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Numerical Simulation of Gas-Dynamics in the Cooling System of the Block-Container of the Gas-Turbine Engine.

Egor Tiunov[1],Mark Khazin[2]
[1] *(The Mining Equipment Operation Department, Ural State Mining University, Yekaterinburg, Russia)*
[2] *(The Mining Equipment Operation Department, Ural State Mining University, Yekaterinburg, Russia)*
Corresponding author: Egor Tiunov

ABSTRACT: To increase the service life of gas-turbine engines, timely ventilationin the block-container, where the turbine is located, is required. To boostthe ventilationefficiency, it is desirable to know the dynamics of the process of heating of the inner zone of the engine block and to monitor its conditions during operation. The overheating of the space inside the block-container because of poor ventilation as a reason of getting out of order control measure systems, the often engine stops that's consequence reducing life, and increase in the cost of gas, electricity, heat. Known dimensional models of overheating of the space inside of engine block are analyzed. The work presents the problem description, mathematical principles, and the numerical results of a 2-D modelling. The mixed thermal transfer models in the closed area in the parallelepiped form with a local heating of a cylindrical surface, simulating a block-container of a gas-turbine engine, are described. The paper presents theoretical solutions that increase the reliability of the unit by providing the required temperature conditions in the block-container of the power unit.

KEY WORDS: gas-turbine engine, block-container, ventilation, cooling, thermal state, Navier-Stokes equations.

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I. INTRODUCTION

The ventilation and cooling systems of the block-container (BC), where the gas turbine engines (GTE) are located, play a crucial role in transporting the gas safely. One of the main problems of GTE is the overheating of the internal zone of BC, because of the heating of the engine housing during its operation. The overheating reduces engine efficiency, causes to unnecessary downtime for its cooling, changes in material properties of parts and premature failure of turbine. Heating of this zone increases with the wear of the seals and exhaust (oxidized) gas leakage from the gas outlet part of the engine. Zone heating temperature can reach 100 ^{0}C; that creates additional thermal effects on gas turbine system (lubricants, instrumentation, electric power and other) and is a direct source of fire hazard. In particular, one-way supply of cooling air can cause to uneven distribution of gas dynamic parameters inside of BC, and uneven cooling of the GTE body in the transverse direction. As a result, temperature increases in the stagnant areas with the local overheating of the walls of BC, which causes on the reliability of automatic control system, emergency protection and firefighting systems, and even to the destruction of the engine piping parts because of the thermal bending of its hull [1, 2]. That is why the ventilation and cooling systems of that sort have been a major field of study.

