International Journal of Applied Engineering Research, ISSN 0973-4562 Vol. 10 No.24 (2015) pp. 45150-45155
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Mathematical Model Of Liquid Vapor Compression System For Multicircuit Cooling Systems Of High Mobile Platform

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Abstract- The descriptions of the structure, the principle of operation and the mathematical model of the liquid-vapor compression cooling system, through which an effective cooling of a mobile platform power plant at elevated ambient temperature is possible. The proposed model allows to simulate the thermodynamic processes of heat and mass transfer and heat transfer, depending on the system load, its design parameters and the material of heat exchangers, the mass flow of refrigerant and coolant flow, taking into account the ambient temperature. The result of mathematical modeling showed that by the coolant temperature increase up to 127 °C, an average temperature pressure in a heat exchanger-condenser between the refrigerant and air increased. Therefore the amount of waste heat to the atmosphere was significantly increased. This will ensure an efficient operation of a cooling system at an elevated ambient temperature and will improve the weight and size of a cooling system in general.

Keywords: liquid-vapor cooling system, freon, compressor, boiling, evaporation, mathematical model, temperature difference.

1. INTRODUCTION

The cooling system (CS) is one of the main components of any vehicle drive. The specific power, the operation modes and conditions of a vehicle, as well as the weight and size and the efficiency of the system depend on its effectiveness [4]. Taking into account the trend of specific power increase for vehicle power units and the ongoing developments of perspective traction systems with a combined motor (internal combustion engine with an electric transmission) [2], the issue on the effectiveness of a CS, particularly at a high ambient temperatures, has a particular relevance.

Today, there are various ways of these issues solution, which are divided into quantitative and qualitative ones.

The quantitative method is implemented by increasing the area of a heat transfer, coolant flow circulating in the system, or the mass air flow through a radiator. During the implementation of this method, engineers have to deal with the problem of CS element characteristics optimization, as the possibility of the radiator frontal area, its depth and weight increase is limited by the dimensions of a system installation site and the technical requirements to it. In order to increase the mass consumption of coolants the installation of more powerful blowers is required. The drive power depends on the hydraulic and aerodynamic resistance value concerning heat exchangers and it is proportional to heat carrier transfer speed.

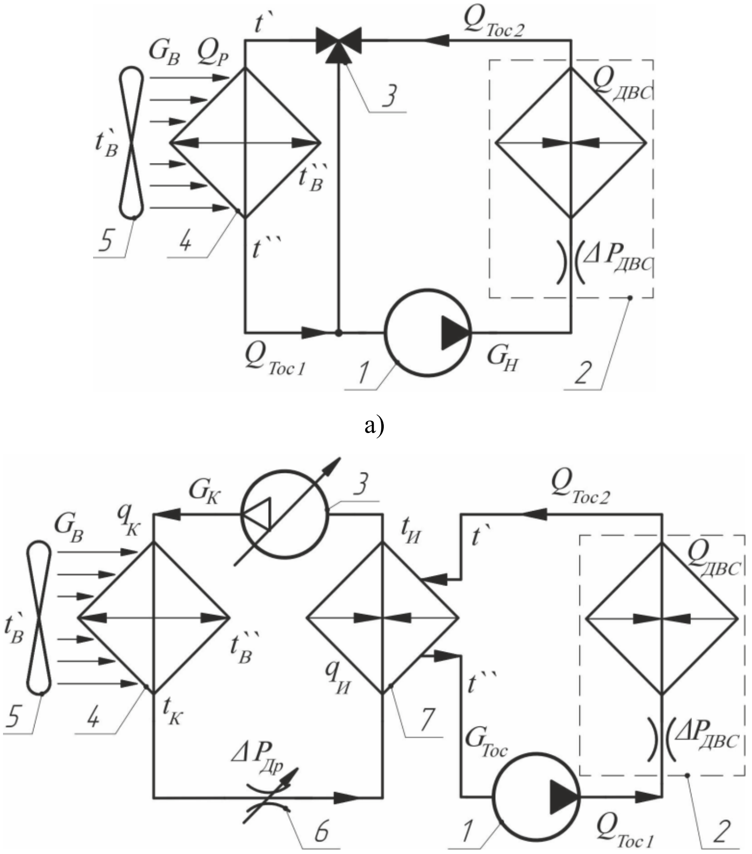
Qualitative method is implemented either by forced turbulence of the flow in the channels of a heat exchanger, resulting in an increased hydraulic resistance, or to the coolant temperature increase above the boiling point under normal conditions (high-temperature cooling system), and a corresponding pressure increase (above atmospheric one) in the system pressure. For example, at the temperature increase of a diesel engine coolant from 80 to 120 °C and the outdoor temperature of +50 °C the efficiency of the cooling system increased 2.33 times [5].

