THERMAL ANALYSIS OF A CLAD PIPE USING SIMULATION

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Abstract: Cladding is a process where one material covers another for protection or to obtain a specific property that is not exist in one of the two materials, but exist in the second material. The use of clad pipes provide an optimum and the cost-effectiveness solution when operating under highly corrosive conditions (crude with H2S, CO2, or in offshore area) or in high pressure operations. This paper introduces briefly the clad pipes and presents the results of thermal behaviour simulation of the clad pipe which utilized to perform a mesh sensitivity study. A (10″) Stainless Steel clad pipe, which consists of a thin-walled inner Stainless Steel pipe and an outer Carbon Steel pipe, was used as a model in the current study. Finite element analysis was used as an experimental method to determine the stresses and the deformations on the clad pipe due to applied tensions and heat. In addition, the clad pipe was put under the same temperature conditions during the winter and summer times that in Sarir Oil Field to show the heat flux and the temperature gradient across the cross section of the clad pipe. Abaqus software was used to simulate the process. The results of thermal behaviour simulation of the clad pipes were obtained for different mesh types and sizes. A comparison between the different mesh types was carried out to determine the appropriate mesh type for the model. A mesh sensitivity study was performed to obtain the most accurate results. The simulation results show that the most appropriate mesh type for the current model is Tet (free), C3D4T: A 4-node thermally coupled tetrahedron, linear displacement and temperature (model 3). Because it has the maximum S (max) value (2.900E + 09Pa), and most accurate results are obtained when the global mesh size range is from (≤0.02 for the outer pipe and from ≤ 0.009 for the inner pipe).

Keywords: Clad Pipe, Thermal Analysis, 3D Finite Element Modelling.

INTRODUCTION

Pipe Cladding

Combines the advantage of a high strength carbon steel outer pipe (backing steel) with an inner layer of corrosion resistant alloy, yielding improved pipeline (Berg and Schnaut, 2009). Clad pipes are widely used in oil and gas industry, they are produced by cladding of a thin Corrosion Resistance Alloy (CRA) pipe and a thick carbon steel pipe by different manufacturing methods. The use of clad pipes provides an optimized and cost-effectiveness solution when operating under highly corrosive conditions (crude with H_2S, CO_2, or in offshore area) or in high pressure operations.

For example, The problems associated with the corrosion in pipelines due to the presence of hydrogen sulfide in crude oil in some of AGOCO`s oil fields (Nafoora Field GOSP 1, 7, 9, and Beda Field) can be avoided by using clad pipes instead of addition of expensive chemicals (which costs millions $ every year). Table 1 shows H_2S concentrations in pipeline system from Beda & Nafoora oil fields to Ras Lanuf in 2008.

CRA clad pipe can be classified into two types depending on the method used to bond the two materials, metallurgical bond (CRA clad pipe), and mechanical bond (CRA lined pipe).

Metallurgical bond (CRA clad pipe)

Metallurgical bond can be created by hot rolling, explosive bonding or weld overlay, and co-extrusion, the metallurgical bond clad pipes are expensive and there are only few suppliers who have the ability to produce these pipes.

Mechanical bond (for CRA lined pipes)

Two major methods are used to create the mechanical bond between the steel and a CRA

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material, the expanded lined and rolled lined steel pipe.

DESCRIPTION OF NUMERICAL SIMULATION

Based on the finite element (FE) analysis package ABAQUS, a 3D model was developed to provide two analyses for a clad pipe (coupled temperature and displacement analysis & heat transfer analysis). The main purpose of the simulation is to perform a mesh sensitivity study, and to show the temperature gradient across the cross section of a clad pipe, the max. stress & heat flux.

The model is a (10″) stainless steel clad pipe, which consists of two pipes, a thin-walled inner stainless steel pipe of thickness (2mm), and diameter (254mm) the inner pipe is the "liner" pipe (it works as a coating to protect the main pipe from corrosion. In this model, the outer pipe is a carbon steel with a thickness (10mm). The 3D model for the stainless steel clad pipe is shown in (Fig. 1).

Table 1. H_2S Concentrations in Pipeline System from Beda & Nafoora oil fields to Ras Lanuf in 2008.