The analysis of the published articles shows that the thermal aspects of the problem of air cooling, heat exchange and ways of its intensification through the cooling channels in heatproof shields are developed much deeper than its gas-dynamic aspects of the air-ventilation systems.For example, the author proposed a one-dimensional gas volume model with an artificial account of the effects of jet streams [3]. This model provides the possibility of obtaining temperature gradient temperature advances by its height but gives only a partial description of the distribution of temperatures in the room.The authors of works [2-9] performed numerical studies of certain aspects in order to determine the thermal state of the GTE block-container in a three-dimensions formulation using the methods of the computational aerohydrodynamic. The accuracy of the numerical solution depends on the specification of the boundary conditions in modeling the thermal state of the gas turbine engine. As a rule, the most correct thermal boundary condition is possible with the conjugate formulation [1]. However, such formulation of the thermal state problem for BC of GTE implies the inclusion of all solid bodies in the calculated region with the flowing air, and the cycled air, the exhaust gases, oil, as well as the atmospheric air adjacent to BC. All of this requires the big computing resources that is unacceptable since the mathematical model should not only adequately describe the essential aspects of phenomena, but also be simple enough to applied in practice. This can be achieved by including simplifying assumptions of the simulated part of the space with the specified the boundary conditions.This is necessary to make assumptions based on the temperature measurement data if the simulated part of the space is limited by the ventilation air with the setting of the Dirichlet and Neumann conditions on the temperature of the surfaces of solid bodies facing the inside of the BC and heat fluxes.For example, enclosing structures of the BC are isothermal [4, 6] or adiabatic [2, 5], consider the engine as a heat source with a constant heat release [6] or else represent the outer surface as a set of blocks with predetermined temperatures [4, 5]. Here, we should note that the using of the data performed "after-fact" contradicts the idea of predicting the thermal state of the BC. Moreover, this approach excludes the possibility of calculating the temperature of the outer surfaces of the BC, although this temperature is of particular interest to the designer, since its maximum value is limited by the labor protection standards.There is a more efficient approach for engineering practice that consists in the one-dimensional modeling of the solid-state thermal conductivity of enclosing structures of the BC with the assignment of third-kind convective boundary conditions on their outer surfaces, as was done in [7, 8].This makes it possible to calculate the temperature of the outer surfaces of the BC, assuming that the coefficients of heat transfer from these surfaces to the atmospheric air are known. In conditions of low thermal conductivity of the outer surfaces of the BC and natural convection outside it, such boundary conditions are quite conservative for their successful practical use.A similar description of the remaining solid bodies in the BC, can increase the sufficiency of the mathematical model. For example, third-class boundary conditions on the engine body could help to circumvent the problem of correcting the experimentally measured thermogram, depending on the mode of operation of the engine, which arises when using the boundary conditions of the first or of the second kind [9].At the same time, the heat transfer coefficients to the inner surface of the engine can be calculated with the corresponding criterial equations using the data of the thermo-gasdynamic calculations of the engine.A serious obstacle to the realization of such an approach within the framework of the simplest one-dimensional mathematical model of the solid-state thermal conductivity is the use in GTE of locally inhomogeneous multi-layered cases with the supply and removal of cooling air into interlayer cavities. This difficulty can be overcome by the transition to modeling in the "semi-conjugate" formulation [11], as was done in [3], where boundary conditions of the third kind on the GTE body were specified, and the thermal conductivity through the case was calculated in a three-dimensional setting.The study [7] confirms the essential contribution of radiant heat transfer inthe thermal state of the walls of the BC. Therefore, when specifying the boundary conditions of radiant heat exchange, it is important to use reliable values of the emissivity (blackness) of the solid-bodies surfaces.The degree of blackness is a complex function. Therefore, in the absence of experimental data, the choice of reliable numerical values of the degrees of blackness for specific surfaces from a wide range of reference data with conditions such as the surface condition, the degree of oxidation is usually characterized only by qualitatively.In the respected papers [3, 7, 8], in which the solid body radiation was simulated in the BC, the choice of the degree of blackness of their surfaces is not commented upon.The thermal state of the BC also depends from heat emissions of the surfaces of equipment such as nodes, instruments, pipelines, electrical wires, as well as from the leakage of the working fluid from the engine casing.The additional heat dissipations were taken into account by setting the temperature of the surfaces of the auxiliary equipment elements and pipelines [3]. The leakage of hot air from GTU was taken into account in the work [5]. However, the questions of determining the temperatures of the surfaces, locations of leaks of the working fluid used as the boundary conditions are not covered.Thus, in known studies there is no a generalized approach to the numerical modeling of the thermal state of the BC of the GTE by the methods of computational aerohydrodynamic, and the issues of ensuring the correctness and reliability of the boundary conditions of the corresponding problem have not been considered so far.

The purpose of this work is to formulate a general statement of the problem for the thermal state of the BC of a GTE, to develop an appropriate mathematical model and to evaluate with its help the effect of thermal boundary conditions on the distribution of the temperature of solid and gaseous bodies in the volume of the BC.

II. MATERIALS AND METHODS

2.1 Hypothesis

The ventilation and cooling systems can be defined as a system that keep an optimum temperature inside the engine block. The turbines are defined as a system designed for driving a compressor for the transport of gas as a part of gas pumping units (GPU).Under the thermal state of the BC, we mean the distribution of the temperature in its solid and gaseous bodies in the BC's space and its variation in time.