In its turn, the use of high-temperature CS as the part of an internal combustion engine combined with an electric transmission is not possible due to the restriction of maximum insulation temperature [4], and, therefore, the inlet coolant.

One of the solutions that allow to improve the efficiency of a CS and maintain the intensity of heat transfer at ambient temperatures increase up to 50 °C or more may be the use of a vapor-liquid cooling system, the modeling of thermal physical processes to which this article is devoted.

2. VAPOR-LIQUID COMPRESSION DEVICE

The principal circuits of classical and vapor-liquid cooling system device of a combined ICE are shown on Figure 1, a and b, respectively. It is characterized by the presence of additional refrigerant circulation circuit established between the circulation contour of the coolant CS of a vehicle and an external heat exchange radiator as compared to a classical scheme. An additional contour comprises the following elements: adjustment compressor 3 (see Fig. 1b), an adjustable throttle 6 and a heat exchanger - evaporator 7. Tetrachloride carbon is used as a refrigerant (freon - 10).



a)

б)

Figure 1 - Schematic diagrams of ICE cooling systems: a - classic; b - with liquid-vapor compression system; 1 - coolant pump; 2 - ICE collector; 3 - thermostat (for scheme A), compressor (for the circuit b); 4 - radiator, condenser - heat exchanger (for the scheme b); 5 - fan; 6 - throttle; 7 - exchanger-evaporator.

In a system with liquid-vapor compression system (see Fig. 1, b) the process of heat and mass transfer occurs at phase changes of refrigerant, heat absorption during the process of evaporation and heat release during the condensation process.

3. MATHEMATIC MODEL

In order to simplify the mathematical model, let's put down the equation of thermal balance for the evaporator and condenser separately. For the heat exchanger-evaporator the heat flow from the hot coolant (antifreeze - 65 for this system) to the refrigerant during its phase transition from liquid to gaseous state is determined by the heat balance equation, kJ/s:

$$Q_И = G_И \cdot q_И = G \cdot c_p \cdot (t' - t''), \quad (1)$$

where $G_И$ - the mass flow of refrigerant in the heat exchanger-evaporator, kg/s;

$q_И = i_1 - i_4$ - specific fuel consumption per refrigerant flow unit during boiling, kJ/kg,

here i_1 and i_4 - the enthalpies of a refrigerant within the operating points of the process (see. Fig. 2), kJ/kg;

G - the mass flow of a coolant, kg/s;

c_p - the heat capacity of a coolant in a heat exchanger-evaporator, kJ / (kgK);

t' and t'' - coolant temperatures at the evaporator inlet and outlet, respectively, °C. For a heat exchanger-condenser the heat flow from a hot refrigerant to the outside air at its phase transition from gaseous to liquid state, is recorded as the heat balance equation, kJ/s::

$$Q_{\text{К}} = G_{\text{К}} \cdot q_{\text{К}} = G_{\text{В}} \cdot c_{p_{\text{В}}} \cdot (t''_{\text{В}} - t'_{\text{В}}), \quad (2)$$

where $G_{\text{К}}$ - the mass flow of the refrigerant vapor in a heat exchanger-condenser, kg/s;

$q_{\text{К}} = i_2 - i_3$ - heat consumption rate per unit of refrigerant consumption during condensation kJ/kg, here i_2 and i_3 - the enthalpies of the refrigerant at the operating points of the process (see. Fig. 2), kJ/kg;

$G_{\text{В}}$ - mass flow of ambient air, kg/s;

$c_{p_{\text{В}}}$ - the heat capacity of air in a heat exchanger-condenser, kJ/(kgK);

t'_B and t''_B - the air temperature at the inlet and outlet of a heat exchanger-condenser, respectively, °C.