Location	API Gravity (at 60o F)	S.G. Of Oil (at 60o F)	H_2S in Oil (mg/liter)
Beda	34.5	0.852	229
Nafoora	35.7	0.846	210

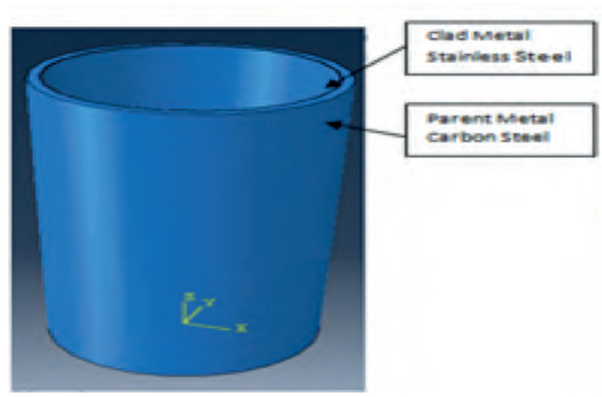

Fig. 1. The 3D Model.

Coupled Temperature and Displacement Analysis

The 3D model clad pipe was kept fixed at one end and, at the other end a tensile load of 350 kPa was applied. The clad pipe is at 317.15K, which is the ambient temperature (max temperature at Sarir Oil Field 44^{o}C), the internal surface of the clad pipe was at 339.15K (66^{o}C), due to the hot crude oil flow in the clad pipe, all other sides are supposed to be insulated. The clad pipe expands due to the heat flow, the numerical modelling involved two steps, the initial step (which is automatically created by Abaqus) and step-1 (at which the load was applied). At the initial step the boundary conditions for the fixed end of the clad pipe were applied. Whereas, the boundary conditions for the free end of the clad pipe and the tensile load were applied at step-1. The solution processes for Coupled Temp- Displacement Analysis are shown in (Fig. 2). Table 2 shows the properties for the used materials (Carbon Steel & Stainless Steel).

Different mesh types were examined by copying the 3D model twice (Model- 2 & Model- 3) to run the job for three different mesh types. Table 3 and Fig. 3 show the three mesh types.

Mesh Sensitivity Study

To change the mesh density, model 3 has been copied to create seven new models. The size of the mesh has been changed, and the results have been compared to carrying out the mesh sensitivity study. Table 4 shows mesh sizes for the eight models.

Heat Transfer Analysis

The same 3D model was used to perform the following heat transfer analyses, all heat transfer analyses were performed assuming (no winds), wind velocity was neglected:

Steady state heat transfer analysis: For this analysis two BCs were created to verify the temperature gradient across the cross section of the clad pipe during winter and summer times in Sarir oil field.

Steady State and transient heat transfer analyses: Assuming that the clad pipe is not thermally isolated during two seasons, winter and summer, (conduction, convection and radiation were taken into consideration). For these heat transfer analyses one BC was created (the temperature for the hot crude oil 66^{o}C), predefined field was created in the initial step, conduction, convection and radiation were simulated by creating interactions.

Table 5 shows the boundary conditions for the steady state heat transfer analysis (BC1 is the maximum and minimum temperature degrees in Sarir Oil Field during the summer and the winter), BC2 is the oil temperature.

Table 6 shows the created interactions for the non isolated pipe heat transfer analyses. For conduction heat transfer, tie constraints has been created to

Table 2. Thermal and Mechanical Properties for Carbone Steel & Stainless Steel.

	Property	Value
Parent Metal (Carbon steel)	Young's Modulus	200GPa
	Poison's ratio	0.3
	Density	7850 kg/m3
	Thermal Conductivity	42 W/m.k
	Specific heat	490 j/kg.k
	Thermal expansion Coeff.	0.000014 (m/m.ºC) *14e-6*
Clad Metal (Stainless Steel)	Young's Modulus	197.5 GPa
	Poison's ratio	0.27
	Density	7970 kg/m3
	Thermal Conductivity	15 W/m.k
	Specific heat	510 j/kg.k
	Thermal expansion Coeff.	0.000016 (m/m.ºC)

