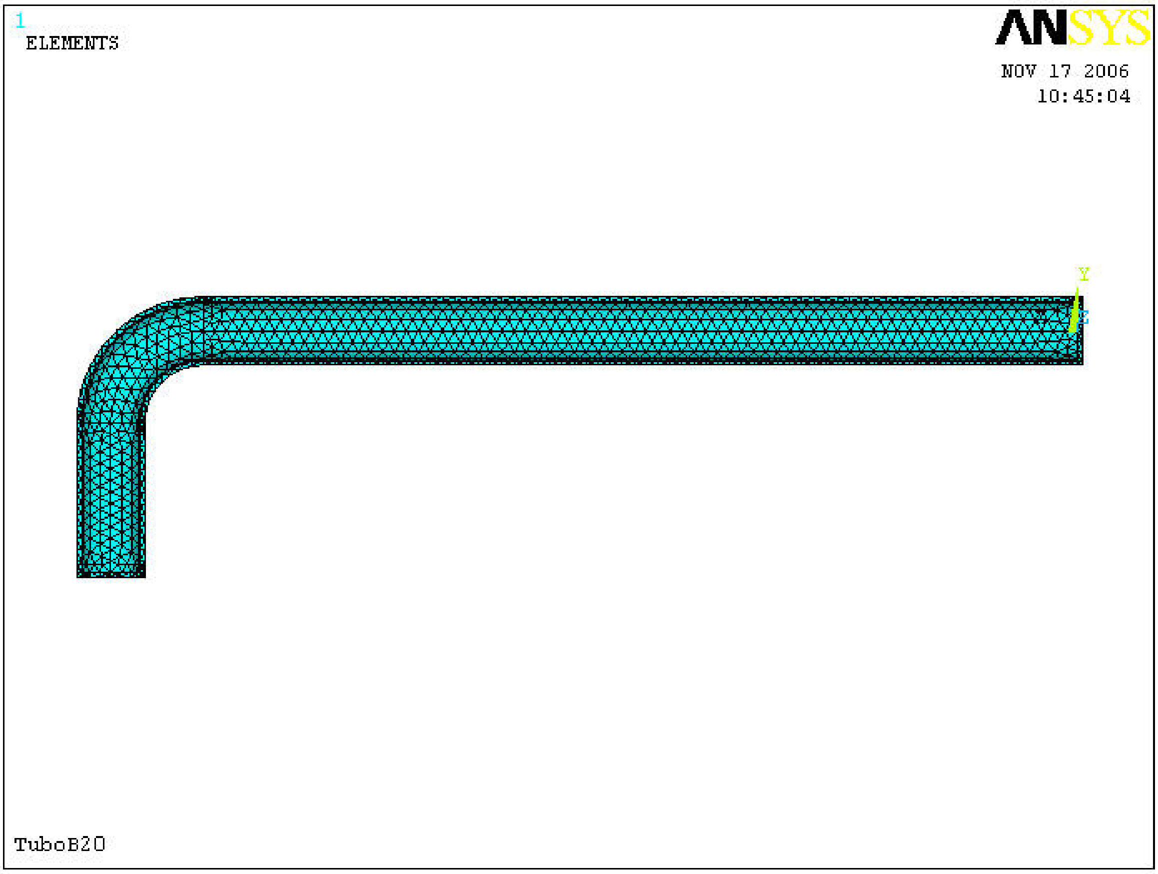

Figure 7. Finite element mesh

Coupled thermo-mechanical analysis was performed considering both thermal load (temperature profiles) and mechanical load (internal pressure) simultaneously applied. Experimental results obtained from Rezende *et al.* (2006) were simulated on the model.

According to Rezende *et al.* (2006), thermal stratification occurred in a very well defined interface. Therefore, for simplification, the model considered the thermal loading as a step temperature change at this interface separating the domain in two different regions: (i) the hot region, with temperature of 482K (209°C), and (ii) the cold region, with temperature of 316K (43°C). The material stiffness was also different in these two regions. The hot-cold regions interface was defined from Rezende *et al.* (2006) as shown in Fig. 8.

