Thermal and structural analyses of firefighting robot

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***Abstract*—In this study, designed firefighting robot especially for forest fires was analysed using Computer Aided Engineering (CAE) methods. Structural and thermal analyses were carried out after the frame and shell design of the robot body and material selection. To determine the structural strength of robot static forces (self-weight of the chassis and additional forces arising from other components of the robot such as wheels, pallet and diesel engine) were applied to chassis frame. To get more reliable results, the structural analysis was conducted with three different forces as 750, 1,000 and 2,000 kg. Occurred stress, strain, displacement and safety factor values were computed. In thermal part; a heat-insulating and fireproof plate was built. Robot shell was composed with three parts using; galvanized steel with the thickness of 5 mm as the main plate, 5 µm cubic boron nitride coating for non-flammability and 50 mm silica aerogel for thermal insulation. After design and combination process, thermal insulation calculations and analysis were conducted using Matlab and Ansys Workbench Steady State Thermal tools. Heat energy of the fire was transferred to shell combination with convection and radiation. The temperature gradient of fire was derived using required logarithmic function. The numeric calculations and analysis were carried out for 30, 300, 900 and 1,800 seconds time intervals. The temperature variation of the ambient and inside area temperatures and insulation properties of the combined shell material were obtained from calculations and analysis. The results were compared. Structural analysis showed that the yield strength of the selected material for chassis (AISI 1018) was almost five times more than occurred maximum stress with 2,000 kg forces. It was obtained from thermal computations and analysis that while temperature of the environment was almost 1,450 °C, the inside area was about 34 °C. The designed and combined shell material provided extremely great insulation (about %98) that has vital importance for firefighting.**

Keywords—computer aided engineering; firefighting; non-flammability; thermal computations and analysis;

I. Introduction

Since human kind first encountered with fire, besides the fact that they have utilized from it, they needed to combat against it. Along with this combat action, it can be considered that early intervention to fire, securing the lives of firefighters, and saving lives of people who trapped within the fire are the key elements of this combat. In Turkey; 1,200 forest fire incidents are reported; and 22,000 ha forest area is destroyed annually [1]. Despite knowledge of safety know-hows, people all over the world still confront frequent explosion and fire hazards [2]. Forest fires generally results in environmental pollution and destruction [3].

MVF-5 [4] is a multifunctional firefighting robot that manufactured by Croatian company in 2013 DOK-ING to control the fires in unreachable areas and life threatening conditions. It is a remote controlled machine that operated with GPS-INS (Global Position and Inertial Navigation) System. MVF-5 extinguishes the fires with high-pressure cannon on hydraulic arm which pumps the water up to 55 meters away without intervention of firefighters. This machine has a high temperature resistant shield and fireproof coating to protect the system from external high temperature conditions and big flames. MVF-5 is able to withstand 700 ˚C for 15 minutes or 400 ˚C for 30 minutes. It has capability to carry 2,200 liters water and 500 liters foam tanks. Usage areas of MVF- 5 are oil refineries and terminals, military storages, chemical plants and nuclear power plants. Martinson et al. [5] developed a robot (Octavia) which can be used as a team member for firefighting tasks in 2012. In the system, when human team leader indicates the location of the fire using speech-gesture and clears the obstacles, robot finds the exact location of the fire with its sensors and extinguishes the fire with CAF (compressed air foam) system. Octavia has 48 DoF in body, arms and head. It is mounted on a two wheeled Segway base for mobility. Robot uses the perceptual system to understand what team leader means and behaves correctly.

Today, many computer-based tools have been available to help design and analysis cycle of robots [6]. Solid modelling using CAD methods assists the robot designers to define the parts and assembly of the system and to utilize the geometry in applications such as simulation, analysis and prototyping. Virtual prototype simulations, static, kinematic, dynamic and thermal analyses can be conducted with CAE methods [7].

In this article we focused on the structural and thermal analyses of designed firefighting robot. In structural part; static forces were applied to chassis frame to determine the structural strength of robot. Occurred stress, strain, displacement and safety factor values were computed. In thermal part of the study; thermal insulation calculations and analysis were conducted using Matlab and Ansys Workbench Steady State Thermal tools.

II. DESIGN OF FIREFIGHTING ROBOT

In the mechanical design process of the firefighting robot several issues were considered such as compact size, sufficient stiffness, toughness, management of time and cost. Components of the robot were drawn using parametric solid modelling technique. Subsequently, created parts were assembled to build up the 3D model. Design of the robot is shown in Figure 1.