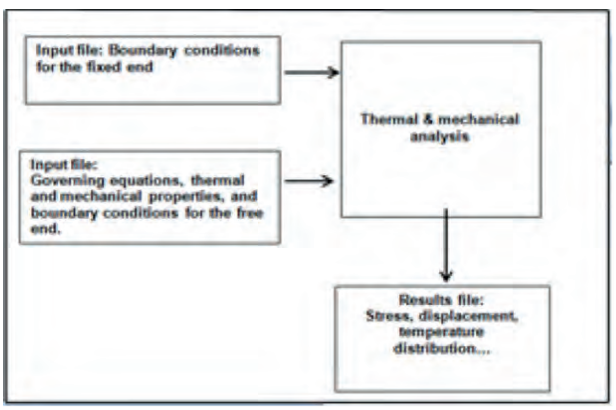

Fig. 2. The Solution Processes for Coupled Temp- Displacement Analysis.

Table 3. Mesh Types.

Model	Mesh Type
Model- 1	6840 Linear hexahedral elements of type C3D8T
Model- 2	12149 Linear wedge elements of type C3D6T
Model- 3	38453 Linear tetrahedral elements of type C3D4T

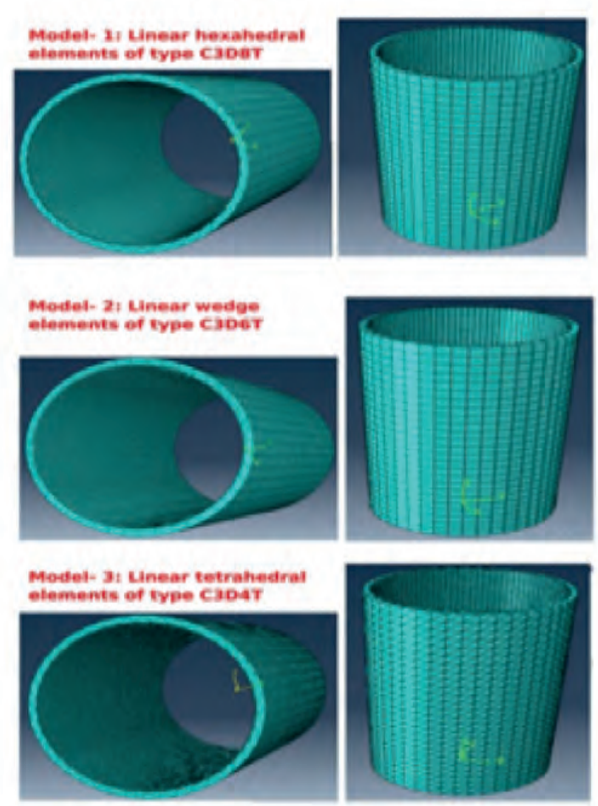

Fig. 3. The Mesh Type.

identify the surface connection between the two metals (CS & SS).

The value of Stefan- Boltzmann Constant is 5.67 E-008, and the Emissivity for the carbon steel is 0.63. The natural convection heat transfer coefficients during summer and winter were determined by using excel spreadsheets, the natural convection heat transfer coefficient correlations (S.I. units) was calculated by using the following correlations:

$$Nu = \left\{0.6 + \frac{0.387\,Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2$$

$$Gr = \frac{D^3\,\rho^2\,g\,\Delta T\,\beta}{\mu^2}, \quad Nu = \frac{h\,D}{k}, \quad Pr = \frac{\mu\,C_P}{k}$$

For Ra , Ra = Gr Pr

Natural convection heat transfer coefficient during summer and winter for air in Sarir Oil Field were found about 3.94W/m^2-K, and 5.62W/m^2-K respectively.

Steady state heat transfer analysis: While the hot crude oil is flowing in the clad pipe, the properties of Sarir crude oil, according to AGOCO`s Operation Department are shown in (Table 7). The specific heat of Sarir crude oil was determined as a function of API gravity and Temperature by using the following formula (Bengtson, 2013):

$$C_P = (-1.39\times10^{-6}\times T + 1.874\times10^{-3})\times API + (6.312\times10^{-4})\times T + 0.352$$

Where: C_P = btu/ (ibm. ºF), T = ºF.

The specific heat of Sarir crude oil is 0.5079 btu/(lbm. ºF, which is equal to 2.1265 K.j/KG. K The thermal conductivity for Sarir crude oil was determined by using the following formula:

$$k = 0.118\,\rho^{-1}[1 - 0.00054(T - 273)]\times10^3$$

Table 4. Mesh Size.

