Proceedings of TEAM 2015

7th International Scientific and Expert Conference
of the International TEAM Society

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CONTENT

THERMO-MECHANICAL ANALYSIS OF TANK WAGON FOR TRANSPORTATION OF MOLTEN SULFUR

Vladimir Milovanović[1*], Nikola Jovanović[1], Jelena Živković[1], Aleksandar Dišić[1], Snežana Vulović[1] and Miroslav Živković[1]

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Abstract

An example of specific engineering problem solving by using the thermo-mechanical analysis is given in this paper. Theoretical bases of using the finite element method for numerical solving of heat conduction problem through continuum are presented. Temperature field used as an input for thermo-mechanical calculation is determined by heat conduction calculation. The main purpose of thermomechanical calculation is to check the strength of the wagon after the reconstruction of the heating system that is used for heating of the transported medium.

Keywords:

Heat conduction, FEM analysis, wagon analysis

1. Introduction

Numerical simulations are widely used for solving various problems in industry because they reduce time and cost in developing of new products. The advantage of simulations is that potential problems on product are eliminated in design phase, which leads to significant reducing of product's cost. The most powerful and widely used tool for numerical simulations is Finite element method (FEM). Theoretical bases for numerical solving of the heat conduction problem through continuum, using the finite element method, are presented.

The aim of this paper is the strength calculation of the wagon for sulfur transportation. Wagon for sulfur transportation has been in the exploitation phase for years and reconstruction of the heating system of the transported medium is planned. Heating system of the original variant was located in the interior of the wagon and it was planned to relocate it on the outside. The calculation should confirm that reconstructed wagon structure meets all the criteria prescribed by standards.

2. Theoretical Bases

Differential equation of the energy balance is based on the fundamental conservation of energy principle. Namely, change of the material inner energy in the unit of time, in elementary volume, is equal to the quantity of heat energy accumulated in that same volume in the unit of time, or it is valid for [1]:

$$\frac{dQ}{dt} = \frac{dU}{dt} \tag{1}$$

where dQ and dU are changes of the heat and the inner energy in the volume dV in elementary time interval dt. Change of the inner energy can be formulated as:

$$\frac{dU}{dt} = \rho C_p \frac{dT}{dt} dV \tag{2}$$

where: ρ – material density, C_p – specific heat and T – temperature. According to Figure 1, dQ/dt can be formulated as:

$$\frac{dQ}{dt} = \left(q_x + \frac{\partial q_x}{\partial x} dx - q_x \right) dydz + \left(q_y + \frac{\partial q_y}{\partial y} dy - q_y \right) dxdz + \left(q_z + \frac{\partial q_z}{\partial z} dz - q_z \right) dxdy - qdV \tag{3}$$

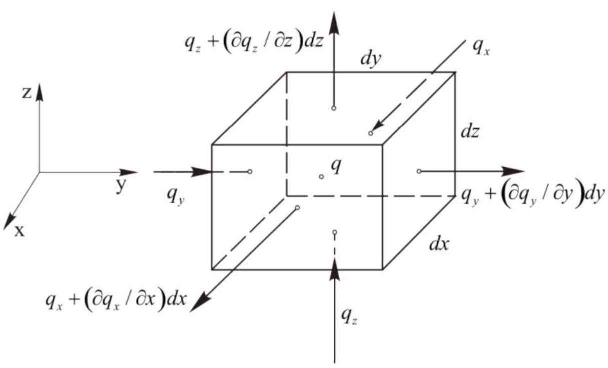

Figure 1. Elementary volume dV with heat flux components

where q_x, q_y and q_z are components the of heat flux vector. These components represent the heat quantity that passes through the unit surface in the unit of time. Power of the heat source *q* represents the heat quantity in the unit of time and the unit of volume. Signs of the flux components are considered in equation (3). Positive sign corresponds to the positive flux projection on the direction of the outer normal unit vector on the surface and negative flux through the surface corresponds to the accumulation of the heat energy *dV*. It is considered that *q>0* if there is a heat source in the volume *dV* (in the point of the material), but *q<0* in the case of the heat sink.

Heat conduction through continuum is defined by Fourier's law of heat conduction:

$$q_i = -\lambda_i \frac{\partial T}{\partial x_i} \qquad i = 1,2,3 \tag{4}$$

where λ_i, or λ_x, λ_y and λ_z, are coefficients of the heat conduction in the case of orthotropic material. In the case of isotropic material, the following is valid:

$$\lambda_x = \lambda_y = \lambda_z = \lambda \tag{5}$$

Replacing equations (2) and (3) in the equation of energy balance (1) and using the equation (4), differential equation for isotropic material obtains the following form:

$$-\rho C_p \frac{dT}{dt} + \sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left(\lambda_j \frac{\partial T}{\partial x_j}\right) + q = 0 \tag{6}$$

When it comes to the practical problem solving, the temperature field *T(x,y,z,t)* solution is searched for satisfying initial and boundary conditions and it represents a unique solution. Initial conditions are given only for unsteady problems and they mean that temperature distribution at the initial moment of time *t=0* is known:

$$T(x,y,z,0) = f_0(x,y,z) \tag{7}$$

Boundary conditions can be:

- given fluxes on the contact surface:

$$q_n = q_n(x,y,z,t) \tag{8}$$

- given heat convection:

$$q_h = h(T_0 - T_s) \tag{9}$$

where T_s is the surface temperature, T_0 is the environment temperature and h is the coefficient of convection. By using the Galerkin method, differential equation (6) transforms into the equation of construction balance whose solving is presented in references [1-3].