A. Design Specifications

The robot was designed to carry out the special firefighting tasks that occur at open areas. These types of fire disasters generally occur at the forests and mountains. So it is too hard to reach to fire area using conventional firefighting vehicles. There are two main problems; hard terrestrial conditions and slope. To handle these problems; body shell of the robot was designed with the combination of galvanized steel with the thickness of 5 mm as the main plate, 5 µm cubic boron nitride coating for non-flammability and 50 mm silica aerogel for thermal insulation. That can be called as composite structure that provide light, non-flammability and excellent heat insulation features. By using this combination robot can be produced light, compact, fast and robust to operate in tough terrestrial environmental conditions.

A special traction system that comprise the wheels and pallet was developed to answer the condition of working environment. Wheels and pallet were connected to robot chassis with hydraulic cylinders. If more speed is required for the case; the pallet system is pulled up by the mechanism via cylinders and robot can move faster. In other case; if the environment has greater slope angle and ground is muddy soil, in addition to wheels pallet system is added to motion for more traction to prevent sliding and spinning.

The designed robot has ability to enter the fire zone that has vital importance for firefighting operations. In some fire scenarios that is almost impossible to reach to flame from distance. So fireman try to come close to fire zone and that may cause to injuries and loss of lives. To handle these problems; body of the robot was designed to resist fire up to 30 minutes and 1400 °C without any fault. Body shell combination of the robot can protect the components such as batteries, electric motors, drivers, cables and etc. from fire. In this time period the fireman can enter the robot and wait for the help safely. This feature of the robot is tested with experimental applications in the future works. With the additional features explained above the designed firefighting robot is expected to be stronger, faster, more technological and efficient for firefighting operations.

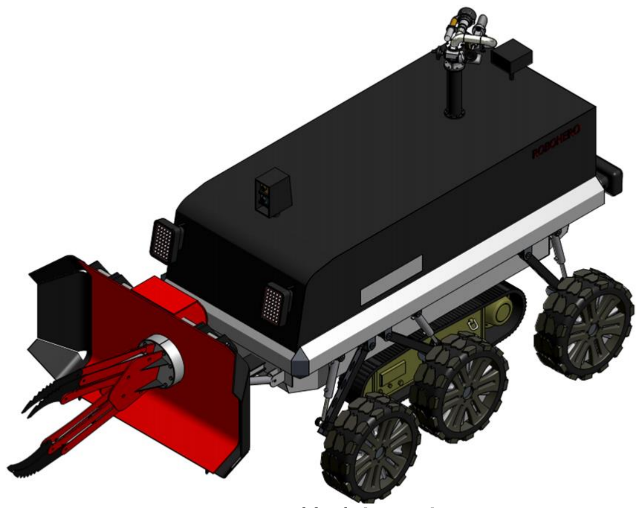


Fig. 1. Design of firefighting robot

B. Material of Firefighting Robot

Since the synthesis of the boron nitride in its cubic crystallographic structure, Cubic Boron Nitride (cBN) is a material that has exceptionally high hardness and special properties. For practical use, cBN is, after diamond, the second known hardest material and is today being increasingly used as cutting and drilling tools in substitution for diamond based tools owing to superior thermal stability and chemical inertness. Contrary to diamond, its structure is stable up to 2,000 °C. In addition, the decrease in the hardness of diamond is accentuated beyond 500 °C becoming inferior to that of cBN at 800 °C and above. Furthermore, it was realized that cBN stayed inert in contact with steels, cast irons, and super alloys at operational conditions for which diamond would react and loose machinability [8].

Silica aerogels have high porosity, extremely low density solids composed of interconnected particles that form an open nanostructure. As a result of the low thermal conductivity of silica and nanometer pore sizes the thermal conductivity of silica aerogel is very low. Low thermal conductivity and optical properties make silica aerogels desirable for insulating applications such as cover layers for windows and solar collectors. The properties of aerogels that make them such good insulators also make them inherently fragile and brittle [9].

AISI 1018 mild/low carbon steel has excellent weldability and produces a uniform and harder case and it is considered as the best steel for carburized parts. AISI 1018 mild/low carbon steel offers a good balance of toughness, strength and ductility. Provided with higher mechanical properties, AISI 1018 hot rolled steel also includes improved machining characteristics and Brinell hardness. Specific manufacturing controls are used for surface preparation, chemical composition, rolling and heating processes. All these processes develop a supreme quality product that are suited to fabrication processes such as welding, forging, drilling, machining, cold drawing and heat treating.

Robot shell was consisted of using; galvanized steel with the thickness of 5 mm as the main plate, 5 µm cubic boron nitride coating for non-flammability and 50 mm silica aerogel for thermal insulation. AISI 1018 steel was selected as chassis frame material. The mechanical and thermal properties of AISI 1018 steel, silica aerogel and galvanized steel and cubic boron nitride are given in Table I.

