Mathematical model of the condensation process in the crankcase space of a piston engine warmed up under negative temperatures of a cold climate

V N Kaminsky¹, A V Kostyukov¹, A V Kolunin² and I V Materi²

¹Federal State Budgetary Educational Institution of Higher Education "Moscow Polytechnic University", Moscow, Russia
²Branch of Federal State-Owned Military Educational Institution “Khrulev Military Academy of Logistics” of the Ministry of Defense of the Russian Federation in Omsk (OABII), Omsk, Russia

Abstract. In recent years, there has been a trend of increasing activities in the development of polar territories. Negative temperatures are a characteristic feature of the North. Negative temperatures have a negative impact on the state of power installations of land, air and water transport, mobile, stationary power plants and small-scale mechanization facilities. The engine is least adapted unit for operation in such conditions. There is a chain of negative factors that consistently provides a connection between the state of the lubrication systems and the negative temperatures, in which the equipment is operated. Condensation processes are a primary link in this chain. The existence of condensation processes in the crankcase space when a piston engine is warmed up at negative temperatures is experimentally proved. The percentage of engine oil watering and the dew point temperature of crankcase gases are determined in the conditions of a full-scale experiment. However, the high labor intensity and significant financial costs of organizing such experiments require the search for other methods of testing. A mathematical representation of reality, which allows you to obtain objective and adequate experimental data information, can be one of the ways to solve this problem.

I. Introduction

In recent years, an interest in the polar regions of our planet has been actively growing. Interests have an economic and strategic basis. Governments of a number of states claim their rights to the Polar territories, which store huge reserves of hydrocarbons and other minerals. The solution of transport issues related to the provision of exploration, development, production, and supply is largely assigned to the means of land transport. The engine, figuratively called the "heart of the machine", ensures the functioning of the entire "organism".

Further development of the northern territories is possible on the basis of the application of advanced technologies in the design, production and operation of piston engines of land transport vehicles. Piston engines provide the conversion of thermal energy into mechanical (electrical) energy. Piston engines can have both certain design differences and common structural elements. We would especially like to mention the lubrication system. The functions of the lubrication system include improving the friction conditions, removing heat from the friction zone, removing wear products, and protecting parts from chemically active compounds. The condition of the lubrication system largely determines the reliability and service life of the engine.

Negative temperatures are a characteristic feature of the Polar territories. Negative effects of negative temperatures on the condition of piston engines are well known.

In the simplest sense, it is clear that low temperatures have a thickening effect on the condition of oils. Viscosity is a property of a substance to resist external influences that cause its flow [1]. Consequently, at a low temperature mode, the oil flow and pump ability through the channels of the lubrication system slow down. Thus, the friction conditions of the surfaces of the mating parts deteriorate.
In addition, during production, the oil is provided with a package of additives responsible for the performance properties. The additives are able to fulfill their function in a proper way only under optimal temperature conditions. During the operation, the additives decompose, and the package of the additives is reduced. In low-temperature conditions, the process of decomposition of additives slows down, which negatively affects the activity of their functioning and the performance properties of the oil.

However, there is another chain of negative factors that consistently provides a connection between the negative temperatures, in which the equipment is operated, and the state of the lubrication systems. The primary link in this chain is condensation processes [2].

Due to the fact that the hydrocarbons that enter the cylinders begin to oxidize, a complex of new substances appears, which also includes water, represented in a gaseous state. The formed steam is safely removed from the cylinder (the exhaust system is used for this), but some of it enters the crankcase [3]. Figure 1 shows a description of the process of moving the crankcase gases (as an example, the power plant of the YaMZ-240 model is used).