The purpose of modeling ofthe thermal state of the BC is to determine the temperature, speed and direction of the ventilation air within the BC, as well as the temperature of the inner and outer walls of the BC at arbitrary points, in the steady and unsteady (including emergency) modes of operation, taking into account the thermal radiation of the heated elements of the equipment in the BC, as well as the leakage of the exhaust gases from the GTE.
Let's consider the environment of the BC that is equipped a ventilation system, the GTE, and equipment as a system consisting of the following energy-interconnected elements:

- Engine;
- Equipment;
- Enclosing structures;
- Ventilation air;
- Leakage of the exhaust gases;
- Atmospheric air;
- Heat-radiating bodies surrounding the BC;
- Heat-conducting medium located under the floor of the BC.

The transfer of energy in the form of heat between the elements of the system is due to the following physical phenomena:

- Three-dimensional viscous flow of the ventilation air inside the BC;
- The mix of the ventilation air with the leakage of the exhaust gases;
- Convective heat exchange between the ventilation air and the surfaces;
- Convective heat exchange between the atmospheric air and external surfaces of the enclosing structures;
- Radiant heat exchange between surfaces facing inward of the BC;
- Radiant heat exchange between the environment and the outer surfaces of the enclosing structures.

In order to describe the state of individual physical subsystems of the complex system under investigation, it is required to involve heterogeneous mathematical models.
The phenomena of viscous flow, and convective heat-transfer can be described by the system of continuity equations (1)for the binary mix:

$$\frac{\partial u_i}{\partial x_i} = 0, i = 1,2,3 \qquad (1)$$

The inert mass conservation is in the equation (2):

$$p\frac{\partial Y}{\partial t} + pu_i\frac{\partial Y}{\partial x_i} = \frac{\mu}{S_c}\frac{\partial^2 Y}{\partial x_i^2}, i = 1,2,3 \qquad (2)$$

The momentum conservation with Navier-Stokes is in the equation (3):

$$p\frac{\partial u_j}{\partial t} + pu_i\frac{\partial u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \mu\frac{\partial}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + pg_j, i = 1,2,3 \qquad (3)$$

And energy conservation is in the equation (4):

$$p\frac{\partial h}{\partial t} + pu_i\frac{\partial h}{\partial x_i} = \frac{\mu}{Pr}\frac{\partial^2 h}{\partial x_i^2} + \frac{\partial q_i^R}{\partial x_j}, i = 1,2,3 \qquad (4)$$

The phenomenon of thermal conductivity in a solid body with the equation of conservation of energy in the form of the heat equation (4a):

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x_i^2}, i = 1,2,3 \qquad (4a)$$

Which is closed by the equation of state (5):

$$p = \rho\frac{RT}{M} \qquad (5)$$

The phenomenon of radiant heat transfer by the radiation transfer equation in the form (6) for the radiating medium or in the form (6a) for diathermic medium:

$$\frac{1}{\beta_0}\frac{dI(\vec{r},\vec{s})}{ds} + I(\vec{r},\vec{s}) = (1-\omega_0)I_b(\vec{r}) + \frac{\omega_0}{4\pi}\int_{\Omega'=4\pi} I(\vec{r},\vec{s}')\, d\Omega' \qquad (6)$$