TABLE I. MECHANICAL AND THERMAL PROPERTIES OF MATERIALS

	Mechanical Properties of Materials				
	Properties of Material	***AISI 1018 Steel***	***Silica Aerogel***	***Galvanized Steel***	***Cubic Boron Nitride***
1	Density ρ (g/cm^3)	7.87	0.1	7.85	3.49
2	Young Modulus E (GPa)	205	0.001-0.1	200	41-97
3	Ultimate Tensile Strength σ_{ts} (MPa)	440	0.0160	310-393	41-55
4	Yield Strength σ_y (MPa)	370	-	241-338	-
5	Poisson Ratio *v*	0.29	0.24	0.29	-
6	Shear Modulus G (GPa)	80	0.00042-0.004	80	-
	Thermal Properties of Materials				
7	Specific Heat Capacity C_p (J/g.˚C)	0.486	840	0.470	0.793
8	Thermal Conductivity k (W/m.K)	51.9	0.004	52	20

III. STRUCTURAL ANALYSIS

In order to determine the structural behavior of firefighting robot on the model characteristic static analysis was carried out using Finite Element Analysis (FEA). This approach increased the design process progress and efficiency [10, 11]. The force applied chassis area was about 0.7 m^2. 750, 1,000 and 2,000 kg forces were applied to chassis. Therefore; structural analysis was executed with 10, 14 and 28 kPa pressures forces and standard earth gravity.

Structural analysis was conducted using Ansys Workbench Static Structural Module. Safety factors, maximum equivalent stresses and strains for whole chassis frame were calculated.

The parameters obtained from design environment such as dimensions, component weights etc. were used as input for analysis. The material of the chassis was defined as AISI 1018 also known as structural steel. Before the computation, the model was simplified to increase the analysis speed and computation precision. The finite element model of the robot arm was composed of 86,619 nodes and 17,988 elements. Mesh view of the chassis is shown in Figure 2.

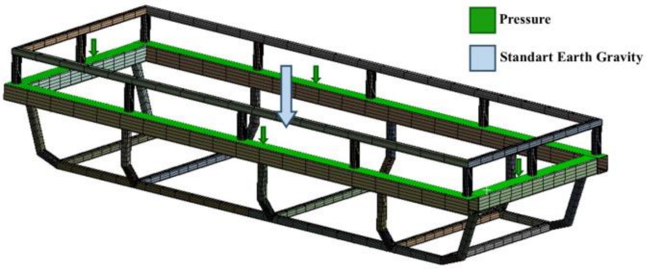


Fig. 2. Structural analysis mesh view

IV. THERMAL COMPUTATIONS AND ANALYSIS

Thermal calculations and analysis were carried out for specified 1x1 m^2 section area of robot shell combination. Heat transfer was occurred from fire ambient to shell with convection and radiation. The temperature gradient of fire was derived using required logarithmic function (1) [12].

$$T = 345\,log10\,(8t + 1) + 20 \tag{1}$$

Heat transfer from fire ambient to interior surface was calculated using (2).

$$Q(t) = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} \tag{2}$$

In where; "$T_{\infty 1}$" represents the temperature gradient of fire, "$T_{\infty 2}$" is temperature of inside air. "R_{total}" total thermal resistivity of all system was calculated using thermal resistivity all of the elements (3).

$$R_{total} = \frac{L}{kA} + \frac{1}{h_{combined}A} \tag{3}$$

"L" use as thickness of layers, "k" represents the thermal conductivity of selected shell material. As fire behaves as an infinite thermal energy source for specified time interval and ambient temperature assumed as constant, Steady State solution method was applied.

The numeric calculations and analysis were carried out for 30, 300, 900 and 1,800 seconds time intervals. The temperature variation of the fire ambient, inside area and insulation properties of the combined shell material were obtained from calculations and analysis (Figure 3).

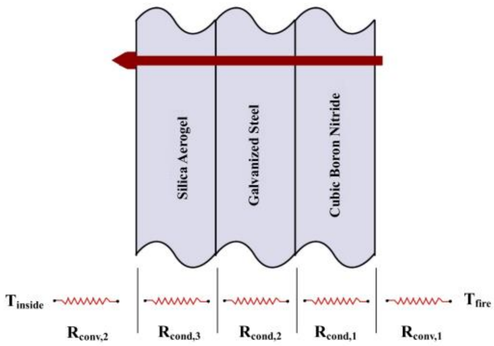


Fig. 3. Thermal resistance network from fire to inside

V. RESULTS AND DISCUSSION

A. Structural Analysis

Structural analysis results under static loads are given in Table II.