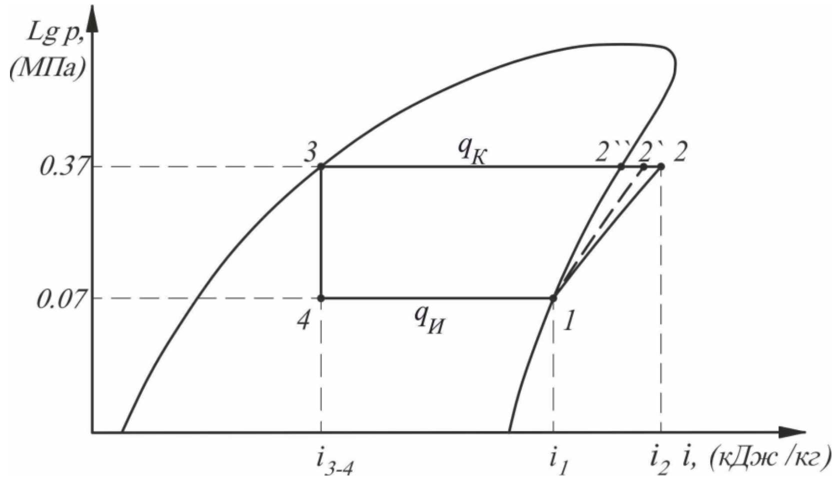


Fig. 2 – The diagram of the thermodynamic operation of a cooling liquid-vapor compression system.

The equations of heat transfer:

- For a heat exchanger-evaporator, kJ/s:

$$Q_{\text{И}} = k_{\text{И}} \cdot F_{\text{И}} \cdot \Delta t_{\text{срИ}}; \quad (3)$$

- For a heat exchanger, condenser, kJ/s:

$$Q_{\text{К}} = k_{\text{К}} \cdot F_{\text{К}} \cdot \Delta t_{\text{срК}}, \quad (4)$$

where $k_{\text{И}}$ and $k_{\text{К}}$ - the coefficients of heat exchanger-evaporator and condenser respectively, kW/(m² K);

$F_{\text{И}}$ and $F_{\text{К}}$ - the areas of heat exchange for a exchanger-evaporator and a condenser, m²;

$\Delta t_{\text{срИ}}$ and $\Delta t_{\text{срК}}$ - temperature difference in an exchanger-evaporator and a condenser, °C.

In its turn, the temperature difference at a small change in the temperature difference between heat carriers along the heat exchange surface, according to [1] (at $\Delta t_{\text{б}} / \Delta t_{\text{м}} < 2$):

- For a heat exchanger-evaporator, °C:

$$\Delta t_{\text{срИ}} = \frac{1}{2} \cdot \left(t' - t_{\text{И}} + \left(t'' - t_{\text{И}} \right) \right); \quad (5)$$

- For a heat exchanger-condenser, °C:

$$\Delta t_{\text{срК}} = \frac{1}{2} \cdot \left(t_{\text{К}} - t'_{\text{В}} + \left(t_{\text{К}} - t''_{\text{В}} \right) \right), \quad (6)$$

where $t_{\text{И}}$ - the refrigerant evaporation temperature in the heat exchanger-evaporator, °C;

$t_{\text{К}}$ - the temperature of the refrigerant condensation in a heat exchanger-condenser, °C.

