Modeling of the processes of heating organic coolant in the system of heat losses recuperation of the mobile compressor unit on the basis of a low-speed single-stage

G I Chernov¹, V L Yusha¹, K V Sherban¹, A M Kalashnikov¹

¹ Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

E-mail: gi_chernov2002@mail.ru

Abstract. The article considers the modeling of the processes of heating organic coolant in the system of heat losses recuperation of the mobile compressor unit. The modeling of the liquid fuel heating, its boiling and vapor overheating was carried out in the ANSYS environment. The modeling results were compared with the available engineering methods, and proved the applicability of the considered modeling method.

1. Introduction

It is known that all the energy required for the mobile compressor unit (MCU) drive is released in the form of heat into the environment by cooling gas, lubricants and coolants, as well as communications [1, 2]. In mobile compressor units more than half of the energy supplied to the power unit (as a rule to the internal combustion engine) as a result of fuel combustion in its working chamber is discharged into the atmosphere together with the exhaust gases, as well as through the oil, coolant and charge air cooling system [3]. Slow-speed single-stage compressors with unique cooling conditions of the actuation gas in the cylinder are of special interest [4, 5].

The ways of solving the given problem for a mobile compressor unit (MCU) with the existing compressor units are proposed in papers [6, 7]. The present the results of the thermodynamic analysis of the various structural schemes of MCU heat losses recuperation. However, these studies have not addressed the coolant such as the fuel supplied to the power unit. Meanwhile, there are several ways to make internal combustion engines more efficient [3, 8], including an increase in the temperature of the fuel supplied to the engine, allowing to enhance the quality of the spray and the combustion efficiency [1, 9, 10, 11]. Obviously, the fuel may be one of the coolants in the MCU recovery heat losses recuperation system. At the same time, elements of the recuperation system may include similar in design cylindrical cooling cavities of fuel injectors, internal combustion engine cylinders and long-stroke slow-speed single-stage reciprocating compressors. In this regard, the task of developing a methodology for calculating organic fuel heating processes in the cooling systems of such units is urgent.

2. Statement of the problem

The given study investigates the processes of heating, boiling and overheating of organic fuel vapor (kerosene) in the channels of the elements of heat losses recuperation system in a mobile compressor unit on the basis of a slow-speed single-stage reciprocating compressor.
3. The object of the research
The object of the study is a cylindrical wall with inner cooling channel. Such an element is a base for such sources of heat loss, as cylinders, nozzles, and end nodes. Kerosene is taken as fuel.
The channel in the cylindrical wall, may generally be twisted with a variable radius loop along the length of the winding, as shown in Figure 1. In addition, the winding step may also vary.

Figure 1. Fuel heat channel scheme

4. Research methodology
A well-known system of convective heat transfer equations is used as a method of calculating the kerosene heating in ANSYS environment. The main assumptions are the following:
1. The process of liquid flow and heat transfer are stationary. This assumption is determined by the fact that the calculation of the thermal-hydraulic processes is based on a complex systems of differential equations; while the process unsteadiness leads to a drastic complication of the equation system, making it difficult to obtain the solutions.
2. The temperature of the heating wall of the moving flow remains constant. This assumption follows from the first one.
3. In a liquid flow there are no internal heat sources.
The main computational equations used in the analysis of the flow are the following:
– The continuity equation expressing the law of conservation of mass.
– The Navier-Stokes equations, expressing the law of momentum change, on the basis of which the distribution of the velocity in the flow region is found out.
– The energy equation, which expresses the law of conservation of energy, which is the basis for the distribution of the temperature field in the liquid flow.
– The Newton–Richman equation, allowing to determine the heat flow, supplied to the flowing medium by the heating wall.
The above equations forms a system that describes the heating of a moving-phase medium, when liquid or gas moves in the channel. When the liquid is boiling, the system composed of two subsystems is built. One subsystem describes the motion of the liquid, the other describes the vapor equilibrium with the liquid. The relationship between these subsystems is described by the following equations concerning the interaction of the phases at their interface.
– The equation, describing mechanical equilibrium through the equality of the liquid and vapor shear stresses at the interface border [12];
\[ \mu' \cdot \left( \frac{\partial V'}{\partial n} \right)_{\text{int}} = \mu'' \cdot \left( \frac{\partial V''}{\partial n} \right)_{\text{int}}, \]
where \( \mu' \) is the coefficient of dynamic viscosity of the liquid phase; 
\( V' \) is the line tangent to the interface component of the liquid phase velocity; 
\( \mu'' \) is the coefficient of dynamic viscosity of the vapour phase; 
\( V'' \) is the line tangent to the interface component of the vapour phase velocity.