TABLE II. STRUCTURAL ANALYSIS RESULTS

Criteria	**Values**		
Applied Force (kg)	750	1,000	2000
Maximum Deformation (mm)	0.08	0.1	0.2
Equivalent Stress (MPa)	28	35.6	66
Equivalent Strain (mm/mm)	0.00015	0.00018	0.00034
Safety Factor	13	10	5

The total calculated displacements for 750, 1,000 and 2,000 kg were about 0.08, 0.1 and 0.2 mm, respectively. According to Mott's recommendation for machine member's deflection ranges (from 0.0005 to 0.003 m/m) [13] displacements are within allowable limits. Maximum stresses are not overcame the yield of the material. It can be understood from the structural analysis that AISI 1018 material can be used as chassis frame material for firefighting robot. The factor of safety also indicates that selected chassis material is 5 times stronger for the intended loads. Displacement computation results with Ansys Workbench Static Structural with 750 kg load and self-weight of chassis is shown in Figure 3.

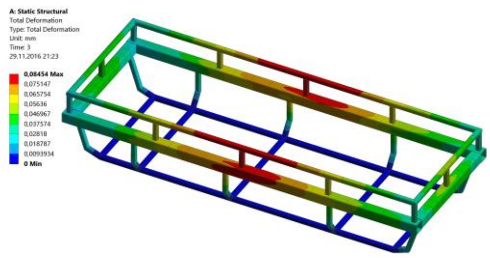


Fig. 3. Displacement calculation results with Ansys Workbench Static Structural

B. Thermal Calculations and Analysis

The calculated temperature gradient of fire according to time is shown in Figure 4. As understood from the figure that fire temperature increased extremely fast and reached almost 850 °C level in first 30 second period and affected the ambient and robot chassis significantly. After 30 seconds fire temperature increased slower when compared with the first period. Therefore; first time zone between 0-30 seconds is most critical for insulation and non-flammability.

Inside area temperature distribution of firefighting robot with numerical calculations using Matlab for 30 seconds and 1,800 seconds time periods is shown in Figure 5. Inside area of the robot was only 32.8 °C while the ambient temperature that affects the robot's exterior wall was about 850 °C in 30 s time period. The similar scenario was obtained from 1,800 seconds calculations.

Although; ambient temperature reached the 1,450 °C the inside area temperature increased only 2 °C from 30 to 1,800 seconds time period. These results showed that shell material combination of firefighting robot can provide extremely great insulation and (about %98) and non-flammability feature.