$$\frac{\partial I}{\partial s} = 0 \qquad (6a)$$

where u_i, u_j- the components of the velocity vector in the direction of the corresponding axes of the Cartesian coordinates x_i, x_j; ρ- the density;Y- the mass fraction of the inert impurity;t- the time;μ - coefficient of dynamic viscosity;$Sc \equiv \mu / D\rho$- the Schmidt number;D- the diffusion coefficient;p- the pressure;g_j- the component of the acceleration of gravity in the direction of the x_j axis;$h = \int_{T^0}^{T} c_p(T)dT$ - specific enthalpy;T- the temperature of the gas; T^0- standard temperature;c_p- the specific isobaric heat capacity of the gas;$Pr \equiv \mu c_r / \lambda$- the Prandtl number;$\lambda$ - the coefficient of thermal conductivity;q_i^R–the component of the flux density of thermal radiation in the direction of the x_i; $a = \lambda/\rho c$- coefficient of thermal diffusivity;c- the specific heat of the solid body;R- the gas

constant;*M*- the molecular weight;$\beta_0 = k_a + \sigma_s$- the volume damping coefficient;k_a - volume absorption coefficient;σ_s- the volume scattering coefficient;*I*–the intensity of thermal radiation;$\vec{r}$- the radius vector of an arbitrary ray in the direction of propagation of thermal radiation $\vec{s}$; $\omega_0 = \sigma_s / \beta_0$ –scattering albedo;$I_b = \sigma T^4 / \pi$ – the intensity of thermal radiation of an absolutely black body;σ- the Stefan-Boltzmann constant;Ω' - the unit solid angle vectorcharacterizing the direction of propagation of thermal radiation due to scattering of photons$\vec{s}'$;
The equations (1) - (4) are considered with the assumption that the effects of compressibility, viscous heating, thermo-, baro- and self-diffusion are negligible [12].The equation (6) is based on the assumption of quasistationary, coherent and isotropic radiation transfer [13].Using the additional assumption about the closeness of thermophysical properties of ventilation air, and exhaust gases, one can exclude from the analysis the phenomenon of their mixing and exclude the equation (2) from the mathematical model of the thermal state of the BC.If we take into account that the mass fraction of the triatomic gases (CO2 and H2O) in the exhaust gases is less than the mass fraction of diatomic gases (N2 and O2), we can assume an additional diathermicity of the exhaust gases and use the equation (6a) in the mathematical model of the thermal state of the BC.The Boussinesq hypothesis of the turbulent viscosity with the Reynolds averaging procedure [12] is used in equations (1), (3), (4) in order to account for the turbulent nature of the motion of the ventilation air and exhaust gases.We use the Launder-Spalding turbulence model [14] for closing the system of averaged equations:

$$\rho \frac{\partial k}{\partial t} + \rho u_i \frac{\partial k}{\partial x_i} = \frac{\mu_T}{\sigma_k} \frac{\partial^2 k}{\partial x_i^2} + G_k + G_b - \rho \varepsilon \qquad (7)$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho u_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\mu_T}{\sigma_\varepsilon} \frac{\partial^2 \varepsilon}{\partial x_i^2} + (C_{\varepsilon 1}(G_k + G_b) - C_{\varepsilon 2} \rho \varepsilon) \frac{\varepsilon}{k} \qquad (8)$$

where k- the kinetic energy of turbulence;$\mu_T = c_\mu \rho k^2 / \varepsilon$ - coefficient of turbulent viscosity;$G_k = \mu_T \frac{\partial u_j}{\partial x_i} \left(\frac{\partial u_j}{\partial x_i} + \right.$ *∂ui∂xj* and *Gb=μT1PrTgiρ∂ρ∂xi* - the source conditions, caused by the viscous stresses, and buoyancy;$Pr_T \equiv \mu_T c_p / \lambda_T$ -the turbulent Prandtl number; λ_T- the turbulent coefficient of thermal conductivity; ε - rate of dissipation of the kinetic energy of turbulence;c_μ, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, σ_ε- empirical coefficients.

The system of partial differential equations (1), (3), (4), (4a), (6a), (7) and (8), supplemented by the algebraic equation (5) and corresponding to the boundary conditions, describes the thermal state of the BC.