![Figure 1. Approximate diagram of the flow of crankcase gases by way of example of the YaMZ-240 engine](image)

If the thermal mode corresponds to the operating instructions, the formed vapors are not retained in the catheter, since they are effectively removed from the power plant thanks to the operation of a special system (crankcase ventilation system). In the low-temperature implementation of the actual cycle, water vapor cannot be completely removed because some of it is subjected to condensation on the oil, as well as on other surfaces. It should be noted that water and oil, when combined, form emulsions. Scientists have proved that water is able to form conglomerates from products characterized by the lack of aggregate stability. Such products are, for example, additives and their decomposition products. In addition, conglomerates can also be formed from fuel fractions, due to incomplete combustion. The dynamics of the consumption of the washing potential, which was originally planned during production, increases. Thus, the pH of the oil decreases, which leads to an increase in the degree of its acidity [4]. On the surfaces of the parts, black ointment-like deposits are deposited, which are called "low-temperature" ones. Low-temperature deposits that change the state of the lubrication systems are shown in Fig. 2.
Therefore, scientific questions arise: “How much water condenses during engine warm-up in the crankcase space? What is the value of the dew point temperature of the crankcase gases?” As you know, the gas dew point temperature (dew point temperature) is the value of the gas temperature, at which water vapor contained in a gas and cooled isobarically becomes saturated.

II. Problem Statement
There are a number of experimental studies proving the presence of condensation processes in the crankcase space. The study had full-scale nature. The presence of such processes and their activities were determined by the moisture content of the oil samples, which were selected through a specially installed sampler when the engine was warmed up without stopping it in conditions of negative temperatures of a cold climate.

However, such methods are time-consuming, costly, and rarely conducted, primarily for research purposes.

A good alternative to full-scale experiments can be a mathematical representation of reality, which allows us to obtain output parameters that are adequate to the experimental data. The output parameters are the mass amount of water condensate formed during the engine warm-up period, and the dew point temperature of the crankcase gases. When solving the difficult task of developing a mathematical model, it is necessary to take into account a number of factors that affect the activity of condensation processes.

III. Theory
The model has assumptions, it is created on the basis of the ideal gas theory [5]. In this connection, the first assumption is defined: "The gas located in the volume of the crankcase space is ideal".

The processes occurring in the crankcase space during the implementation of the actual cycle of a piston engine are poorly understood. The problematic nature of the study consists in a variety of factors that interact with each other and influence mechanical, physical-chemical, gas-dynamic, and hydrodynamic processes. The movement of the parts is carried out by bubbling of the working oil. Based on these conditions, the second assumption is determined: "The movements of oil and gases in the crankcase space are separate."

When implementing a real cycle, there is such a negative factor as incomplete combustion of fuel. The completeness of fuel combustion depends on the design features, operating modes, operating conditions. It is measured as a percentage of losses relative to the amount of heat introduced with the fuel into the combustion chamber, and is related to the engine efficiency. When developing the model, a third assumption was introduced: "The fuel burns completely, without forming by-products of incomplete fuel combustion".

The crankcase ventilation system removes crankcase blow-by gases due to excessive pressure in the volume of the crankcase space. In this case, the passage sections of the ventilation ducts and oil
separation devices ensure their smooth passage, and the pressure in the studied space cannot significantly differ from the atmospheric one. On the basis of the latter, the fourth assumption is determined: “The pressure in the crankcase space corresponds to the pressure of atmospheric air.”

In the described model, the studied space is the crankcase space. It is clear that in different positions of the three-dimensional system located within the framework of the crankcase space, the temperatures differ to a certain extent and cannot be identical. Thus, the fifth assumption is determined, which facilitates the solution of the problem and does not significantly affect the calculation error: “The temperature is uniform in the entire volume of the crankcase space and is determined by the arithmetic mean values of the temperature sensor signals.”

The initial data are:
– fuel composition in mass fractions: C-carbon, H-hydrogen, O-oxygen;
– excess air coefficient: \( \alpha \);
– air composition in mass fractions: \( \text{N}_2 \)-hydrogen, \( \text{O}_2 \)-oxygen;
– gas pressure \( P \) (atmospheric pressure);
– atmospheric air temperature \( t_a \);
– mathematical description of instantaneous temperature values \( t \) in the volume of the crankcase space depending on the heating time \( \tau \) can be represented by the regression equation;
– a mathematical description of the instantaneous values of the crankcase gas flow rate \( Q \) as a function of the coolant temperature \( t \) can be represented by a regression equation. Since the breakthrough of gases through the interfaces of the parts of the cylinder-piston group is carried out inside the cylinder liner, which is in heat exchange interaction with the coolant, the temperature of the coolant is determined as an argument for the dependence. As is known, the activity of condensation processes largely depends on the consumption of crankcase gases. At the same time, it should be taken into account that the consumption of crankcase gases is not constant, especially in conditions of significant temperature ranges. The dimensions of the thermal gaps in the interfaces of the cylinder-piston group parts depend on the temperature state of the engine. In these calculations, it is possible to use the average value as the initial data, however, the average values increase the error of calculations. A mathematical description in the form of a regression equation is preferable to an average value with the expectation of a low error.

