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HEAT TRANSFER AND THERMAL STRESS ANALYSIS OF WATER COOLING JACKET FOR ROCKET EXHAUST SYSTEMS

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Abstract: *The article focuses on the heat transfer and thermal stress analysis of water-jacket cooling for rocket exhaust systems. Due to the large number of tubes used in the water-jacket cooling adapters, a full geometry 3d analysis of fluid flow, heat transfer and stress would be prohibited in terms of computational time and hardware resources. Moreover, a coupled fluid-thermal-stress analysis of such a complex geometry would cause an even greater number of numerical problems. Consequently, equivalent thermal and mechanical properties were calculated in order to decrease the resource needed to evaluate the rocket exhaust system. Using a constant heat flux for the interior wall (value estimated numerically from a previous full 3D exhaust gas flow computation) and a constant free air convection heat flux coefficient for the exterior wall, the equivalent heat transfer coefficient was computed based on the total heat transfer rate through the interior and the exterior walls assuming zero heat flux through the symmetry walls. An equivalent layered shell material is defined in order to model both the fluid and the structural domain of water-cooling adapter. The mechanical and thermal characteristics of this equivalent material are defined based on the simpler fluid-thermal-stress analysis of just one water cooling tube. Finally, some applications are presented to model the thermal stress problem of the full water-jacket cooling adapter.*
Keywords: *rocket exhaust system, thermal transfer, stress analysis*

Introduction

A heat exchanger is a device built to transfer heat from one medium to another in the most efficient way [1]. Heat exchangers are extensively used in domestic applications (air condition, space heating, refrigeration), energy industry (petroleum, power plants, refineries, natural gas processing), cars industry (radiators, air conditioning), turbojet engines (turbine blade cooling systems [2]), or space industry (rocket engine combustion chamber and nozzle cooling systems).

A straight tube exchanger (Figure 1) is the most common type of heat exchangers. This type consists of a pressure vessel with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids.

One variant of this type of straight tube heat exchangers is the water- cooling jacket system, which is used to cool a sheet of metal instead of another fluid. Using a bundle of tubes fitted in the metal sheet; the cool fluid runs through the tubes and gets heated by the metal sheet which instead cools off.

Such a heat exchanger can be used to cool the metal surface of a device exposed to very high temperatures (hot gases from an exhaust system or from a combustion chamber).

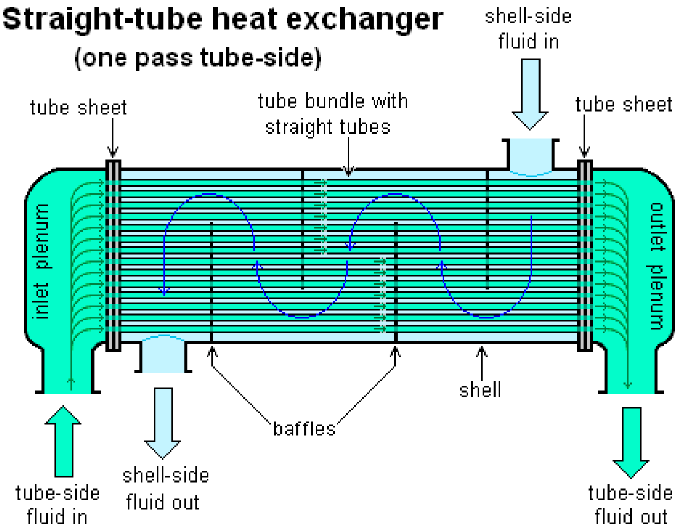

Figure 1. Straight-tube heat exchanger 1 pass (Licensed under CC BY-SA 3.0 via Wikimedia Commons)

The objective of the study is to decrease the resource needed to evaluate rocket exhaust systems using some equivalent thermal and mechanical properties for water-jacket cooling adapters’ numerical model. These equivalent properties will be used to model the heat transfer and to perform thermal stress analysis of the rocket exhaust systems in a faster and more efficient way. The exhaust system of the rocket engine test bench was fitted with a water cooling adapter with a length of 1.4m and a diameter of 2m. A mass flow of 155 kg/s of water at 285-300°K is passing through 500 channels with a rectangular section of 5mm x 10mm. The available pressure at the first collector is 8.5 bar.