2.2 Modeling

Two problems with different boundary conditions were solved in order to study the effect of thermal boundary conditions on the temperature distribution of solid and gaseous bodies that are part of the container block:

a) **Fig. 1** shows the GTE thermogram that is measured without blowing it with cooling air; **Tab. 1** shows the high degrees of blackness of the surfaces of the solid bodies;

b) **Fig. 1** shows the hypothetical thermogram with reduced by 10% temperatures of sections of the outer surface of the engine casing, imitating the cooling by cooling air; **Tab. 1** shows less blackness of the surfaces of the solid bodies.

The relative heating of the outer surfaces of the walls was determined by the formula:

$$\bar{\theta} = \frac{T - T_B}{T_{max} - T_B} \qquad (9)$$

where T - the temperature of the outer surface of the wall; T_B - the temperature of the ventilation air at the entrance to the BC; T_{max}- the maximum temperature of the outer surfaces of the walls.

The numerical solution was found in the two-dimensional space through the cover of the BC by a hybrid grid with about 3 million cells**Fig. 2**. The inputs: the direction of the flow, the temperature of the ventilation air and the exhaust gases, and the parameters of turbulence. The outputs: the excess static pressure is zero. On all surfaces of the solid bodies with a viscous flow, the boundary condition of "sticking" was established using empirical functions for the walls in the turbulence model. On the outer surface of the GTE, a first-kind thermal boundary condition was set through the temperature distribution on the surface of the body, assumed to be constant **Fig. 3.**On the outer surfaces of the enclosing structures, the third-kind coupling conditions were defined with a one-dimensional model of solid-state thermal conductivity: the ambient temperature and the Newton-Richman heat exchange law between the surface of the aircraft and the environment is characterized by the heat transfer coefficient. In the model of one-dimensional solid-state thermal conductivity of the walls of enclosing structures their thicknesses and coefficients of thermal conductivity were indicated.The radiation transfer equation was solved by the discrete ordinate method [13]. The numerical integration was calculated iteratively by the control volume method using the scheme of approximation of the first-order convective terms "against the flow" [15]. The equation of continuity in the limit of small Mach numbers was satisfied using the SIMPLE pressure correction procedure [16].

III. RESULTS AND DISCUSSION

Calculations showed that the flow of ventilation air inside the BC has a complex asymmetric spatial structure with a lot of stagnant zones.The air is heated from the hot outer surfaces of the GTE case and the parts irradiated by the GTE. The air has the greatest temperatures in the areas between the engine and the sub-engine frame, near the most heated sections of the engine and in the stagnant zone near the clutch case.**Fig. 3** that the right wall of the BC is heated to a greater extent than the left. **Fig. 3** shows the maximum temperatures on the external surfaces of enclosing structures near the turbine due to the radiation of high-temperature parts of the engine casing.

The hypothetical thermogram with the reduced temperatures of the outer surface of the BC by 10% and smaller degrees of blackness of the solid bodies showed a significant decrease in the temperatures of the enclosing structures.This can be explained by the strong influence of the parameters on the radiant component of the heat flux from the high-temperature sections of the engine.The problem 1 showed the actual increase of the temperatures of the parts of the outer surface of the engine casing that is cooled by cooling air caused by the use of the thermogram in conditions without the cooling of the engine. This causes to overestimated results of the temperatures of the enclosing structures irradiated by the engine.
The obtained results correspond with the data of full-scale tests of GTU [2].

IV. CONCLUSION

The general statement of the thermal state of the BC of the GTE is formulated. The corresponding mathematical model that allows to analyze the movement of ventilation air within the BC and the temperature at each point in the calculated area, including the outer and inner walls of the BC, under different modes of operation of the GTE is developed.A numerical study of the thermal state of the gas turbine engine under the various boundary conditions was performed. The results showed a high sensitivity of the enclosing structures to the temperatures of the outer surface of the engine casing and the degrees of blackness of the solid bodies.
The further research directions were established in the development of a methodology for accounting of:

- The correction of thermal and hydrodynamic boundary conditions with the GTE operation modes, fans and the position of control measurement systems;
- The heat emissions from equipment;
- The leaks of the exhaust gases;
- The thermal conductivity through the enclosing structures.