Determination of the mass of the products that make up the working fluid when implementing the actual engine cycle

1. To calculate the volume of air required to burn fuel weighing 1 kilogram, it is necessary to use the expression (1):

\[
V_a = \frac{1}{0.208} \left( \frac{C}{12} + \frac{H}{4} - \frac{O}{32} \right),
\]

where \( C \), \( H \), and \( O \) are the mass fractions of the corresponding chemical elements that make up the fuel.

2. To calculate the molar mass that carbon has, it is necessary to use the expression (2):

\[
M_{C_{12}} = \frac{C}{12}.
\]

3. To calculate the molar mass that nitrogen has, it is necessary to use the expression (3):

\[
M_{N_{2}} = N_{2} \alpha_{1} I_{0}.
\]

4. To calculate the molar mass that oxygen has, it is necessary to use the expression (4):

\[
M_{O_{2}} = 0.21 (\alpha - 1) I_{0}.
\]
5. Thus, the total molar mass of the carbon, oxygen and nitrogen components of the fuel can be determined by the expression (5):

\[ M_{c,x} = M_{\text{CO}_2} + M_{N_2} + M_{O_2}. \]  

(5)

6. The calculation of the molar mass of water in the vapor state is determined by the formula (6):

\[ M_{H_2O} = \frac{H}{2}. \]  

(6)

7. The calculation of the mass of carbon is made in accordance with the expression (7):

\[ m_{\text{CO}_2} = M_{\text{CO}_2} \cdot \mu_{\text{CO}_2}. \]  

(7)

where \( \mu_{\text{CO}_2} \) is 12.01 g/mol.

8. The calculation of the mass of nitrogen is made in accordance with the expression (8):

\[ m_{N_2} = M_{N_2} \cdot \mu_{N_2}. \]  

(8)

where \( \mu_{N_2} \) is 14.007 g/mol.

9. The calculation of the mass of oxygen is made in accordance with the expression (9):

\[ m_{O_2} = M_{O_2} \cdot \mu_{O_2}. \]  

(9)

where \( \mu_{O_2} \) is 15.999 g/mol.

10. Thus, the total mass of all dry gases is determined by the sum of three terms (10):

\[ m_{\text{c,x}} = m_{\text{CO}_2} + m_{N_2} + m_{O_2}. \]  

(10)

11. The molar mass of dry gases is determined by the dependence (11):

\[ \mu_{\text{c,x}} = \frac{m_{N_2} \cdot \mu_{N_2} + m_{\text{CO}_2} \cdot \mu_{\text{CO}_2} + m_{O_2} \cdot \mu_{O_2}}{m_{\text{c,x}}}. \]  

(11)

12. By the expression (12), the total mass of water vapor can be determined:

\[ m_{H_2O} = M_{\text{H}_2O} \cdot \mu_{\text{H}_2O}. \]  

(12)

where \( \mu_{\text{H}_2O} \) is 18.06 g/mol.

13. Thus, the total mass, which is characterized by the working fluid, is calculated using the expression (13):

\[ m = m_{\text{c,x}} + m_{H_2O}. \]  

(13)
Determination of the mass flow rate of crankcase gases

14. The procedure for calculating the density of gases that are part of the analyzed fuel is described in detail below.

The mass flow rate of crankcase gases \( Q_m \) is determined from the product of the density \( \rho \) by their volume flow rate \( Q \), the latter is expressed by a mathematical dependence describing the value of the flow rate \( Q \) on the coolant temperature \( t \):

\[
Q_m = \rho Q.
\]  
(14)