In order to derive a mathematical model of a heat exchanger-evaporator the temperature is determined at the inlet of a cooling system platform t'' = 70°C. The evaporator inlet temperature is expressed from the equation (1) as follows:

$$t' = \frac{q_{\text{И}} \cdot G_{\text{И}} + G \cdot c_p \cdot t''}{G \cdot c_p}. \quad (7)$$

Similarly, we also act for a heat exchanger-condenser model, derive the ambient temperature from the equation (2) the values of which are not controlled:

$$t''_{\text{В}} = \frac{q_{\text{К}} \cdot G_{\text{К}} + G_{\text{В}} \cdot c_{p_{\text{В}}} \cdot t'_{\text{В}}}{G_{\text{В}} \cdot c_{p_{\text{В}}}}. \quad (8)$$

The amount of heat transmitted from an antifreeze to a refrigerant through a heat exchanger-evaporator wall is determined by the solution of combined equation of heat transfer (3), the temperature difference (5) and the temperature of antifreeze at inlet (7):

$$\frac{Q_{\text{И}}}{k_{\text{И}}\cdot F_{\text{И}}}=\frac{q_{\text{И}}\cdot G_{\text{И}}}{2\cdot G\cdot c_p}+\left(t''-t_{\text{И}}\right). \quad (9)$$

The mass flow rate in a heat exchanger-evaporator from (9):

$$G_{\text{И}}=\frac{2\cdot G\cdot c_p\cdot Q_{\text{И}}+2\cdot G\cdot c_p\cdot t_{\text{И}}\cdot k_{\text{И}}\cdot F_{\text{И}}-2\cdot G\cdot c_p\cdot t''\cdot k_{\text{И}}\cdot F_{\text{И}}}{q_{\text{И}}\cdot k_{\text{И}}\cdot F_{\text{И}}}$$

(10)

Refrigerant heat transferred to ambient air through the wall of a heat exchanger-condenser is obtained from the equations of heat transfer (4), the arithmetic mean temperature difference (6):

$$\frac{Q_{\text{К}}}{k_{\text{К}}\cdot F_{\text{К}}}=\frac{1}{2}\cdot\left(t_{\text{К}}-t'_{\text{В}}+\left(t_{\text{К}}-t''_{\text{В}}\right)\right). \quad (11)$$

The mass flow of a refrigerant in a heat exchanger-condenser is expressed from (2), (8) and (11):

$$G_{\text{К}}=\frac{t_{\text{К}}-t'_{\text{В}}}{\dfrac{q_{\text{К}}}{k_{\text{К}}\cdot F_{\text{К}}}+\dfrac{q_{\text{К}}}{2\cdot G_{\text{В}}\cdot c_{p\,\text{В}}}}. \quad (12)$$

Taking into account the fact that the circulation of a refrigerant through a heat exchanger-evaporator and a heat exchanger-condenser is provided by a compressor, the mass feed of which is equal to $G_{\text{Н}}$, kg/s we have:

$$G_{\text{Н}}=G_{\text{И}}=G_{\text{К}}. \quad (13)$$

On the basis of equation (13), the mass flow equations (10) and (12) are compared. At the same time we express the amount of heat that a heat carrier provided to a coolant in an evaporator and then finally the mathematical model of a liquid-vapor compression of a cooling system is obtained after simplification:

$$Q_{\text{И}}=\frac{G_{\text{В}}}{G}\cdot\frac{q_{\text{И}}}{q_{\text{К}}}\cdot\frac{c_{p\,\text{В}}}{c_p}\cdot\frac{k_{\text{И}}\cdot F_{\text{И}}\cdot k_{\text{К}}\cdot F_{\text{К}}}{\left(2G_{\text{В}}\cdot c_{p\,\text{В}}+k_{\text{К}}\cdot F_{\text{К}}\right)}\cdot\left(t_{\text{К}}-t'_{\text{В}}\right)-k_{\text{И}}\cdot F_{\text{И}}\cdot\left(t_{\text{И}}-t''\right)$$

(14)

The resulting model is an equation that takes into account all main parameters of the system:

- The technical parameters of a throttle and a compressor through the variables $q_{\text{К}}$, $q_{\text{И}}$, G, c_p; heat exchanger-condenser $k_{\text{К}}$, $F_{\text{К}}$ and heat exchanger -evaporator $k_{\text{И}}$, $F_{\text{И}}$ parameters.