CFD analysis of water-jacket channel

A CFD simulation of one cooling channel was performed in order to evaluate the heat transfer coefficients. Assuming a constant heat flux of 3 MW/m^2 for the interior wall (value estimated numerically from a previous full 3D exhaust gas flow computation), a constant free convection heat flux coefficient of 5W/m^{2}K for the exterior wall (free air convection, standard atmosphere) and a mass flow of 0.31 kg/s, the thermal solution was computed in ANSYS Fluent for rough channel walls (k_s=0.2 mm). The turbulence was solved using the realizable k-eps model with the enhanced wall treatment for the near-wall solution [3]. The near wall mesh in the fluid domain was calculated to obtain a y+ larger than 30.

Figure 2 shows the cross-sectional temperature distribution. The temperature of the exterior wall varies from 290°K to 330°K (Figure 3) and the peak temperature at the interior wall (the one exposed to the heat source) does not exceed 575°K (Figure 2). These values are well inside the range of operating conditions for the steel grade used to manufacture the water-jacket adapter.

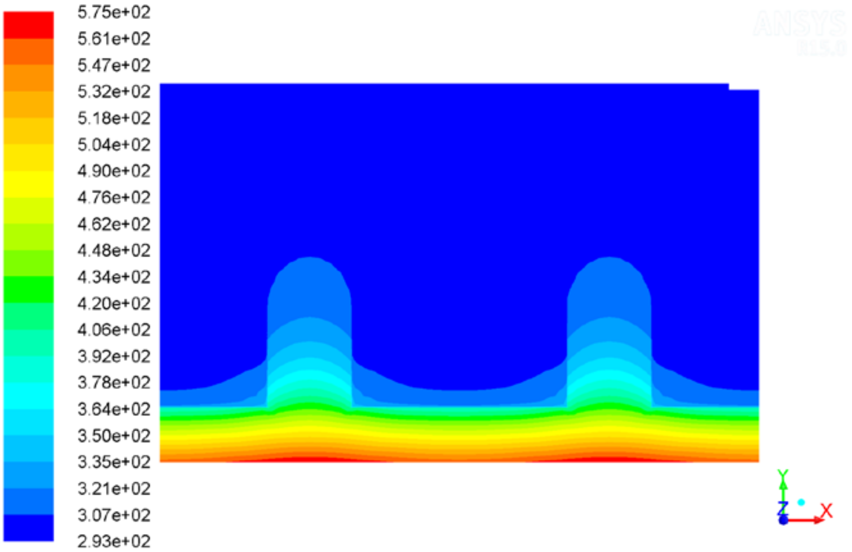

Figure 2. Cross section temperature distribution on solid and fluid domain

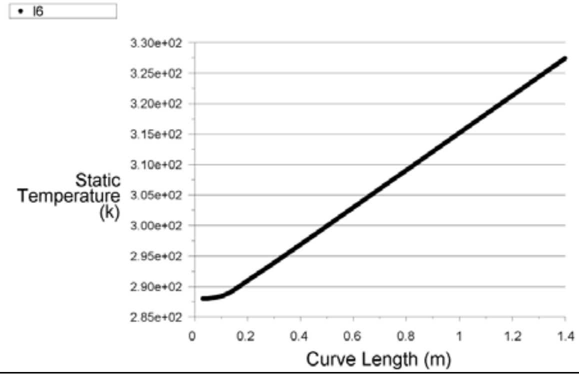

Figure 3. Exterior wall temperature

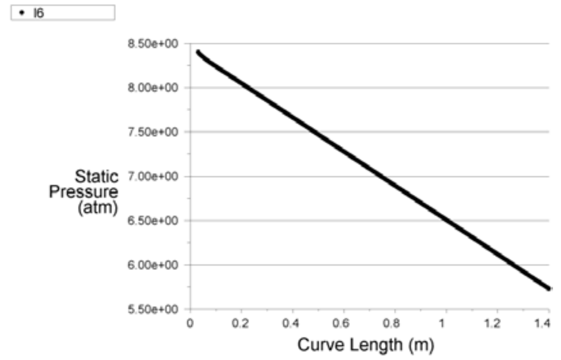

Figure 4. Water pressure loss

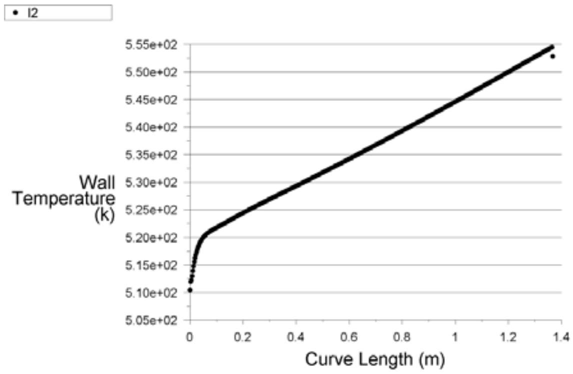

Figure 5. Inner wall temperature

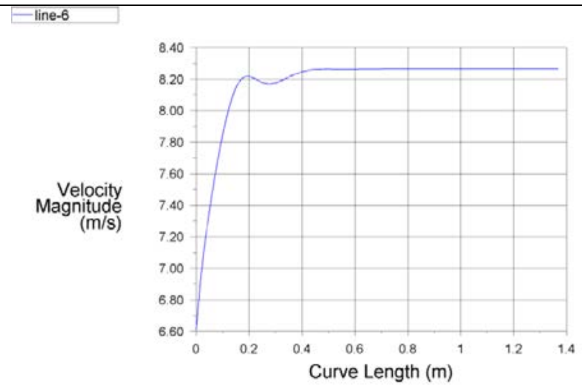

Figure 6. Velocity profile across channel

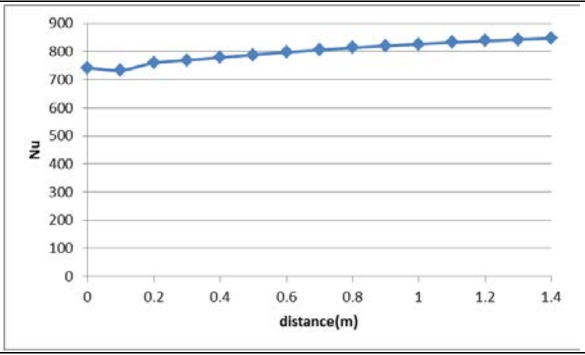

Figure 7. Nusset number

