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The analysis of ANSYS package applicability for calculating the elements of the heat losses recuperation system in the power unit of the mobile compressor unit

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Abstract

The article analyses the issues of the calculation technique applicability for the fuel heating process in the channels of the elements comprising the heat losses recuperation system for the internal combustion engines (ICE). The technique on the basis of ANSYS package is presented. The technique was used to calculate fuel heating in the channels with complex configuration that can be implemented in a heat losses recuperation system in ICE. The comparison of the integral computation results obtained in the ANSYS environment with the calculation results received by the standard engineering techniques has shown their satisfactory convergence. Also the results of calculating the length of a kerosene heating channel with round and triangular cross section are compared and analyzed. It is shown that the heating area in the channel with round cross section, with the heating leading to the kerosene boiling, is longer than in the channel with triangular cross section.

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Keywords: heating fuel; recuperation of heat losses; ANSYS

Nomenclature

ρ	density, kg/m^3;
V_x, V_y, V_z	components of the vector of the moving fluid particle velocity on axes x, y and z;
P	the fluid pressure at any point of the flow, Pa;
μ	dynamic viscosity, Pa·s;

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λ	heat conduction coefficient of the moving medium, W/(m·K);
t	temperature, ^{0}C;
c_p	heat capacity at constant pressure, J/(kg·K);
t_f	fluid temperature near the wall surface;
α	the local heat transfer coefficient, W/(m^2·K);
n	coordinate, directed towards the liquid orthogonal to the surface;
R	gas constant for the given gas;
z	compressibility coefficient;
Q	heat flow rate, W.

1. Introduction

It is known that almost all the energy supplied to the compressor is converted into heat energy and then it is exhausted into the atmosphere in the cooling systems for gas, lubricating and cooling liquids, and during pipe transportation of pressurant gas [1,2]. It is also known that as a result of fuel combustion in the working chamber, more than half of the energy supplied to the power-unit (generally, internal combustion engine) is released into the atmosphere with the exhaust gases in the cooling systems for oil, cooling liquid and charge air [3]. Effective utilization of these heat losses is a significant scientific and technical problem.

Solutions of this problem for the mobile compressor unit (MCU) are presented in works [4,5]. These publications present thermodynamic analysis of various structural diagrams of MCU heat losses recuperation, and provide the dependencies showing how the efficiency of the MCU with the heat losses recuperation system is affected by the efficiency of the system's individual elements. In particular, the impact of the internal combustion engine (compressor drive) efficiency is shown. Obviously, the higher the efficiency of the internal combustion engine (MCU drive), the higher the entire system's efficiency, in general.

There are several known ways to improve the ICE efficiency [3,6]. The increased temperature of the fuel supplied to the engine results in the increasing of the internal combustion engine efficiency. The increase of the fuel temperature before the injection reduces its viscosity, which in its turn leads to a better atomization and complete fuel combustion [1,7,8,9]. One of ways to increase the fuel temperature is to heat it in the channels of the fuel injection nozzle casing [3], which is in contact with the walls of the engine combustion chamber, its temperature reaching 2800°K in gasoline engines and 1800°K in diesel ones [3]. In addition, the fuel can be a heat-bearing agent of the heat losses recuperation system in MCU internal combustion engines, which suggests the need for development of the corresponding calculation techniques.

2. Study subject

The study subject is a cylindrical wall with an internal cooling channel. This is a base for such sources of heat losses in internal combustion engines as cylinders, nozzles, and bearing units. Kerosene is taken as a fuel since its thermal-physical properties are similar to gasoline and diesel ones (Table 1 [6], parameters values are given at 0°C).

Table1. Comparison of gasoline, kerosene and diesel fuel properties in a liquid state.

Parameter	Fuel		
	Gasoline	Kerosene	Diesel fuel
Density, kg/m^3	786	839	870
Heat conduction, W/(m·K)	0.127	0.119	0.118
Heat capacity, J/(kg·K)	1958	1886	1848
Surface tension, N/m	0.0233	0.028	0.032
Diffusion coefficient, m^2/s	$8.4\cdot10^{-6}$	$6.4\cdot10^{-6}$	$3.0\cdot10^{-6}$

The channel in the cylindrical wall can be done as a twisted loop with a variable radius along the length of the winding, as shown in Fig. 1. In addition, the spacing of the winding can also change. For problem simplification the straight channel was considered at the first stage.