– The equation, describing mass transfer, while phase changing at the interface:

\[
(\rho' \cdot V'_n)_{\text{int}} = (\rho'' \cdot V''_n)_{\text{int}}, \quad (2)
\]

where \( \rho' \) is the liquid phase density, kg/m³; 
\( V'_n \) is the normal to the interface component liquid phase velocity; 
\( \rho'' \) is the density of the vapour phase, kg/m³; 
\( V''_n \) is the normal to the interface component of the vapour phase velocity.

– The equation, describing heat balance during the heat transfer between the liquid and the vapour phases to the interface:

\[
-\lambda' \left( \frac{\partial t}{\partial n} \right)_{\text{int}} = r \cdot \rho'' \cdot V''_n \quad (3)
\]

where \( \lambda' \) is the heat transfer coefficient of the liquid phase; 
\( r \) is the evaporation specific heat, J/kg.

The left side of this equation determines the density of the heat flow supplied to (withdrawn from) the interface from the liquid phase. The right side of this equation describes the density of heat flow, withdrawn from (supplied to) the interface from the vapor phase.

The continuity, momentum change, energy, heat and Newton - Richman equations given above include thermal properties of the medium, which generally depend on the temperature.

The equations defining the dependence of the moving medium properties on the temperature when presented in an analytical form are quite complicated, so these dependencies are usually given in the form of tables, which are insert in the library of substance properties in special software systems such as ANSYS CFX.

The developed system of differential equations describe all possible cases of heat transfer during the flow moving in the channel. To select from an infinite number of possible solutions only the right set of equations, is should be supplemented by the single-valued conditions, which are divided into geometrical single-valued conditions, physical single-valued conditions and boundary conditions.

Geometrical single-valued conditions include the fact that the channel where the flow moves, should be considered with two types of cross-section (round and triangular one), the basis of triangular cross-section being an equilateral triangle. In both cases, the cross sectional area was assumed the same and equal to 176 mm². This corresponds to the diameter of 15 mm and side of the triangle 20.2 mm.
The physical conditions include establishing the dependencies of the moving medium properties (kerosene) on the temperature in the form of tables, which are insert in the library of substances properties in ANSYS CFX.

The boundary conditions for the calculation of heat transfer is the establishing of liquid kerosene temperature at the channel inlet at the level of 20°C, and the establishing of liquid kerosene velocity at the channel inlet as a set of values of 0.1; 0.5; 1.0 m/s. When calculating the liquid kerosene heating mode, its boiling and heating kerosene vapor, mass flow rate was assumed constant. The boundary conditions also included the establishing of the heating temperature of the channel side wall as a set of multiple values that changed when changing the flow heat mode. The pressure at the flow channel inlet was set in an arbitrary manner, as not the absolute value of the pressure but its gradient at the heating area under consideration is of interest.

5. Analysis of the calculation results

The calculation of the given system of equations with the described single-value conditions was made in ANSYS CFX environment involving the CFX application. The building of the channel models geometry was made in the Geometry module, the construction of the calculated finite element mesh - in CFX-Mesh, the establishing of boundary conditions and calculation parameters - in CFX-Pre, the solution - in CFX-Solve, the visualization and analysis of the results - in CFX-Post. The units of all the values comply with SI.