Model	Inner pipe mesh size	Outer pipe mesh size	Number of Elements
Model 3- b	0.01	0.03	27624
Model 3- a	0.0095	0.025	31385
Model 3	0.009	0.02	38453
Model 3- 1	0.0085	0.015	47306
Model 3- 2	0.008	0.01	75068
Model 3- 5	0.0077	0.007	145182
Model 3- 4	0.0076	0.006	182366
Model 3- 3	0.0075	0.005	257920

Table 5. Boundary Conditions for the Steady State Heat Transfer Analysis.

Season	BC1 Temp. (°C)	BC2 Temp. (°C)
Summer	44	66
Winter	0	66

Table 6. Interactions for the Non Isolated Pipe Heat Transfer Analysis.

Heat Transfer Method	Interaction	Type of Interaction
Convection	Int-1	Surface Film Condition
Radiation	Int-2	Surface Radiation

Table 7. Sarir Crude Oil Properties and flow Information.

Property	Value
Flow type	Turbulent
Re	4600
Density	837 kg/m^3
API	36.5
Viscosity	1.1e^{-5} m^2/s

The thermal conductivity for Sarir crude oil at 66 °C is 135.96 m.W/(m K).

The heat transfer coefficient for Sarir crude oil was determined by using excel spreadsheet, h = 103 kJ/hr-m^2-K, which is equal to 28.611 W/m^2-K. Since Prandtl Number, Pr = 26.9 and Re = 4600, the following correlation was used to determine the heat transfer coefficient for Sarir crude oil:

$$Nu_o = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)}$$

Where $f = (0.790 \ln Re - 1.64)^{-2}$

For: $0.5 < Pr < 2000$

$3000 < Re < 5\times10^6$

RESULTS

Comparing the Different Mesh Seizes

The jobs have been created, submitted and running to get the result of the three models. The results are shown in (Figs 4, 5 & 6 and Table 8).

The maximum stress values for the three models have been compared and it has been found that the best type of mesh for the current project is: Tet (free), C3D4T. A 4-node thermally coupled tetrahedron, linear displacement and temperature. which is for model 3. Because it has the maximum S (max) value, thus the meshes will converge faster.

Mesh Sensitivity Study Results

The jobs have been created for the different mesh size models, the simulations have been run, and the results are represented in (Table 9). The relations between the number of elements and the maximum stress, and the number of elements and the deformation (Figs. 7) are shown in (Figs. 8 & 9).

Heat Transfer Analysis Results

For the thermally isolated, steady state heat transfer analysis the temperature gradients during the winter and the summer are shown in (Fig.10). For the non isolated, steady state and transient heat transfer analyses (where the heat applied with no crude oil flowing inside the clad pipe) the maximum heat fluxes during the winter and the summer are shown in (Table 10).

From the transient analyses, the number of nodes has been selected to plot the relation between the temperature and the time, in summer and winter times, to verify how the temperature changing during the time until reaches the steady state. The relation between temperature and time is shown in (Figs.11 and 12). The times needed to reach the study state in winter and summer were found 214.1s, and 201.3s respectively.

For the non isolated, steady state heat transfer analysis, with the crude oil flowing inside the clad pipe, the maximum heat fluxes during the summer and the winter are shown in (Figs.13 & 14).

CONCLUSION

Two types of thermal analysis, (coupled temperature and displacement analysis and heat transfer analysis), have been carried out on a 10″ stainless steel clad pipe, thickness, 2mm for SS, and 10mm for CS. The aim of these thermal analyses

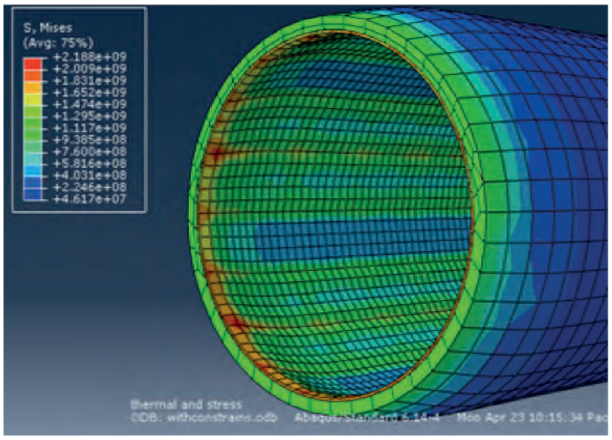

Fig. 4. Model 1, Stress Results.