Mechanical loading considered was constant internal pressure of 2 MPa. The model was considered clamped in both ends. Problem symmetry allowed the modeling of only one-half of the real structure. Material behavior was assumed linear and elastic.

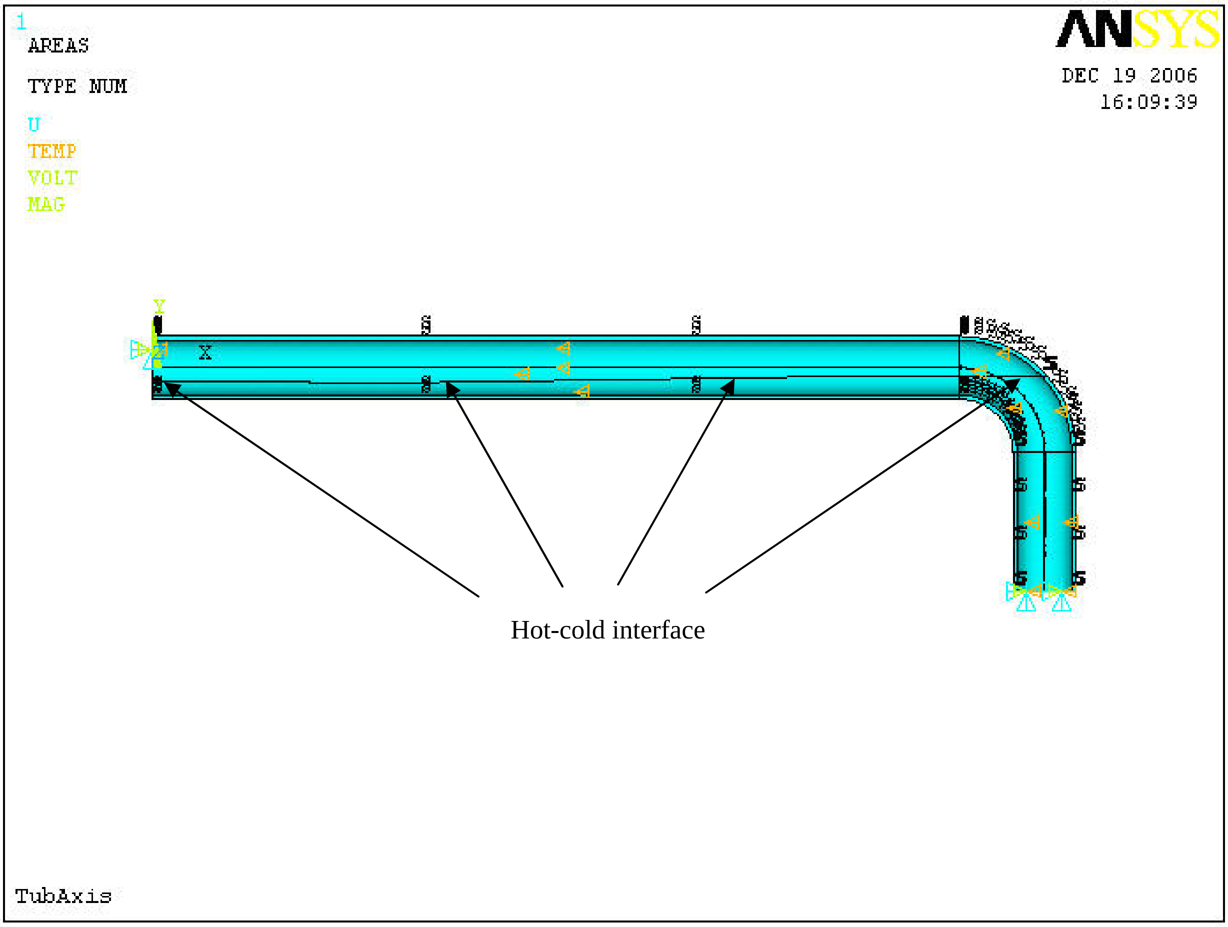

Figure 8. Thermal stratification hot-cold interface

3.3. Finite element analysis and future experiment design

Strain fields obtained in the finite element analysis will be used as first approximation to design a new experiment for thermal fatigue evaluation. This experiment will take into account how the thermal stratification phenomenon may affect the fatigue life of the pipe material. Therefore, strain fields are expected to be evaluated not only at positions I, II and II but also at positions A, B and C of the pipe (Fig. 4), where instrumentation using strain-gages will be mounted on the future experiment for model simulation comparison.