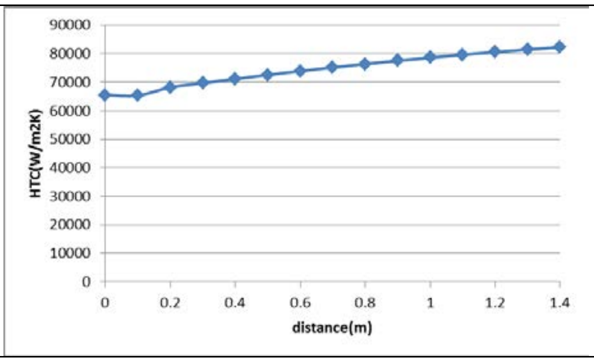

Figure 8. Heat transfer coefficient

In order to evaluate the heat transfer coefficients, different temperatures where imposed at the interior wall of the jacket (310K to 800K, 100K increment) and a 5W/m^{2}K free convection coefficient was imposed on air at a temperature of 287.15K at the outer wall. The equivalent heat transfer coefficient was computed based on the total heat transfer rate through the interior and the exterior walls assuming zero heat flux through the symmetry walls [4, 5].

Table 1 presents the calculated heat transfer coefficient which does not varies significantly with the interior wall temperature.

Table 1. Heat transfer coefficient (HTC) variation with temperature

Design point	Int. Wall Temp (K)	Free stream convection temp (K)	Water temp at inlet (K)	Mass flow rate (kg/s)	Water temperature at exit (K)	Heat flux (W)	HTC (W/m2K)
DP1	310	287.15	287.15	0.33	290.29	4303	9899.0
DP2	400	287.15	287.15	0.33	302.58	21259	9902.3
DP3	500	287.15	287.15	0.33	316.23	40099	9902.8
DP4	600	287.15	287.15	0.33	329.88	58939	9903.0
DP5	700	287.15	287.15	0.33	343.53	77779	9903.1
DP6	800	287.15	287.15	0.33	357.18	96619	9903.2

Equivalent layered shell material for FEM modeling of water-cooling adapter

Due to the large number of tubes used in the water-jacket cooling adapters, a full geometry 3D analysis of fluid flow, heat transfer and stress for the rocket exhaust system would be prohibited in terms of computational time and hardware resources. Moreover, a coupled fluid-thermal-stress analysis of such a complex geometry would cause an even greater number of numerical problems [6, 7].