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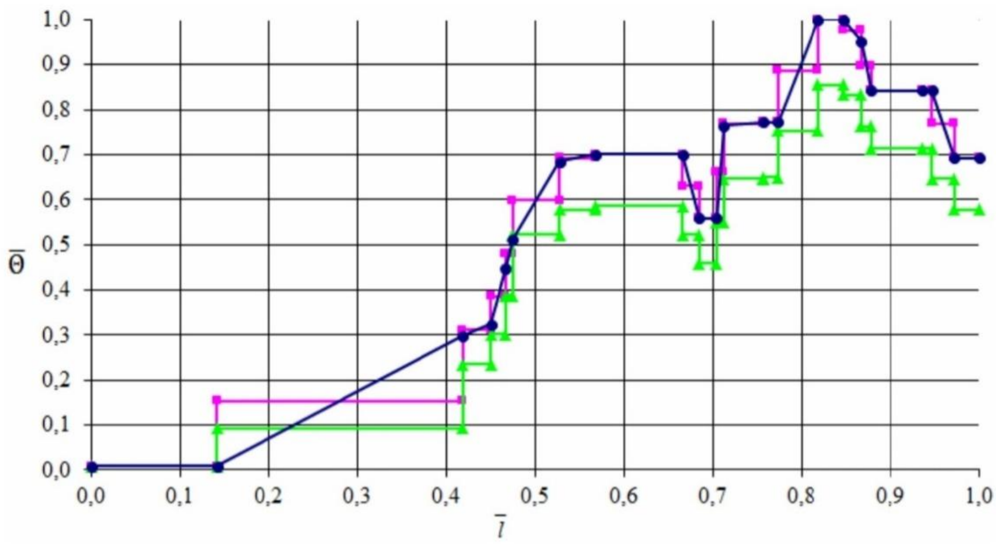
FIGURE AND TABLE



● - the test block-container without the cooling air;
■ - problem 1 with the piecewise-constant function measured;
▲ - problem 2 with the reduced temperature by 10% with cooling air.

Figure 1: The change in the relative heating of the parts of the outer surfaces of the engine casing by its relative length.