The example of calculation of kerosene heating prior to the boiling for the special case at kerosene speed \( V = 0.5 \) m/s and wall temperature \( t_{\text{wall}} = 2000°C \) is shown in Figures 2, 3 and 4. The calculated dependencies of kerosene heating channel length before the boiling state on the velocity of kerosene and the temperature of the heating wall for different configurations of the channel cross-section are shown in Table 1.

![Figure 2. The flow temperature change along the channel length at kerosene velocity 0.5 m/s and wall temperature \( t_{\text{wall}} = 2000°C \): line 1 –channel with round cross-section; line 2 –channel with triangular cross-section](image-url)
Figure 3. Temperature distribution in longitudinal plane, passing through the axis of round cross-section symmetry ($V=0.5$ m/s, $t_{wall}=2000^\circ$C)

Figure 4. Temperature distribution in longitudinal plane, passing through the axis of triangular cross-section symmetry ($V=0.5$ m/s, $t_{wall}=2000^\circ$C)
Table 1. Dependence of the kerosene boil-off section length on the flow rate and the heating wall temperature

| Wall temperature, °C | Velocity V, m/sec | Channel length L, mm |
|----------------------|-------------------|---------------------|
|                      | Round cross-section | Triangular cross-section |
| 800                  | 0.1               | 855                 | 496        |
|                      | 0.5               | 1860                | 1550       |
|                      | 1.0               | 2445                | 1890       |
|                      | 0.1               | 377                 | 130        |
| 1500                 | 0.5               | 938                 | 660        |
|                      | 1.0               | 1165                | 830        |
|                      | 0.1               | 267                 | 83         |
| 2000                 | 0.5               | 680                 | 442        |
|                      | 1.0               | 840                 | 580        |

After the complete kerosene boiling-off at temperature range 280 – 300 °C with its further heating, the vapour heating occurs. The heating continues until the temperature reaches 430 – 450 °C, when kerosene vapour thermal decomposition into more light hydrocarbon fractions begins [13]. Both during liquid kerosene heating and boiling and kerosene vapors heating its movement in two types of channels cross sections was analyzed: the channel with a round cross section and the channel which cross-section is an equilateral triangle. The heating wall temperature took values 1000; 1500; and 2000 °C. The liquid kerosene flow rate at the channel inlet was assumed to be equal to: 11; 55; 110 m/sec. This is determined by a decrease in the kerosene density during its transition to the vapor phase and by mass flow conservation corresponding to the velocities of kerosene movement in its liquid phase: 0.1; 0.5; 1 m/sec.

The example of calculation of kerosene vapor heating before the thermal cracking at heating wall temperature 2000 °C and flow rate 55 m/sec are shown in Figures 11, 12 and 13. The calculated dependences of the kerosene vapor heating channel length before the beginning of the thermal cracking process on kerosene velocity and heating wall temperature for different configurations of the channel cross-section are presented in Table 3.

Figure 5. Temperature changing of the flow vapour phase along the channel length at kerosene velocity 55 m/s and wall temperature 2000°C: curve 1 – channel with round cross-section; curve 2 – channel with triangular cross-section
Figure 6. Temperature distribution of the flow vapour phase in longitudinal plane, passing through the axis of round cross-section symmetry (V=55 m/sec, t_{wall}=2000 °C)

Figure 7. Temperature distribution of the flow vapour phase in longitudinal plane, passing through the axis of triangular cross-section symmetry (V=55 m/sec, t_{wall}=2000 °C)
Table 2. Dependence of the kerosene vapour heating section length before the beginning of its thermal decomposition on the flow rate and the heating wall temperature

| Wall temperature Т, °C | Velocity V, m/sec | Channel length L, mm |
|------------------------|-------------------|----------------------|
|                        | Round cross-section | Triangular cross-section |
| 1000                   | 0.1               | 492                  | 373 |
|                        | 0.5               | 632                  | 493 |
|                        | 1.0               | 699                  | 550 |
|                        | 0.1               | 298                  | 198 |
| 1500                   | 0.5               | 387                  | 266 |
|                        | 1.0               | 424                  | 298 |
|                        | 0.1               | 208                  | 135 |
| 2000                   | 0.5               | 277                  | 181 |
|                        | 1.0               | 308                  | 203 |