- physical parameters: evaporation heat, pressure, and temperature of condensation and evaporation process of a refrigerant through the variables $q_{\text{К}}$, $q_{\text{И}}$, $t_{\text{К}}$, $t_{\text{И}}$; the amount of heat introduced into the system G, c_p; amount of heat from the system $G_{\text{В}}$, $c_{p\,\text{В}}$, $t'_{\text{В}}$; flow and the heat transfer of a coolant and a refrigerant $k_{\text{И}}$, $k_{\text{К}}$ defined from the system of equations (15) (for the heat transfer coefficient of a condenser according to [6] a similar system of equations is used):

$$\begin{cases} q''_{\text{И}}=\alpha''_{\text{И}}\cdot\left(t_{\text{ст}}-t_{\text{И}}\right) \\ q'_{\text{И}}=\dfrac{1}{\dfrac{1}{\alpha'_{\text{И}}}+\dfrac{\delta_{\text{И}}}{\lambda_{\text{И}}}}\cdot\left(t_{\text{И\_ср}}-t_{\text{ст}}\right) \end{cases}, \quad (15)$$

where $k_{\text{И}}=\dfrac{1}{\dfrac{1}{\alpha'_{\text{И}}}+\dfrac{\delta_{\text{И}}}{\lambda_{\text{И}}}}$.

4. SIMULATION RESULTS

In order to determine the characteristics of the cooling system with a vapor-compression unit, the calculation of the system heat capacity was performed according to the proposed model, at the temperature changes from 0 °C to 60 °C and the mass flow of ambient air (see Fig. 3).

In order to evaluate the effectiveness of cooling the Figure 4 a, b, demonstrates the working characteristics of cooling systems with a serial radiator 5460SH-1301010 and liquid-vapor compression system. It should be noted here that the expenditure of the compressor 3 operation (see Fig. 1) is taken into account by mathematical model (14) in the specific consumption of heat during the condensation of the refrigerant $q_{\text{К}}$, and the presented characteristics reflects a real change in the cooling efficiency, taking into account the additional heat provision.

In order to simplify the calculation the heat transfer coefficient for a series radiator and the proposed liquid-vapor system was taken as a constant value.