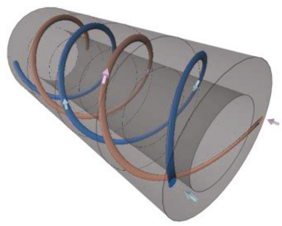

Fig. 1. The diagram of the fuel heating channel in the injector nozzle casing.

3. Methods

The mathematical model of item, including the main assumptions, system of the main equations and unambiguity conditions are considered in work [6]. Fundamental numerical technique, including the peculiarities of creating a geometric model, a grid model, gas (fluid) flow model, and turbulence model, boundary conditions, as well as an example of its implementation are considered in [6]. Further, we will consider some features of numerical methods implementation.

The known system of the equations for convective heat exchange is used as a calculation technique for kerosene heating in ANSYS environment. The following assumptions are set as fundamental.

1. The processes of fluid flow and heat exchange are stationary. This assumption is due to the fact that the calculation of the hydraulic processes is based on complex systems of differential equations, while the nonstationarity of the process leads to a sudden complication of the equations system, which hinders the preparation of the solution.
2. The temperature of the wall, heating the moving stream, remains constant. This assumption follows from the first one.
3. There are no internal heat sources in the fluid flow.
4. the following equations are used as the basic design ones in the analysis of the flow:
   - The equation of continuity, expressing the mass conservation law

$$\frac{\partial}{\partial x}(\rho \cdot V_x)+\frac{\partial}{\partial y}(\rho \cdot V_y)+\frac{\partial}{\partial z}(\rho \cdot V_z)=0 \tag{1}$$

where ρ is density, kg/m^3, and V_x, V_y, and V_z are components of the vector of the moving fluid particle velocity on axes x, y and z.

- Navier-Stokes equation, expressing the law of impulse variation, is used as the basis for distribution of velocity profiles in the flow area:

$$\rho \cdot \left(V_x \cdot \frac{\partial V_x}{\partial x} + V_y \cdot \frac{\partial V_x}{\partial y} + V_z \cdot \frac{\partial V_x}{\partial z}\right) = -\frac{\partial P}{\partial x} + 2 \cdot \frac{\partial}{\partial x}\left(\mu \cdot \frac{\partial V_x}{\partial x}\right) + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial V_x}{\partial z} + \frac{\partial V_z}{\partial x}\right)\right] -$$
$$-\frac{2}{3} \cdot \frac{\partial}{\partial x}\left[\mu \cdot \left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z}\right)\right],$$

$$\rho\cdot\left(V_x\cdot\frac{\partial V_y}{\partial x}+V_y\cdot\frac{\partial V_y}{\partial y}+V_z\cdot\frac{\partial V_y}{\partial z}\right)=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left[\mu\cdot\left(\frac{\partial V_y}{\partial x}+\frac{\partial V_x}{\partial y}\right)\right]+2\cdot\frac{\partial}{\partial y}\left(\mu\cdot\frac{\partial V_y}{\partial y}\right)+\frac{\partial}{\partial z}\left[\mu\cdot\left(\frac{\partial V_y}{\partial z}+\frac{\partial V_z}{\partial y}\right)\right]-$$
$$-\frac{2}{3}\cdot\frac{\partial}{\partial y}\left[\mu\cdot\left(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z}\right)\right],$$

(2)

$$\rho\cdot\left(V_x\cdot\frac{\partial V_z}{\partial x}+V_y\cdot\frac{\partial V_z}{\partial y}+V_z\cdot\frac{\partial V_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial x}\left[\mu\cdot\left(\frac{\partial V_z}{\partial x}+\frac{\partial V_x}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\cdot\left(\frac{\partial V_y}{\partial z}+\frac{\partial V_z}{\partial y}\right)\right]+2\cdot\frac{\partial}{\partial z}\left(\mu\cdot\frac{\partial V_z}{\partial z}\right)-$$
$$-\frac{2}{3}\cdot\frac{\partial}{\partial z}\left[\mu\cdot\left(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z}\right)\right],$$

,

where P is fluid pressure, Pa; and μ is dynamic viscosity, Pa·s.
All members of the equations have the dimension of force per volume unit, N/m^3.