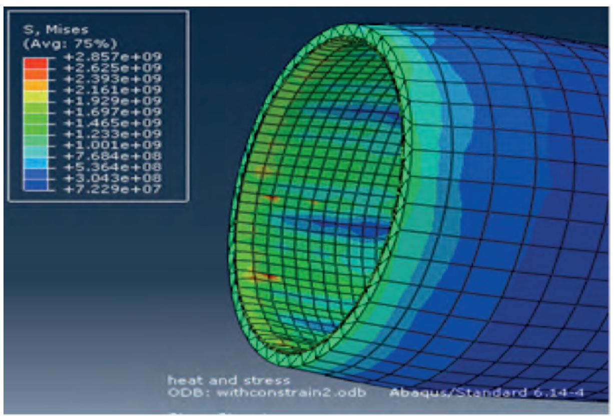

Fig. 5. Model 2, Stress Results.

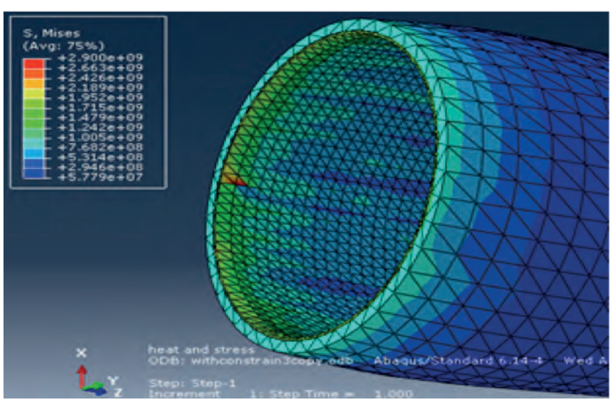

Fig. 6. Model 3, Stress Results.

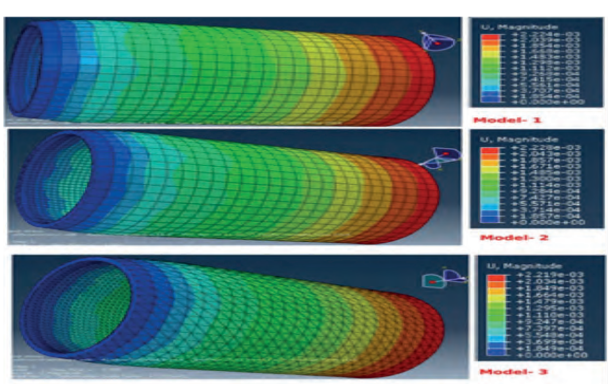

Fig. 7. Deformation.

Table 8. The Results for Model 1, 2, & 3.

Model	**Number of Elements**	**S (max) Pa**	**U (max) m**
Model 1	6840	2.188E+09	2.224E-03
Model 2	12149	2.857E+09	2.228E-03
Model 3	38453	2.900E+09	2.219E-03

Table 9. Mesh Sensitivity Study Results.

Model	**Number of Elements**	**S (max) Pa**	**U (max) m**
Model 3-b	27624	2.02E+09	2.22E-03
Model 3-a	31385	3.17E+09	2.22E-03
Model 3	38453	2.90E+09	2.22E-03
Model 3-1	47306	2.67E+09	2.23E-03
Model 3-2	75068	1.66E+09	2.21E-03
Model 3-5	145182	1.63E+09	2.21E-03
Model 3-4	182366	1.66E+09	2.21E-03
Model 3-3	257920	1.54E+09	2.21E-03

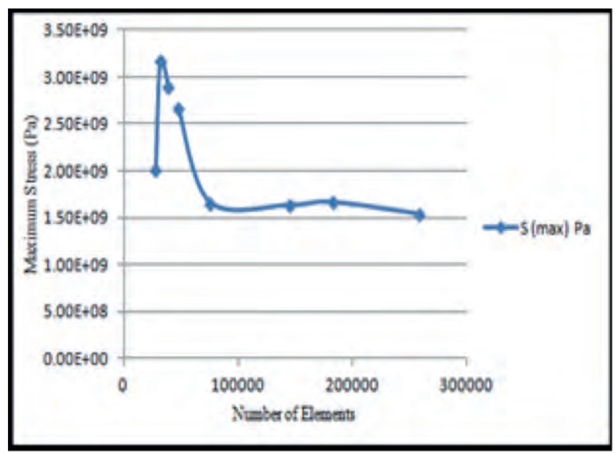

Fig. 8. Relation between the Number of Elements and the Maximum Stress.