An equivalent material is defined in order to model both the fluid and the structural domain with fewer finite elements. The mechanical and thermal characteristics of this equivalent material are defined based on the simpler fluid-thermal-stress analysis of just one water-cooling tube [8].

For the global, simplified FEM model of the adapter, the wall is considered composed by three layers (Figure 9): the inner steel made layer (layer 1); the intermediate equivalent material including the water and steel contribution (layer 2) and the outer steel made layer (layer 3).

The equivalent material has an orthotropic behavior (both mechanical and thermal - axis 1, 2 and 3 in Figure 9), and its characteristics are determined considering simple numerical tests. Figure 10 presents as an exemple the K_{11} coefficient estimation for the equivalent material of layer 2. The resulting equivalent material characteristics are briefly presented in Tabel 2.

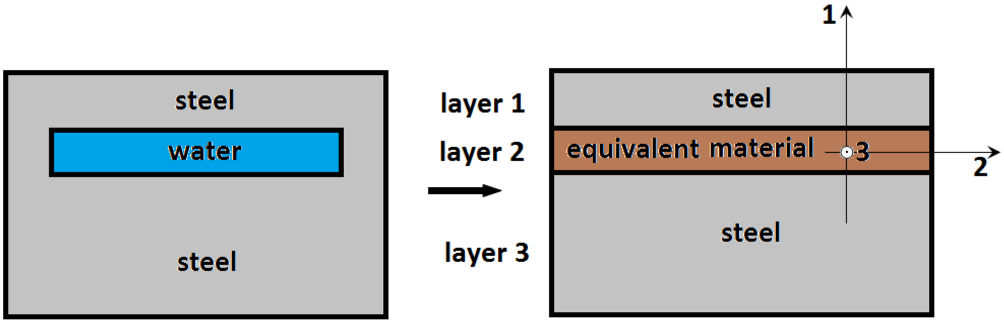

Figure 9. The layered equivalent materials for the cooling jacket

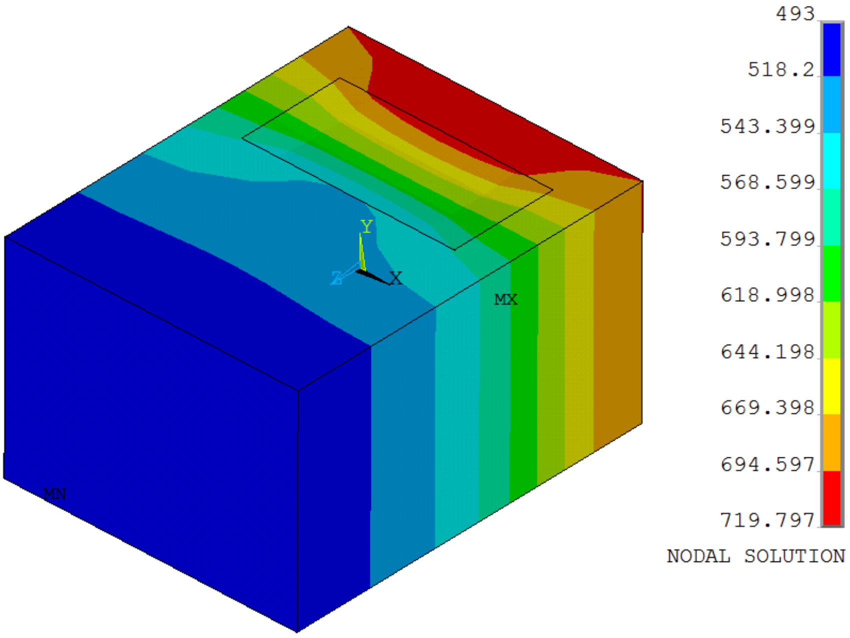

Figure 10 Numerical test for K_{11} coefficient estimation

Table 2. Mechanical & thermal characteristics of the layered shell material

		TEMP [°K]			
		293	**473**	**573**	**673**
Steel	E_1 [N/m^2]	2.12E11	1.99E11	1.92E11	1.84E11
	α [^{o}K^{-1}]	12.5E-6	13E-6	13.6E-6	14.1E-6
	K [W/(m$^\circ$K]	14.45	15.40	16.18	16.96
	C [J/(kg$^\circ$K]	473.1	489.9	498.2	510.79
Equivalent material	E_1 [N/m^2]	0.511E11	0.48E11	0.463E11	0.444E11
	E_2 [N/m^2]	1E1	1E1	1E1	1E1
	E_3 [N/m^2]	0.7866E11	0.7384E11	0.7124E11	0.6827E11