- The energy equation, expressing the energy conservation law, forms the foundation for distribution of the temperature field in the fluid flow area:

$$c_p\cdot\rho\cdot\left(V_x\cdot\frac{\partial t}{\partial x}+V_y\cdot\frac{\partial t}{\partial y}+V_z\cdot\frac{\partial t}{\partial z}\right)=\frac{\partial}{\partial x}\left(\lambda\cdot\frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\cdot\frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\cdot\frac{\partial t}{\partial z}\right)+\mu\cdot\Phi\,,$$

(3)

where Φ is dissipation function, expressing the energy dissipation due to the absence of the viscous forces in the liquid:

$$\Phi=2\cdot\left[\left(\frac{\partial V_x}{\partial x}\right)^2+\left(\frac{\partial V_y}{\partial y}\right)^2+\left(\frac{\partial V_z}{\partial z}\right)^2\right]+\left(\frac{\partial V_y}{\partial x}+\frac{\partial V_x}{\partial y}\right)^2+\left(\frac{\partial V_y}{\partial z}+\frac{\partial V_z}{\partial y}\right)^2+\left(\frac{\partial V_z}{\partial x}+\frac{\partial V_x}{\partial z}\right)^2-$$
$$-\frac{2}{3}\cdot\left(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z}\right)^2 \quad (4)$$

In the above given expressions, λ is heat conduction coefficient of the moving medium, W/(m·K); t is temperature, K; and c_p is heat capacity at constant pressure, J/(kg·K).

One can see from the energy equation that the temperature field in a moving medium depends on the physical properties of the medium and V_x, V_y, V_z velocity fields.

- The heat transfer equation allowing the determination of the local heat-transfer coefficient α with the help of a temperature field $t_{(x,y,z)}$ in a moving medium:

$$\alpha=-\frac{\lambda}{t_w-t_f}\cdot\left(\frac{\partial t}{\partial n}\right)_{n=0}, \quad (5)$$

where t_w is temperature of the heating wall, t_f is fluid temperature near the wall surface, α is local heat transfer coefficient $W/m^2\cdot K$, and n is coordinate, directed towards the liquid orthogonal to the surface, its calculation starting from the heating wall.

- Newton – Richman equation which allows determining heat flow, supplied to the moving medium from the heating wall:

$$\frac{dQ}{dF} = \alpha \cdot (t_w - t_f), \tag{6}$$

where Q is heat flow rate, W, and F is the area of the heating wall surface, m^2.

The above given equations of continuity, impulse variation, energy, heat transfer, and Newton–Richman equation include thermophysical properties of the medium generally depending on temperature:

$$\mu = \mu(t),\ \rho = \rho(t),\ c_p = f(t),\ \lambda = \lambda(t). \tag{7}$$

In case of the moving medium being gas or vapor, the density dependence on temperature is expressed via the equation of state, which has the form of:

$$\rho = \frac{P}{z \cdot R \cdot (t + 273)}, \tag{8}$$

where z is compressibility coefficient, and R is gas constant for the given gas.

The equations defining the dependence of the moving medium properties on temperature are rather complicated in an analytical form, therefore these dependencies are given as tables, which are entered in the library of the substances properties in special software packages, such as ANSYS CFX.

The above mentioned equations form a system, which describes the heating of a moving single-phase medium, when the liquid or gas moves in the channel. The resulting differential equation system describes all possible cases of heat transfer when flow moves in the channel. To find the only possible solution among numerous others, the equations system needs to be enhanced with unambiguity conditions which are divided into the conditions of geometrical unambiguity, physical unambiguity and boundary conditions.

The condition of geometrical unambiguity is that the channel the flux moves in is a straight one with two types of cross section, round and triangular, with an equilateral triangle forming the basis of triangular cross-section. In both cases, the cross-sectional area was taken the same and equal to 176 mm^2. This corresponds to the channel diameter of 15 mm and the triangle side of 20.2 mm.

The physical condition is setting the dependences of the moving medium (kerosene) properties on temperature in the form of tables which are entered in the library of the substances properties in ANSYS CFX.

The boundary conditions for heat transfer calculation is setting the temperature of liquid kerosene at the channel entrance at the 20°C, and also setting liquid kerosene velocity at the channel entrance as a set of values 0.1, 0.5, and 1.0 m/s. Mass flow rate was taken as constant when calculating the modes of liquid kerosene heating, boiling and kerosene vapors heating. The boundary conditions include setting the temperature of the channel side heating wall as a set of several values changing with the heating flux mode. The pressure at the flow entrance in the channel was set arbitrarily, because the pressure changing along the heating area is of interest, rather than the absolute pressure value.