4. RESULTS

Stress and strain fields were obtained from the numerical simulation of the section presenting thermal stratification. The simulation was performed using a thermo-mechanical coupled finite element analysis. Figures 9 and 10 show, respectively, the von Mises strain and stress fields. Strains and stresses variations could be evaluated as (Talja and Hansjosten, 1988):

$$\Delta\varepsilon = \beta\Delta T \tag{1}$$

$$\Delta\sigma = E\Delta\varepsilon\,/\,(1-\nu) \tag{2}$$

Table 2 shows the maximum von Mises strain and stress compared with the values obtained using Eqs.(1) and (2), for $\beta = 18.4x10\text{-}6/K$, $\Delta T = 482 - 316 = 166\ K$, $E_{cold} = 189.9\ GPa$ and $\nu = 0.29$. It can be observed that the values are high for this kind of simulation, indicating that thermal fatigue could occur at components submitted to thermal stratification for the used parameters. Simulation results for maximum von Mises strain and stress occurred in specific areas close to the 90^o knee section. Simulation results presented values 55% and 12% higher, respectively for strain and stress, when compared with calculation values.

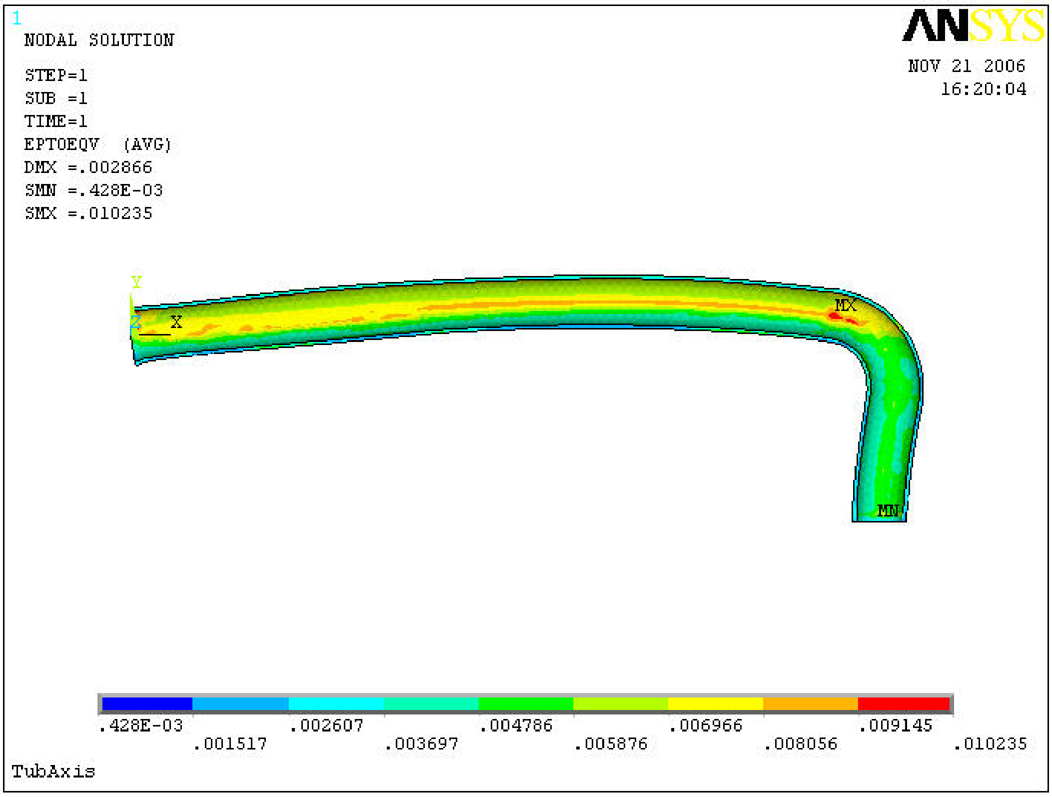

Figure 9. von Mises strain field

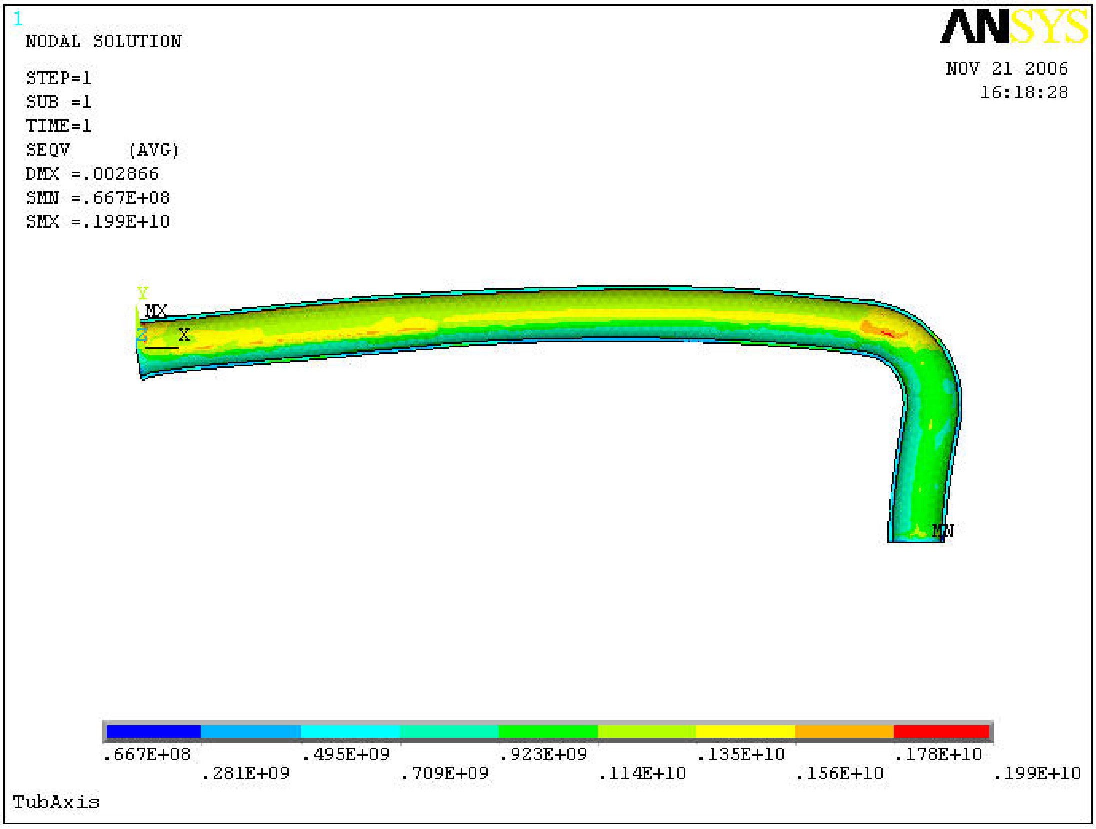

Figure 10. von Mises stress field

Table 2. Results

Results	$\Delta\varepsilon$	$\Delta\sigma$ (GPa)
Simulation results (maximum)	0.0102	1.99
Simulation results (average)	0.0048	0.92
Eqs. (1) and (2) (average)	0.0031	0.82

5. CONCLUSIONS

A numerical simulation performed in a model in order to study the thermal stratification problem is presented in this work. This simulation is intended to serve as baseline to design an experimental proposition to correlate the effects of thermal fatigue due to thermal stratification and related damages caused to pipelines. Strain and stress fields were evaluated so that points of concentration could be identified and correct instrumentation could be designed for the future experiment. Results presented high levels of strain and stress for the parameters used, indicating that thermal fatigue could occur at components submitted to thermal stratification.

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7. RESPONSIBILITY NOTICE

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