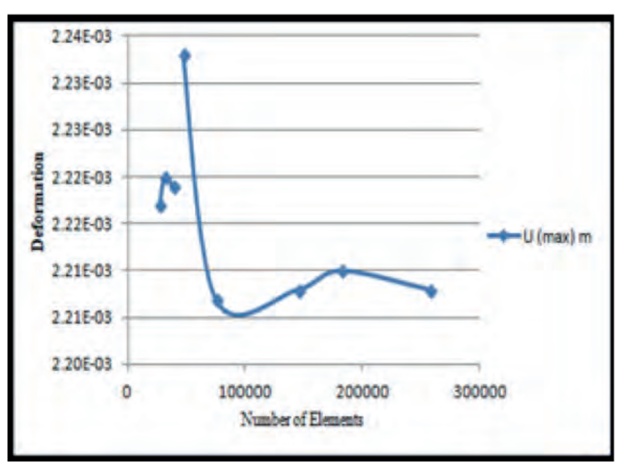

Fig. 9. Relation between the Number of Elements and the Deformation.

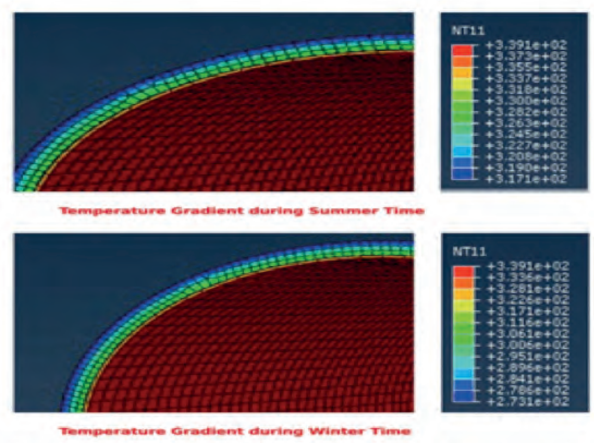

Fig. 10. Temperature Gradient.

Table 10. Maximum Heat Flux for Non Isolated Heat Transfer Analysis.

Heat Transfer Method	Interaction	Type of Interaction
Convection	Int-1	Surface Film Condition
Radiation	Int-2	Surface Radiation

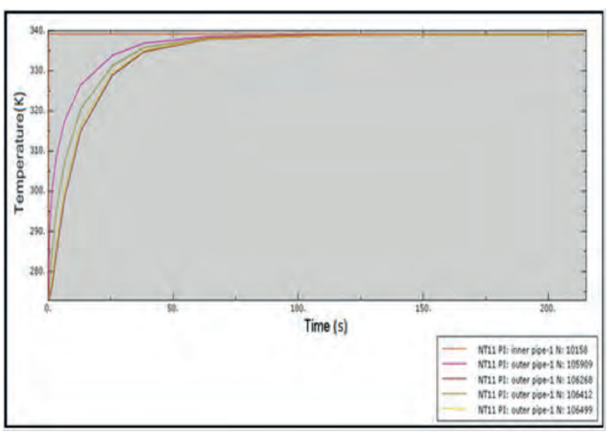

Fig. 11. Time Needed to Reach Thermal Equilibrium in Winter.

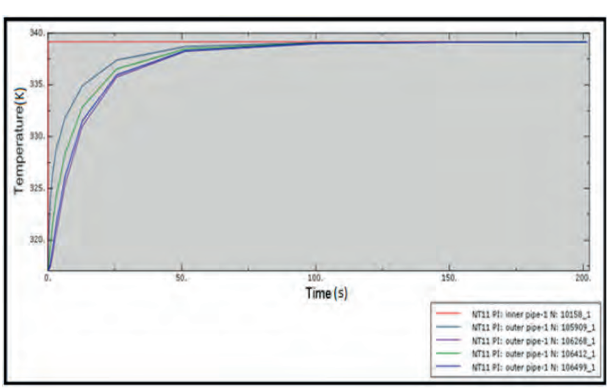

Fig. 12. Time Needed to Reach Thermal Equilibrium in Summer.