3. Technical description of the 4-axle wagon

In order to change the medium heating system the reconstruction of wagon for molten sulfur transportation is done. As part of original structure the heating system was located inside the tank, and because of regular services, corrosion, etc., its reconstruction was planned so it can be relocated outside of the tank.

The reconstructed wagon was designed for the transport of molten sulfur class 4.1, number 15 – RID [4]. Volume of the wagon tank is 38 m^3, and working pressure is 0.15 MPa. The total heating area is 55 m^2, while the temperature of the medium heating is 170°C. The tank insulation is of 150mm thickness, while the material is mineral wool. The cover plate of 0.8mm thickness is placed over the insulation.

The underframe consists of a welded construction. Tank is made of S355J2G3 steel, and external heating half-pipes are made of P355NH steel. Table 1 shows physical and mechanical characteristics of materials. Steel S355J2G3 characteristics are defined by EN10025-2:2007 [5]. Steel P355NH characteristics are defined by EN10028-3:2009 [6].

Table 1. Physical and mechanical characteristics of materials

PHYSICAL CHARACTERISTICS						
Steel mark	E [N/mm^2]		ρ [kg/mm^3]		ν	
S355J2G3	2.1 10^5		7.85 10^{-6}		0.3	
P355NH	2.1 10^5		7.85 10^{-6}		0.3	
MECHANICAL CHARACTERISTICS						
Steel mark	R_e [N/mm^2]		R_m [N/mm^2]		KV [J]	
S355J2G3	355		490		27	
P355NH	355		490		27	
Min. values for proof strength $R_{p0,2}$ (MPa)						
Thickness < 16 mm	50°C	100°C	150°C	200°C	250°C	300°C
S355J2G3	343	323	299	275	252	232
P355NH	343	323	299	275	252	232

4. FEM model

Wagon structure is modelled by using Femap software [7], and the analysis was done in the software PAK MULTIPHYSICS [3] that is based on the finite element method. According to the construction type, shell elements of the appropriate thickness and 3D elements (for modeling of support plate, compensating ring, traction stop) were used for creating the finite element mesh. Structure is modeled in details with 230138 elements and 226668 nodes and within the calculation there is a system of about one million and two thousand equations being solved. General element side length is about 30 mm. Figure 4 shows the 3D model of the whole wagon without bogies. Colours in Figure 2 match the various thicknesses of shell elements. Figure 3 shows the half of the model, which will be used taking in consideration corresponding symmetry of the load case.

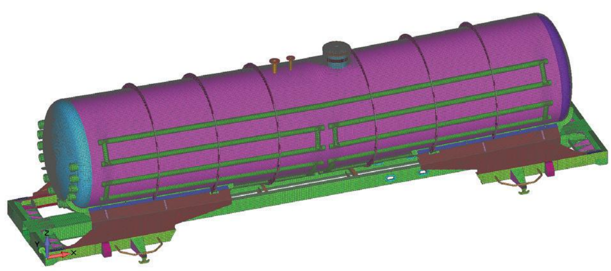

Figure 2. 3D Vehicle model

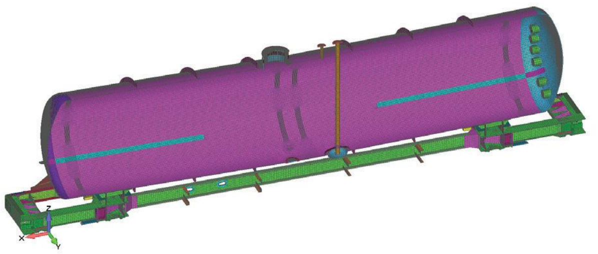

Figure 3. Half of the 3D model

5. Load cases and requirements

According to UIC 577 [8], and BS EN 12663: 2000 [9], Clause 5.2, it is necessary to calculate the wagon structure in relation to different types of loads:

- Exceptional loads, which cover: longitudinal design loads, maximum vertical load, load combinations, lifting and jacking and other;
- Service (fatigue) loads.

The analyses were done for all the variations of loads in accordance with UIC 577 [8], and BS EN 12663:2000 [9]. Results presented in this paper are only for the thermo-mechanical calculation of the wagon loaded with maximal vertical load.