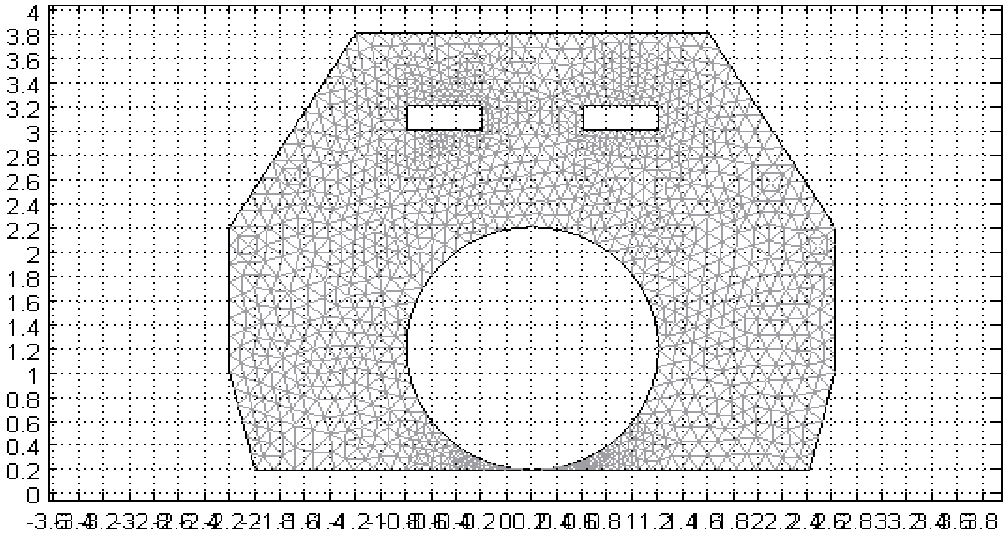
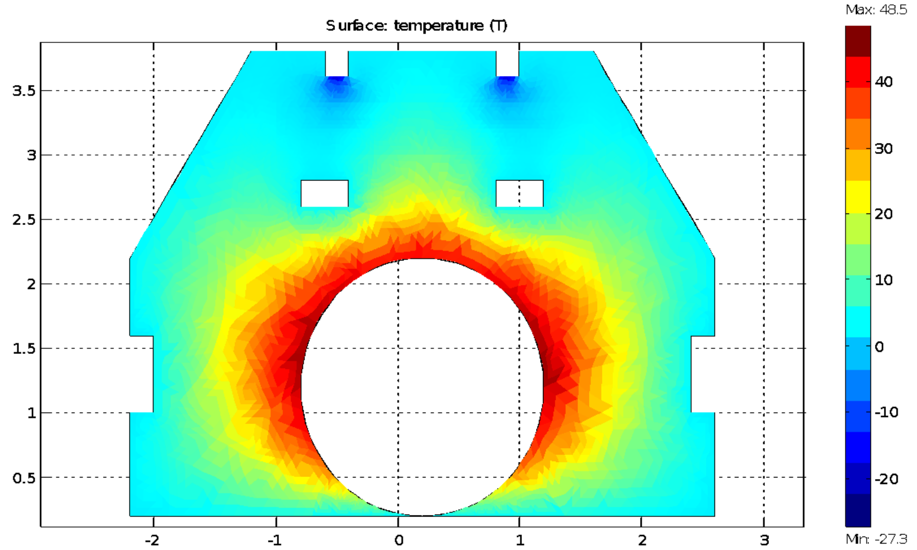
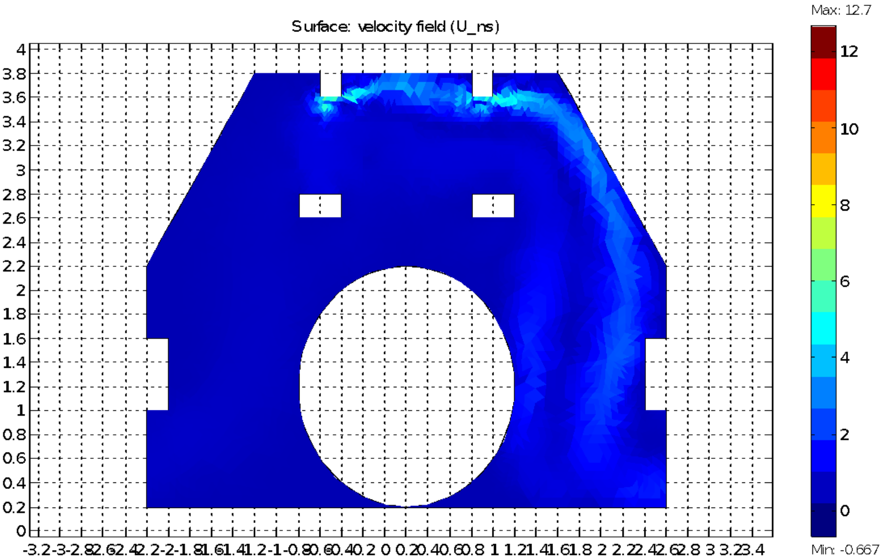


Figure 2: The numerical solution of the finite-element model of air inside the BC



Problem 1



Problem 2

Figure 3: The calculated relative heating of the outer surfaces of the enclosing structures

Table 1: Degree of blackness of surfaces of the solid bodies

Surface	***Problem 1***	***Problem 2***
The walls of the input section and the clutch case	0,75	0,30
The enclosing structures	0,80	0,35
The surface of GTE and sub-engine frame	0,80	0,60

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