4. Results and discussion

The calculation of the given equations system with the described unambiguity conditions was made in ANSYS environment with the involvement of the CFX application. Construction of the channel models geometry was performed in the module Geometry; construction of the finite elements computational grid was done in CFX – Mesh; specification of the boundary conditions and calculation parameters was performed in CFX – Pre, solution was done in CFX – Solve, visualization and the analysis of results was carried out in CFX – Post. The units of all quantities correspond to SI. The calculation results are presented in Table 2, an example of calculation results for a particular case (at kerosene rate V=0.5 m/s and a wall temperature t_w=2000 °C) is given in Fig. 2, 3 and 4.

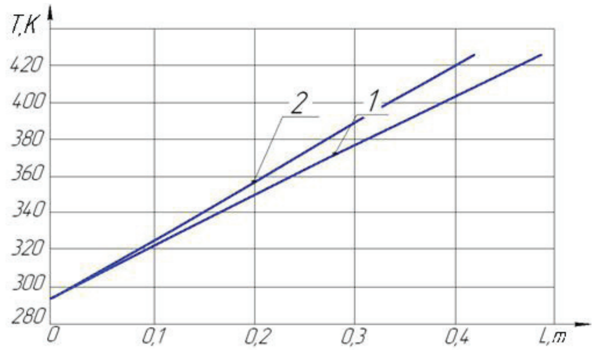

Fig. 2. The change of the flow temperature along the channel at a kerosene velocity of 0.5 m/s and the wall temperature t_w=2000°C: line 1 is the channel with circular cross-section, and line 2 is the channel with triangular cross section.

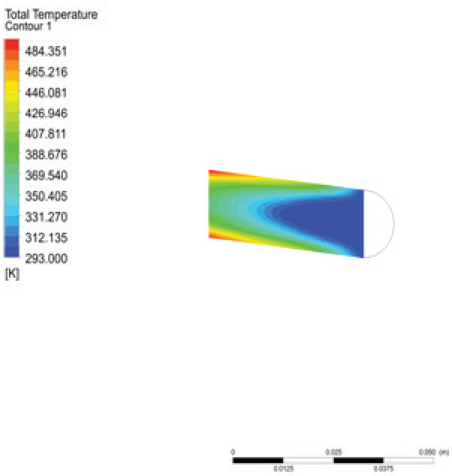

Fig. 3. Temperature distribution in a longitudinal plane passing through the symmetry axis of circular cross-section (V=0.5 m/s, t_w=2000°C).

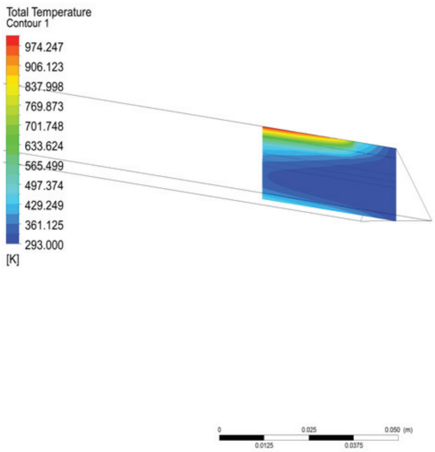

Fig. 4. Temperature distribution in a longitudinal plane passing through the symmetry axis of triangular cross-section (V=0.5 m/s, TW=2000°C).

Table 2. The dependence of the length of liquid kerosene heating area on the temperature of the heating wall and the flow velocity.

Temperature of the heating wall T, °C	Velocity V, m/s	Channel length L, mm	
		Round cross-section	Triangular cross-section
500	0.1	783	550
	0.5	2205	1711
	1.0	2780	2317

	0.1	350	196
1000	0.5	991	735
	1.0	1260	1013
	0.1	224	108
1500	0.5	640	471
	1.0	820	661
	0.1	165	69
2000	0.5	474	319
	1.0	610	456

5. Conclusion

The integral calculation results from the ANSYS medium were compared with the calculation results based on the standard engineering techniques [10], what demonstrated their satisfactory convergence. Furthermore, the analysis of the calculations shows that the length of the heating area, leading to the beginning of the kerosene boiling in the channel with round cross section is larger than that in the channel with triangular cross section. This is due to the large perimeter of triangular cross-section. The increase in flow velocity leads to the increase in the length of the heating area, which is a qualitative verification of the calculation results. All this proves that the presented techniques, developed on the basis of ANSYS package, are applicable for the calculation of fuel heating in the channels with complex configuration that can be used in heat losses recuperation system in internal combustion engines.

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