6. Thermo-mechanical analysis - results

Wagon is filled with molten sulfur up to the filling height that corresponds to the maximum allowed loading capacity of the wagon, which is 65t. Molten sulfur density is 1803.9kg/m^3 [10]. The increase in temperature of 170°C is given on the inner side of half-pipes' model which is in contact with tank. On the inner side of tank model increase in temperature of 130°C is given. Calculation of the heat conducting was done first to determine the temperature field (Figure 4) on the whole wagon and then, the temperature field was used in thermo-mechanical calculation to determine thermal strains. It is considered that the heat from the surfaces of half-pipes and from the tank underneath the insulation is transferred by convection, and the heat transfer coefficient was h_1=0.1 W/m^{2}K. On the other side, the heat from the wagon surface which is outside of the insulation is transfered by convection h_2=1 W/m^{2}K. Heat conduction coefficient is k=52.33 W/mK, while the linear expansion coefficient is α=11.5 10^{-6}1/K.

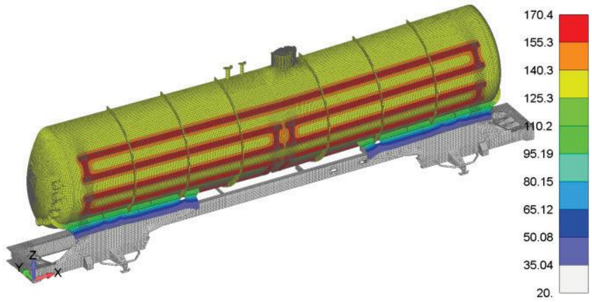

Figure 4. Temperature field – half model of wagon

Von Mises equivalent stress field is presented in Figure 5. Place of maximum value of the equivalent stress is shown in Figure 6.

Obtained stresses in the whole construction are below permissible stress for the static loads [8], [9].

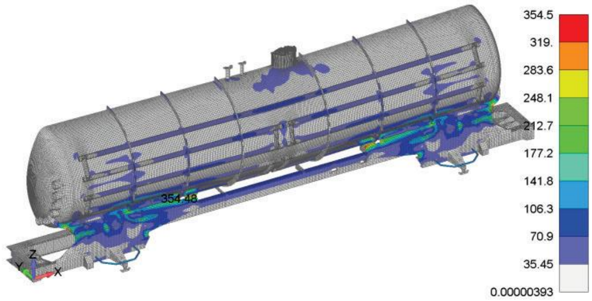

Figure 5. Von Mises equivalent stress field – half model of wagon

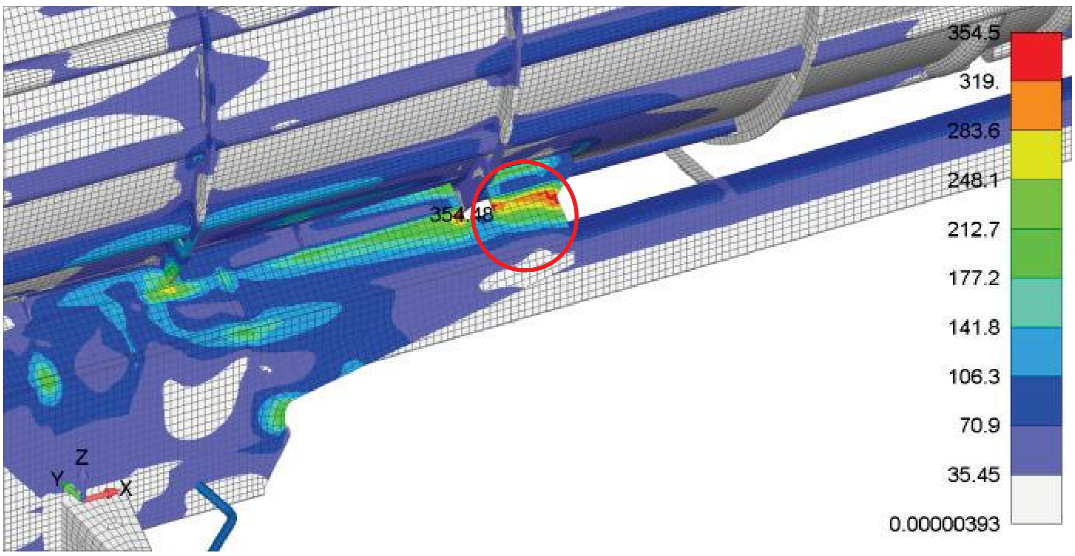

Figure 6. Place of maximum Von Mises equivalent stress

7. Conclusion

The aim of this paper was to demonstrate the possibility of program PAK for solving coupled multiphysics problems. Basic equations for the heat conduction implemented in the program PAK MULTIPHYSICS are presented. Thermo-mechanical analysis of wagon for transportation of molten sulfur is an example of how to successfully solve one practical example that is very commonly found in railway industry.

In this case, the results of thermo-mechanical analysis were used as a test of the reconstruction of the heating system. Based on obtained results and their analysis it can be concluded that the wagon for transport of molten sulfur, with reconstructed medium heating system meets the criteria prescribed by standars.

8. Acknowledgement

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