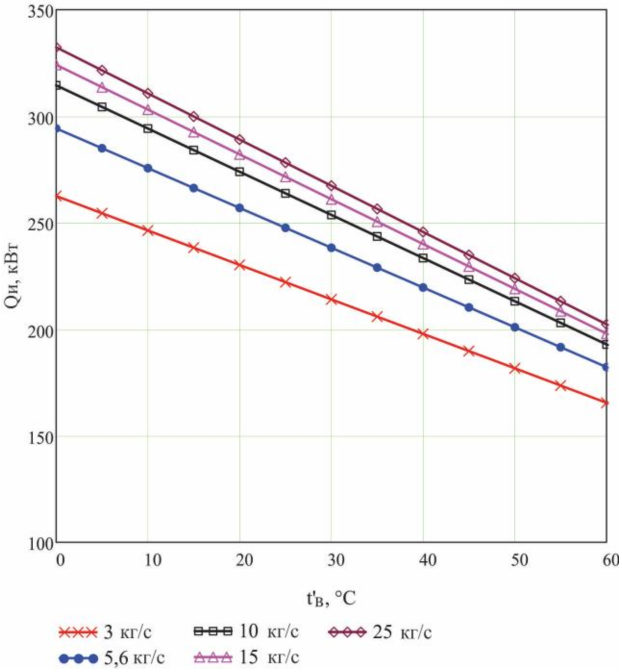
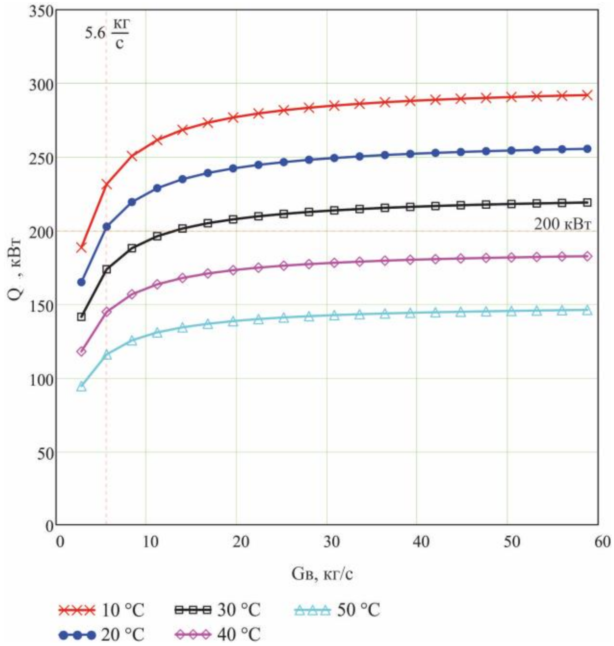
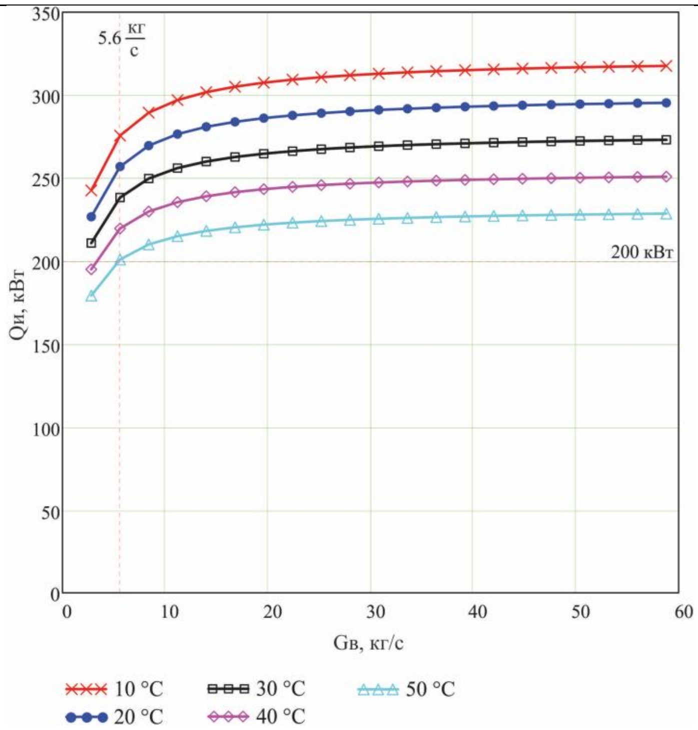


Figure 3 – The dependence of a liquid-vapor compression system thermal capacity on the outdoor temperature.



a)



б)

Figure 4 – Cooling system characteristics: a - a classic one with the radiator 5460SH-1301010; b - with a liquid-vapor compression system;

5. CONCLUSION

Figure 4, a and b, demonstrates the curves describing the cooling system operation with the radiator are located below (according to thermal power scale) the cooling system curves with a liquid-vapor compression system. So, at the mass flow of 5.6 kg/s and an ambient temperature of more than 20 °C, the system heat transfer with the radiator is below 200 kW and the system with vapor-compression unit may withdraw 200 kW from a system up to ambient temperature of 50 °C.

6. SUMMARY

Thus, the obtained result allows to increase significantly the average temperature difference in an exchanger-condenser due to the refrigerant temperature increase up to 127 °C and, therefore, the amount of waste heat to the atmosphere, to ensure an efficient operation of the system at an elevated ambient temperature, and improve the weight and size of the cooling system as a whole.

ACKNOWLEDGEMENT

The work was performed under the contract № 02.G25.31.0004 with the RF Ministry of Education signed on 12/02/2013.

CONFLICT OF INTEREST

The author confirms that the presented data do not contain any conflict of interest.

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