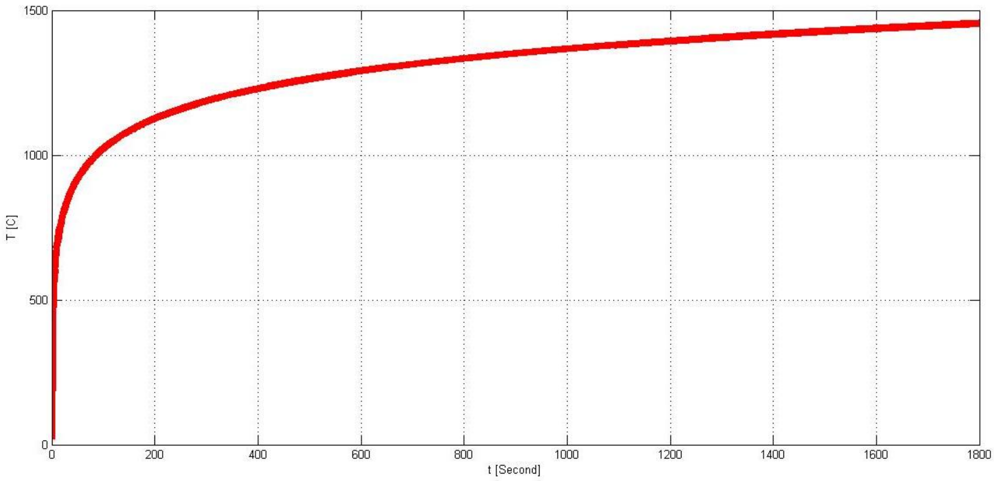
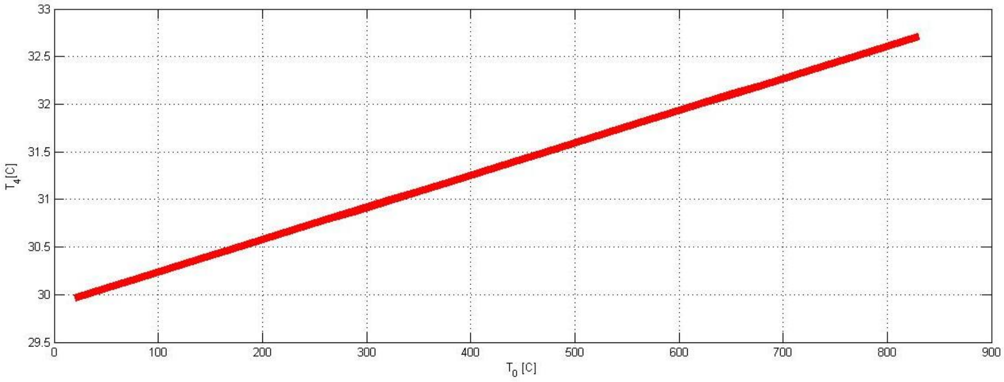
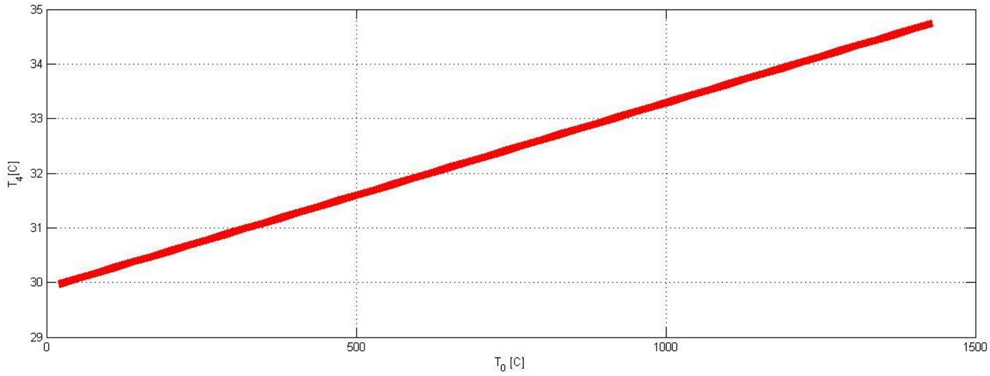


Fig. 4. Temperature gradient of fire according to time



(a)



(b)

Fig. 5. Inside area temperature distribution (a) 30 seconds (b) 1,800 seconds

Thermal analysis results using Ansys Workbench Steady State Thermal tool is shown in Figure 6.

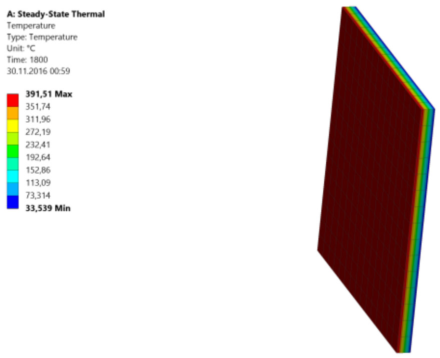


Fig. 6. Temperature distribution of analyzed section

Similar results with numeric calculations were obtained from analysis. Inside area temperatures were found as 32.5 and 33.5 °C respectively for 30 and 1,800 seconds time periods. When the results of numerical solutions and analysis were compared, negligible errors (about ± 1 °C) were observed caused from decimal differences. The results of the analysis are summarized in Table III.

TABLE III. RESULT SUMMARY OF THERMAL ANALYSIS

Criteria	**Values**			
Time (s)	30	300	900	1,800
Fire Temperature (°C)	841.8	1186.2	1350.8	1454.6
Inside Area Temperature (°C)	32.596	33.1	33.4	33.539

VI. CONCLUSION

In this study, firefighting robot especially for forest fires was analyzed using Computer Aided Engineering (CAE) methods. Structural and thermal analyses were carried out after the frame and shell design of the robot body and material selection. Occurred stress, strain, displacement and safety factor values were computed with structural analysis using FEA methods. A heat-insulating and fireproof plate was build. Robot shell was composed with three parts using; galvanized steel as the main plate, cubic boron nitride coating for non-flammability and silica aerogel for thermal insulation. Thermal insulation calculations and analysis were conducted using Matlab and Ansys Workbench Steady State Thermal tools. The numeric calculations and analysis were carried out for 30, 300, 900 and 1,800 seconds time intervals. The temperature variation of the ambient and inside area temperatures and insulation properties of the combined shell material were obtained from calculations and analysis. The results were compared. Structural analysis showed that the yield strength of the selected material for chassis (AISI 1018) was five times more than occurred maximum stress with 2,000 kg forces. It can be concluded that designed and combined shell material provided extremely great insulation (about %98) that has vital importance for firefighting.

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