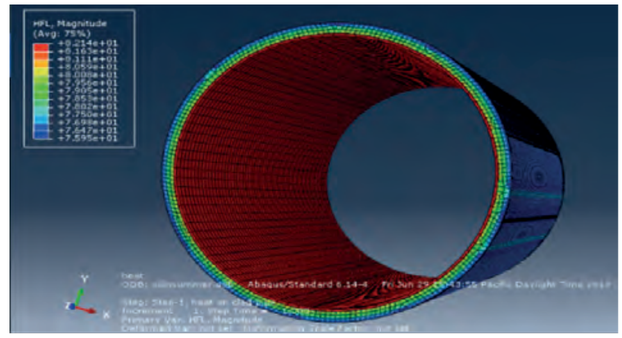

Fig. 13. The Non Isolated, Steady State Heat Transfer Analysis (with oil) in Summer.

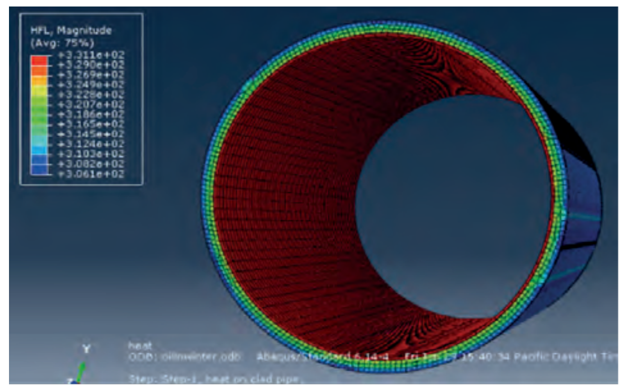

Fig. 14. The Non Isolated, Steady State Heat Transfer Analysis (with oil) in Winter.

is to verify the thermal behavior of the clad pipe when it's used in the Sarir Oil Field instead of the current carbon steel pipe. An FEA model has been developed using the Abaqus software. In the coupled temperature and displacement analysis, the accurate results were obtained by carrying out a mesh sensitivity study. In addition, the temperature gradient, heat flux values, and the transient curves also obtained from the heat transient analyses. The best type of mesh for the current project is: Tet (free), C3D4T; A 4-node thermally coupled tetrahedron, linear displacement and temperature (model 3) because it has the maximum S (max) value (2.900E+09Pa). The accurate results were obtained when the mesh size was not larger than 0.02 for the outer pipe (CS) and 0.009 for the inner pipe (SS).

Three heat transfer analyses were carried out:

- Steady state heat transfer analysis to verify the temperature gradient during the summer and winter times by applying two boundary conditions, the temperature gradients were obtained and showed in figures.
- Steady state and transient heat transfer analysis to determine the heat flux during the two seasons, the heat applied as a BC on the inner

surface of the clad pipe (no oil is flowing in the clad pipe), the heat flux results were obtained.

- The transient heat transfer analysis results show that the clad pipe will reach the thermal equilibrium when heated until 66^{o}C during 214.1s in winter, and 201.3s in summer where Sarir`s temperature conditions were applied.

Finally, a steady state heat transfer analysis to determine the heat flux while the hot oil is flowing in the clad pipe during summer and winter times in the Sarir oil field, the heat flux results were obtained.

NOMENCLATURE

AGOCO	Arabian Gulf Oil Company
BC	Boundary Condition
CM	Clad Metal
CRA	Corrosion Resistance Alloy
CS	Carbon Steel
FE	Finite Element
FEA	Finite Element Analysis
PM	Parent Metal
SS	Stainless Steel
Gr	Grashof Number
Nu	Nusselt Number
Pr	Prandtl Number
Ra	Rayleigh Number
Re	Reynolds Number

REFERENCES

Bengtson, H. (2013). Excel Spreadsheets to Calculate Natural Convection Heat Transfer Coefficients, www.brighthubengineering.com/.

Berg, B. and Schnaut, U. D. (2009). Pipeline Technology Conference in A new production method for CRA Lined Steel Pipe based on sheet metal: 1-13.