The density value is determined by the expression (15):

\[
\rho = \frac{m}{V}.
\]  
(15)

Determination of initial and final moisture content

15. The initial moisture content of gases depends on the hydrogen content in the fuel. It is a constant value and is determined by the ratio (16):

\[
d = \frac{m_{H_2O}}{m_{\text{vap}}}. 
\]  
(16)

16. Determination of the final moisture content.

The amount of moisture contained in the crankcase changes as the engine temperature increases. It can be determined by means of a mathematical dependency. As for the pressure, which is part of the initial data, its value is determined by the saturation pressure \( P_0 \). The latter is a derivative of the thermal, physical characteristics of water [7].

The amount of moisture contained in the engine at a particular step is determined according to the formula (17):

\[
d_i = \frac{\mu_{H_2O}}{\mu_{\text{vap}}} \cdot \frac{P_{H_2O}}{P - P_{H_2O}}.
\]  
(17)

17. To understand what the mass fraction of vapors subjected to condensation is, it is necessary to use the expression (18):

\[
m_{H_2O} = \frac{d - d_i}{dm}.
\]  
(18)

The execution of the algorithm can be terminated if the condition (19) is met:

\[
m_{H_2O} = 0
\]  
(19)

If this condition is not met, the next iteration begins. For each of them, in accordance with the expression (20), the volume of steam that has been subjected to condensation and, accordingly, has passed into the liquid state is calculated:

\[
D_i = Q_m \times m_{H_2O},
\]  
(20)

The mass of water that has passed into the liquid state at all iterations is summed up, thereby determining the final result. The total content of water condensate describes the expression (21):
The start of the next iteration is the application of an expression, the results of which determine the value of the temperature $t$ depending on the duration of the time period $\tau$, during which the heating is carried out.

It should be noted that due to the increase in temperature in the engine, over time, condition (19) will be met, which will lead to the end of the calculation. The parameter $D$ of the dependence (21) has a value equal to the total mass of water that has passed into the liquid aggregate state during the heating of the power plant.

Figure 3 shows a block diagram for calculating the mass of water condensate entering the lubrication system (when the power plant is warmed up).
Figure 3. Diagram of a mathematical model of the condensation process in the crankcase space of a piston engine warmed up under negative temperatures of a cold climate.
IV. Discussion of the Results

Scientific studies have determined the maximum permissible concentration of water in the running oil. Thus, at a content of 0.1% by weight, the active phase of changing the aggregate states of additives begins [8]. The latter, initially dissolved in the production of blending, form a solid or amorphous substance, which is subsequently deposited on the grids of oil collectors and oil filters. Water increases the intermolecular interaction not only in relation to additives. All the products with low aggregate stability change their state. The specified water concentration is critical and unacceptable. It should be noted that a significant part of the deposits on the grid of the oil collector shown in Figure 2 are not additives introduced by blending during production. Asphaltenes can be up to 50% of the mass of such deposits [4].

As is known, asphaltens are the paramagnetic, dispersed phase of the associates of stable free radicals of the oil base. The technological operation of the base oil production "deasphalting" does not provide complete removal of asphaltens. Their presence is manifested in the formation of deposits during watering.

On the basis of this model, the calculated value of the moisture content is obtained. The maximum increase in water, under warm-up conditions on the example of the YaMZ-240 engine, was 0.018%. The first impression of such a minor watering can be very misleading. 0.018% does not exceed the above-mentioned maximum permissible value of 0.1%. Moreover, with an increase in temperature, the activity of water condensate formation will decrease, when the dew point is reached, it will be reduced to zero, and with further heating, the reverse process will begin and the moisture content will return to the original figures.

However, the presence of water will leave a “negative mark” on the properties of the running oil. If we take into account that the working process of ground transport engines in cold climatic conditions has a large temperature range, then multiple reversible processes will ensure the flow of water condensate through the oil volume. The figuratively named “negative mark” has a cumulative character. Water condensate enhances intermolecular interactions [4]. The process of accumulation of deposits changes the state of the lubrication system. Deposits are formed not only on the oil collectors grids as shown in Figure 2 and on the oil filters. The oil collectors grids and oil filters are easy to remove. Operations to replace these elements are not time-consuming. The situation with oil channels is much more complicated. For example, as a result of the rotation of the crankshaft, centrifugal forces occur that collect deposits inside the cranks. Removal of deposits from the oil channels of the crankshaft is carried out during partial or complete disassembly of the dismantled engine. Thus, when operating in harsh climatic conditions, there is a decrease in the throughput of oil pipelines. The friction conditions of the surfaces deteriorate. The final result is a reduction in the engine resource.