	ν_{21}	0.367	0.379	0.381	0.389
	ν_{13}	0.31	0.317	0.320	0,322
	ν_{23}	0.366	0.378	0.380	0.388
	G_{23} [N/m^2]	2.09E7	2.00E7	1.97E7	1.89E7
	G_{13} [N/m^2]	1.5E10	1.44E10	1.38E10	1.3E10
	G_{21} [N/m^2]	2.62E9	2.54E10	2.43E10	2.37E10
	K_{11} [W/(m$^\circ$K]	4.29	4.479	4.671	4.785
	K_{22} [W/(m$^\circ$K]	1.28	1.367	1.482	1.491
	K_{33} [W/(m$^\circ$K]	1.01	1.1	1.18	1.21
	C [J/(kg$^\circ$K]	1159	1236	1268	1303
	α_{11} [$^\circ$K^{-1}]	18.11E-8	19.2E-8	19.99E-8	20.38E-8
	α_{22} [$^\circ$K^{-1}]	21.47E-7	23.46E-7	24.12E-7	24.98E-7
	α_{33} [$^\circ$K^{-1}]	27.31E-7	28.88E-7	29.76-7	30.03E-7

Application: Steady-state stress analysis of the cooling jacket adapter

Equivalent heat transfer coefficient was imposed as a convection coefficient on the walls of the cooling jacket adapters and a full 3D CFD simulation was computed for the burning gases running through the exhaust system.

Convergence was achieved in few steps (iteration between 3D simulation and single channel simulation). Figure 11 presents the pressure field of exhaust gases gusting in the water-cooled jacket and Figure 12 presents temperature field on adapters' walls. Maximum temperature is identical with single channel simulation.

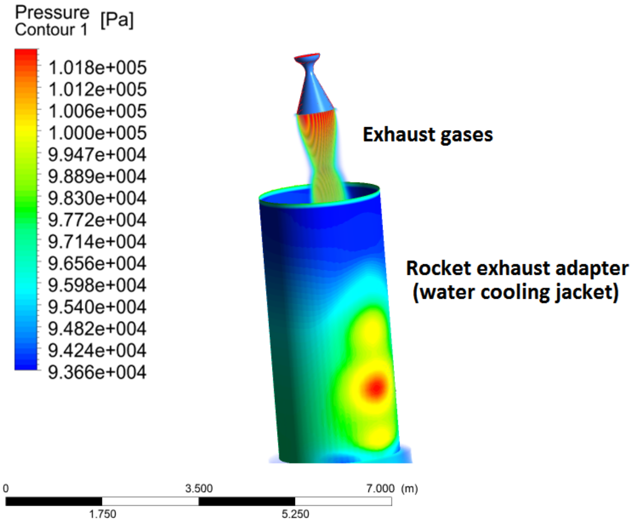

Figure 11. Pressure distribution on water-cooling adapter

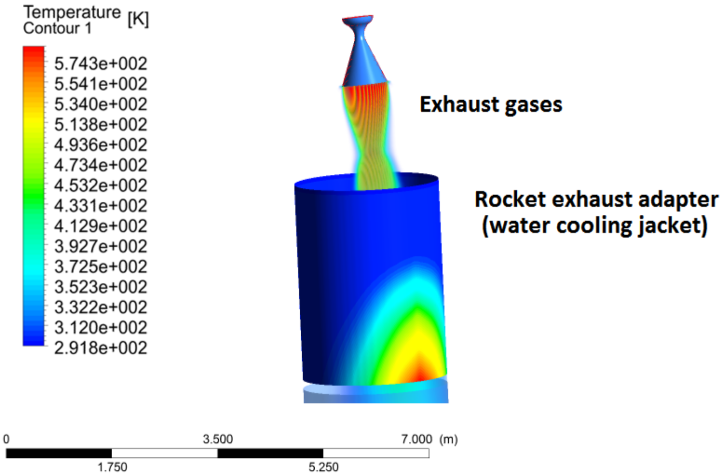

Figure 12. Temperature distribution on water-cooling adapter

The temperature field was transferred to a region of the FEM model of the water-cooling jacket characterized by high values and gradients of temperature. The interpolated values are shown in Figure 13.