6. Conclusion
The comparison of the results of integral calculation in the ANSYS environment with the results of calculation obtained by standard engineering techniques [14], has shown their satisfactory convergence up to 20%. The adequacy of kerosene boiling calculation is proved by satisfactory agreement between the interval of the boiling temperature limits (150 and 280 °C) and the calculated limits interval of the boiling kerosene volume fraction change (1 and 0.4). Furthermore, the calculation analysis shows that the length of the heating area, which leads to the top of the kerosene boiling in a channel with a round cross-section is greater than in a channel with a triangular cross-section. This is determined by a big perimeter of triangular section. The flow rate growing leads to the increasing in the length of the heating section, that is a qualitative verification of the calculation results. All this shows that the technique presented in the article, which was designed on the basis of ANSYS package, is applicable for calculation of fuel heating in the channels of a complex configuration, which can be used in the system of heat losses recuperation in MCU with different types of compression equipment. The preliminary results suggest the possibility of the effective combination of MCU recuperation system with fuel preparation system, including the possibility of fuel thermal cracking.

References
[1] Guilherme B. Ribeiro 2016 Second law evaluation of a lightweight cooling unit Case Studies in Thermal Engineering 7 March pp 47–54
[2] Filkin N. Yu., Yusha, V. L. 2016 Theoretical analysis of changing gas dynamic characteristics of the dust filter with a short diffuser while in operation Procedia Engineering 152 pp 270–275.
[3] Lukanin, V.N., Buslaev, A.P., Novikov A.V. 2003 Traffic flows modelling and the evaluation of energy-ecological parameters International Journal of Vehicle Design 33(4) pp 381–399.
[4] Yusha V L, Dengin V G, Busarov S S, Nedovenchanyi AV and Gromov AYu 2015 The estimation of thermal conditions of highly-cooled long-stroke stages in reciprocating compressors International Conference on Oil and Gas Engineering, OGE-2015 pp 264–269.
[5] Caroline Willich, Christos N. Makides, Alexander J. White. 2017 An investigation of heat transfer losses in reciprocating devices Applied Thermal Engineering 111 pp 903–913
[6] Yusha V L and Chernov G 2013 Effectiveness analysis of using the Rankine cycle and cycle of refrigeration machine for recuperation of heat losses in mobile compressor unite 8th International Conference on Compressors and Coolants (Papiernička, Slovakia, 2013) 45
[7] Yusha V L, Chernov G I and Sadvakasov D H 2016 The Efficiency Analysis for the Heat Losses Recuperation System of the Mobile Refrigeration Unit *Procedia Engineering* 152 pp 339–347.

[8] Kavtaradze R Z, Zelentsov A, Gladyshev S P, Kavtaradze Z and Onishchenko D. 2012 Heat insulating effect of soot deposit on local transient heat transfer in diesel engine combustion chamber *SAE Technical Papers* pp 68–79.

[9] Markov V A, Gladyshev S P, Devianin S and Mikhalsky L. 2010 Method of estimating the quality of the process of creating the fuel-air mixture in a high-speed diesel engine *SAE Technical Papers* pp 76–87

[10] Dent J C 1971 Basis for the comparison of various experimental methods for study spray penetration *SAE paper*, 710571 18

[11] Hiroysu H and Arai M 1990 Structures of fuei spray in diesel engines penetration *SAE paper*, 900475 14

[12] Bessarabov A M, Avseev AV, Avseev V V and Kutepov A M 2004 Hierarchy of dynamic models of nonequilibrium chemically reactive plasma: The possibility of initiation of oscillating chemical reactions *Theoretical Foundations of Chemical Engineering* 38(2) pp 214–218