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SCIENTIFIC PRINCIPLES OF COOLER UNIT CALCULATIONS IN A CAR ENGINE WITH PRESSURE AERODYNAMIC DESIGN

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Summary. The methods and algorithm of energy calculation in a cooler unit of the car engine with pressure aerodynamic design have been investigated; it allows to choose efficient construction parameters and operation modes of the Radiator-Fan system. Fig.2, ref.4.

Key words: methods, algorithm, cooling unit, pressure aerodynamic design, energy calculation.

INTRODUCTION

Energy calculation of a cooler unit is held according to the technical conditions (TC) for making a car, including heat production of a car in a nominal rating, cooling fluid temperature at heat radiator inlet (the highest possible for car operation), air temperature at radiator inlet (the highest possible for a present climatic area), cooling fluid's pump rate under the conditions of an engine nominal rating (according to the engine TC), mode of motion (for the distance of a maximum driving gradient with 7,2% grade and 50 km/h free-running speed) [Burkov V. V., Indeykin A. I. 1978] with account of the types of radiators and fans used.

Heat, aerodynamic and hydraulic calculations are supposed to be done. Moreover, the basic data for aerodynamic and hydraulic calculations are determined as a result of conducting a heat calculation.

SCIENTIFIC PRINCIPLES OF COOLER UNIT CALCULATIONS IN A CAR ENGINE

In the general case, a numerical scheme of a heat calculation is a system that consists of a heat-transfer equation and two heat-balance equations:

$$\begin{cases} dQ = k \cdot \vartheta \cdot dF_2; \\ dQ = W_1 \cdot dT_1 = v_1 \cdot f_1 \cdot \rho_{1_{av}} \cdot Cp_{1_{av}} \cdot dT_1; \\ dQ = W_2 \cdot dT_2 = v_{2_{fr}} \cdot f_{2_{fr}} \cdot \rho_{2_{av}} \cdot Cp_{2_{av}} dT_2, \end{cases} \quad (1)$$

where: k – coefficient of heat-transfer, W/(m^2·K); ϑ – average temperature head, K; F_2 – surface passed by the air, m^2; W_1 and W_2 – water equivalents of heat transfer fluid, W/(h·K); v_1 and v_2 – speed of cooling fluid and air correspondingly, m/s; ρ_1 and ρ_2 – density of cooling fluid and air correspondingly, kg/m^3; f_1 and f_2 – cross-section for fluid and air passing, m^2; C_{P_1} and C_{P2} – thermal heat capacity of cooling fluid and air, J/(kg·K); dT_1 and dT_2 – temperature difference of fluid and air correspondingly, K.

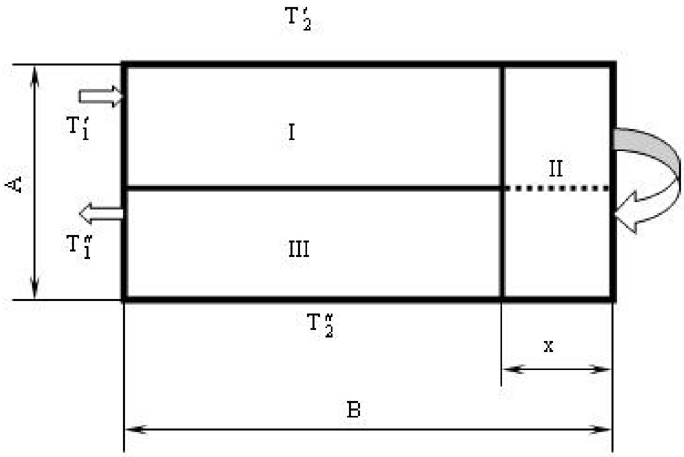

Fig. 1. Calculation scheme of heat transfer fluid flow in a car radiator

We will consider the most widespread case, when the radiator is not fully covered with clothing, i.e. not the whole surface of the radiator is passed by the air, seeped by the fan and the radiator has two fluid flows (fig.1).

As we can see in fig. 1, a car radiator can be nominally divided into three sections, where Sections I and III are covered with clothing, and Section II – not covered. Because of this we must calculate separately each section according to the system of equations (1). So, heat calculation of a cooler unit in a car engine results in solving a system of 9 equations [Kulikov Yu. A., Goncharov A. V., Tomachinsky Yu. N., Verkhovodov A. A. 2007; Kulikov Yu. A., Gribinichenko M.V., Goncharov A. V. 2006]:

for Section I:

$$\begin{aligned}
&\frac{2\cdot Q_I}{k_I\cdot F_{2_I}}-T''_{1_I}+T''_{2_I}=T'_1-T'_2;\\
&\frac{2\cdot Q_I}{v_1\cdot f_1\cdot \rho_{1_{avI}}\cdot Cp_{1_{avI}}}+T''_{1_I}=T'_1;\\
&T''_{2_I}-\frac{Q_I}{v_{2_{frI}}\cdot f_{2fr_I}\cdot \rho_{2_{avI}}\cdot Cp_{2_{avI}}}=T'_2;
\end{aligned} \tag{2}$$

$$k_I=\frac{1}{2\cdot l_{tube_I}\cdot \Delta_{2_I}\left(\frac{1}{\alpha_{1_I}\cdot t_{fin}\cdot F_{1_I}}+\frac{1}{\alpha_c\cdot t_{fin}\cdot F_c}+\frac{1}{\alpha_{2_I}\cdot\left(1+E_{fin_I}\right)\cdot\left(2\cdot l_{tube_I}\cdot\Delta_{2_I}-t_{fin}\cdot F_{1_I}\right)}\right)};$$