The load case was completed with the cooling water pressure. Pressure field of exhaust gases gusting in the water-cooled jacket can be neglected in this calculation (small compared with other loads, important only for global simulation).

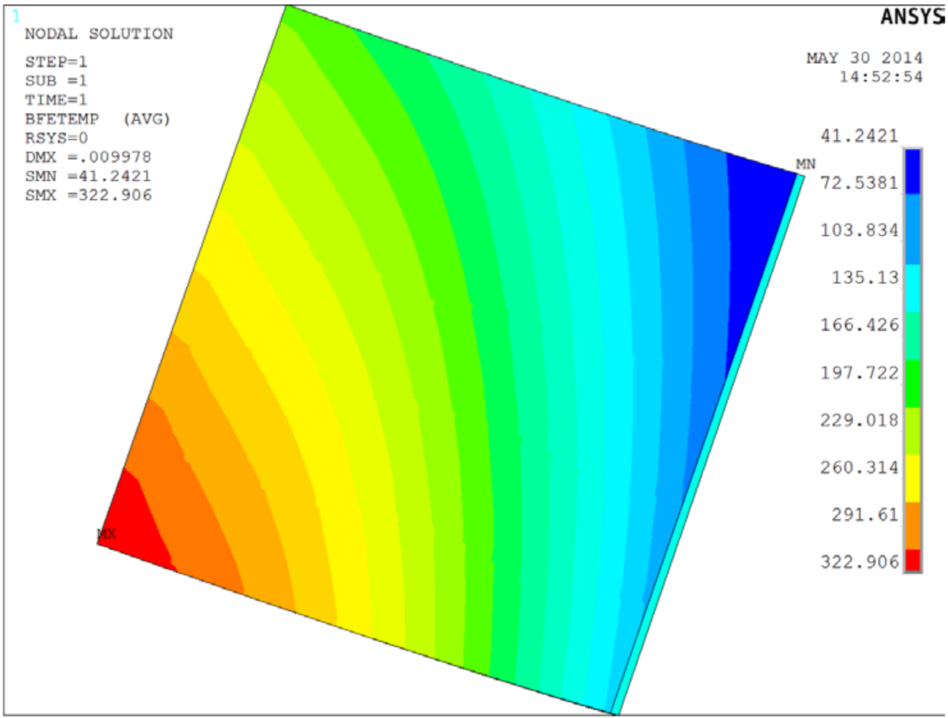

Figure 13. Temperature distribution on jacket's internal wall (^{o}C) steady state analysis

Considering an elastic behavior assumption of the material, a steady–state simulation of coupled fields [9] generated an equivalent stress state as presented in Figure 14. High stress state in the jacket wall occurs mainly due to thermal loading. Thermal expansion of the inner wall in the "hot" region is blocked by the external wall, leading to a total compression stress state in the inner wall. The region with high temperature gradient works in plastic domain. The external wall works in elastic domain under a tensile stress state.

Analysis of the results denotes that equivalent stress state (von Mises) in the "hot" region exceeds the yield values for steel grade selected for manufacturing (for a temperature of about 330^{o}C the yield stress for P355N is 210 N/mm^{2}). These results naturally lead to some conclusions for the future acceptance of the cooling jacket design. In next steps of the study, elastic-plastic models and transient analyses were used in order to evaluate the behavior in critical areas and the life cycle of the rocket exhaust system.