A mathematical model requires checking for compliance with a real, simulated process. The so-called adequacy was determined on the basis of experimental data. The extent to which the mathematical model is adequate was evaluated according to the Fisher criterion. The F-test was used to determine the nature of the deviations in the results. When checking the adequacy of the model, the following indicators were calculated:

- dispersion of adequacy: $S_{\delta}^2 = 45.3$;
- reproducibility dispersion: $S_{y2}^2 = 13.1$;

To calculate the numerical value of the Fisher criterion, the expression (22) was used:

$$F = \frac{S_{\delta}^2}{S_{y2}^2} = \frac{45.3}{13.1} = 3.45,$$

(22)

At the same time, we took into account the following:

- number of degrees of freedom: $V = 5$;
- the confidence level is: $\alpha = 0.95$;
- the critical value is determined: $F_T = 5.78$.

If it is true that $F < F_T$, then the proposed mathematical model can be considered adequate.

$$3.45 < 5.78$$

Compliance with these conditions confirms the adequacy of the mathematical model.

V. Conclusions

The dew point temperature of the crankcase gases cannot be constant, as it depends on the saturated vapor pressure. The latter, in turn, depends on the external (weather) conditions, on the design of the
crankcase ventilation system. However, for the calculated initial data, the dew point temperature was 44 °C. The dew point temperature was "indicated" by the next iterative step, at which the condition of mathematical dependence (19) was first fulfilled and the processes of vapor transition to the liquid aggregate state stopped.

This mathematical model is applicable when operating the equipment in conditions of negative temperatures of a cold climate. The mathematical representation of reality can be implemented when determining the water content of motor oils for the purpose of prospective development of research in this scientific direction, as well as for the accumulation of statistical data and the planning of technological operations to maintain the life cycle, taking into account the influence of negative temperatures on the state of lubricating systems.

VI. References

[1] Lashhi V L and Fuks I G 1992 Role of Viscosity in Evaluating Oil Serviceability (Chemistry and technology of fuels and oils № 11) pp 639-649

[2] Kolunin A V Bur'yan I A and Gel'ver S A 2019 Influence of the Arctic Climate on Watering of Engine Oils in Operating Conditions of Road Transport (IOP Publishing IOP Conf. Series: Journal of Physics: Conf. Series 1260 (11 2019) 062012. Mechanical Science and Technology Update doi:10.1088/1742-6596/1260/6/062012)

[3] Kolunin A V and Buryan I A 2019 Influence of the Temperature State of the Piston Engine on the Consumption of Crankcase Gases (Dvigatelestroyeniye. - Saint Petersburg: Publishing House of OOO «NIDI-Ekoservis» № 4) pp 29-31

[4] Dimitrov E and Qullian R D 1965 Low Temperature Engine Sludge. What? Where? How? (SAE Preprint № 650225)

[5] Graham W 2003 The Cambridge Handbook of Physics Formulas (Department of Physics & Astronomy University of Glasgow) p 203

[6] Buckmaster J D 1985 The Mathematics of Combustion (ISBN:0-89871-053-7 Siam, Philadelphia) p 254

[7] Vedruchenko V R and Lazorev E S 2017 Calculation of Heat Transfer in a Recuperative Condensation Cooler of Combustion Gases (Promyshlennaya energetika- Moscow: NTF "Energoprogress") pp. 27–29

[8] Kolunin A V Dudkin V M and Korneev S V 2006 Water Contamination and Colloidal Stability of Motor Oils (Chemistry and Technology of Fuels and Oils. Volume 42. No. 4 New York. Published by Springer New York Consultants Bureau ISSN: 0009-0922eISSN: 1573-8310) pp. 273–275