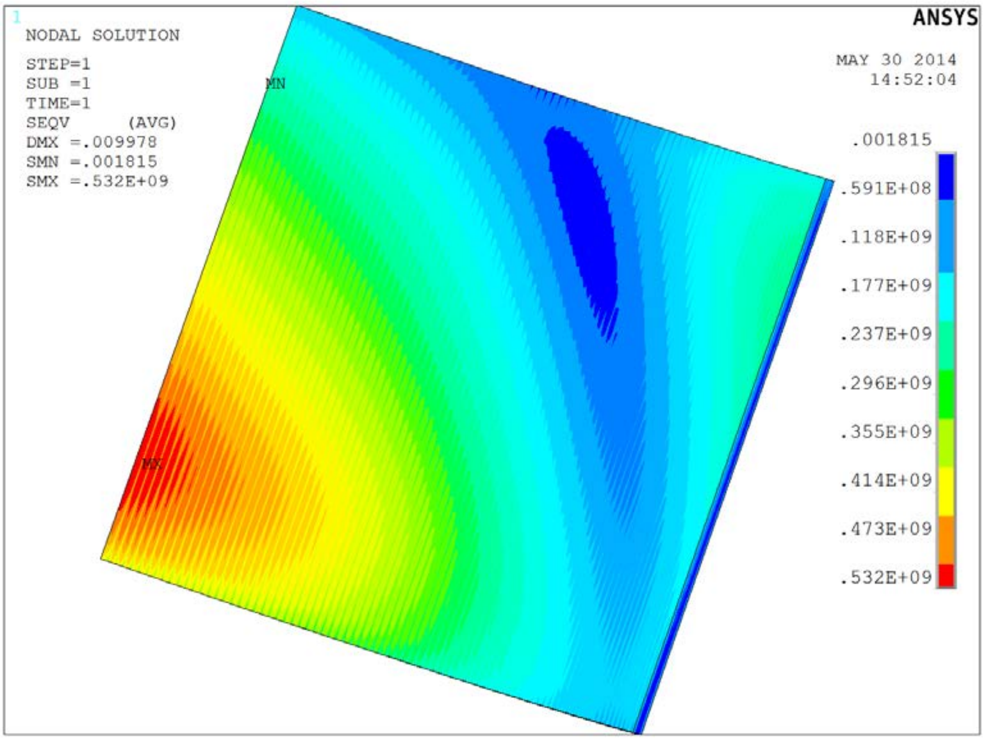

Figure 14. Equivalent stress state in the inner wall of the adapter

Conclusions

Due to the large number of tubes used in the water-jacket cooling adapters, a full geometry 3d analysis of fluid flow, heat transfer and stress would be prohibited in terms of computational time and hardware resources. Moreover, a coupled fluid-thermal-stress analysis of such a complex geometry would cause an even greater number of numerical problems. Consequently, equivalent thermal and mechanical properties were calculated in order to decrease the resource needed to evaluate the rocket exhaust system. These equivalent properties are used to model the heat transfer and to perform thermal stress analysis of the rocket exhaust systems in a faster and more efficient way.

Equivalent heat transfer coefficients can be estimated using only the model of one cooling channel. For the scope of this study the heat flux for jacket’s interior wall was estimated numerically from a full 3D exhaust gas flow computation. The equivalent heat transfer coefficient was computed based on the total heat transfer rate through the interior and the exterior walls assuming zero heat flux through the symmetry walls. Convergence was achieved in few steps (iteration between 3D simulation and single channel simulation until 3D temperature field was close to single channel simulation temperature field). It is shown that the equivalent heat transfer coefficient doesn’t vary significantly with the interior wall temperature (within the temperature range of interest from 300K up to 800K). The peak temperature at the interior wall (the one exposed to the heat source) does not exceed 575°K, value are inside the range of operating conditions for the steel grade used to manufacture the water-jacket adapter.

The study considered different roughness for channel’s walls. Due to large amount of data only the case of k_s=0.2 mm is included. The conclusions are straightforward. A smooth water cooling channel has a smaller water pressure loss throughout the channel but the heat transfer is reduced with respect to rough one. A rough channel has a higher water pressure loss throughout channel but the heat transfer is higher with respect to smooth one. A tradeoff between the two mentioned parameters must be made for final design.

In order to model both the fluid and the structural domain with fewer finite elements, mechanical and thermal characteristics of an equivalent material are defined based on the simpler fluid-thermal-stress analysis of just one water-cooling tube. The equivalent material has an orthotropic behavior (both mechanical and thermal, and its characteristics can be determined considering simple numerical tests. Equivalent properties can be used for the global, simplified FEM model of the adapter. This allows quick iterations of the design reducing significantly the time spent for evaluation. Temperature and pressure fields from 3D can be easily mapped to the region of interest (characterized by high values and gradients of temperature). As shown, high stress state in the jacket wall occurs mainly due to thermal loading. Thermal expansion of the inner wall in the “hot” region is blocked by the external wall, leading to a total compression stress state in the inner wall. The region with high temperature gradient works in plastic domain. The external wall works in elastic domain under a tensile stress state. Consequently, elastic-plastic models and transient analyses must be used in order to evaluate the behavior in critical areas and the life cycle of the rocket exhaust system.

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