for Section II:

$$\begin{aligned}
&\frac{2\cdot Q_{II}}{k_{II}\cdot F_{2_{II}}}-T''_{1_{II}}+T''_{2_{II}}=T''_{1_I}-T'_2;\\
&\frac{2\cdot Q_{II}}{v_1\cdot f_1\cdot \rho_{1_{avII}}\cdot Cp_{1_{avII}}}+T''_{1_{II}}=T''_{1_I};\\
&T''_{2_{II}}-\frac{Q_{II}}{\varepsilon_v\cdot v_{2_{frI}}\cdot f_{2fr_I}\cdot \rho_{2_{avII}}\cdot Cp_{2_{avII}}}=T'_2;
\end{aligned} \tag{3}$$

$$k_{II}=\frac{1}{2\cdot l_{tube_{II}}\cdot \Delta_{2_{II}}\left(\frac{1}{\alpha_{1_{II}}\cdot t_{fin}\cdot F_{1_{II}}}+\frac{1}{\alpha_c\cdot t_{fin}\cdot F_c}+\frac{1}{\alpha_{2_{II}}\cdot\left(1+E_{fin_{II}}\right)\cdot\left(2\cdot l_{tube_{II}}\cdot\Delta_{2_{II}}-t_{fin}\cdot F_{1_{II}}\right)}\right)};$$

for Section III:

$$\begin{aligned}
&\frac{2\cdot Q_{III}}{k_{III}\cdot F_{2_{III}}}-T''_1+T''_{2_{III}}=T''_{1_{II}}-T'_2;\\
&\frac{2\cdot Q_{III}}{v_1\cdot f_1\cdot \rho_{1_{avIII}}\cdot Cp_{1_{avIII}}}+T''_1=T''_{1_{II}};\\
&T''_{2_{III}}-\frac{Q_{III}}{v_{2_{frIII}}\cdot f_{2fr_{III}}\cdot \rho_{2_{avIII}}\cdot Cp_{2_{avIII}}}=T'_2;
\end{aligned} \tag{4}$$

$$k_{III}=\frac{1}{2\cdot l_{tube_{III}}\cdot \Delta_{2_{III}}\left(\frac{1}{\alpha_{1_{III}}\cdot t_{fin}\cdot F_{1_{III}}}+\frac{1}{\alpha_c\cdot t_{fin}\cdot F_c}+\frac{1}{\alpha_{2_{III}}\cdot\left(1+E_{fin_{III}}\right)\cdot\left(2\cdot l_{tube_{III}}\cdot\Delta_{2_{III}}-t_{fin}\cdot F_{1_{III}}\right)}\right)}.$$

In equation systems (2)…(4) T'_1 and T''_1 – temperatures of cooling fluid at the radiator's inlet and outlet in a corresponding section; T'_2 and T''_2 – temperatures of air at the radiator's inlet and outlet in a corresponding section, K.

While making a system of equations (2)…(4) the following assumptions were admitted: thermal heat capacity and density of heat transfer fluid is determined by the average temperature of heat transfer fluid; average temperature head in a radiator equals an arithmetic mean value; Sections I and III are tightly covered with clothing and air velocity is the same in both ones, air velocity fields are level in a radiator's cross-sections. With these assumptions there are 9 indeterminates in the system of equation (Q_I, Q_{II}, T''_{1_I}, T''_{2_I}, $T''_{1_{II}}$, $T''_{2_{II}}$, T''_1, T''_2, $v_{2_{f_I}}$), i.e. the system is closed.

The model of heat calculation in a cooler unit, complemented with the equations for a coefficient of heat-transfer permits to choose a balanced pitch distance between radiator fins with its accepted capacity and environment conditions.

As a result of a heat calculation, we define the initial data (air temperature at the radiator outlet and air velocity in front of the radiator) for conducting the aerodynamic calculation of a cooler unit with pressure aerodynamic design that allows to choose fan blades angle.

The scheme of aerodynamic channel of a cooler unit of the engine with pressure design is represented in fig.2.

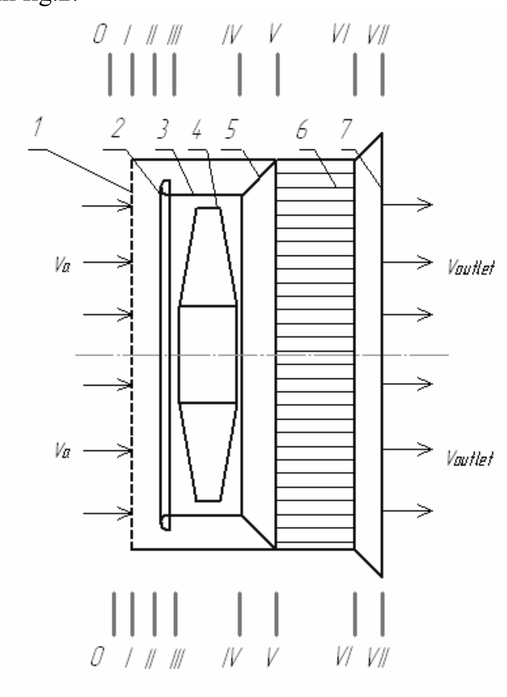

Fig. 2. The scheme of an aerodynamic channel of a car engine's cooler unit:
1 – facing grill, 2 – collector (confusor), 3 – fan casing,
4 – fan, 5 – fan guard, 6 – radiator, 7 – diffuser

The main components of loss of the air flow energy in an aerodynamic channel are shown in the energy equation (fig. 2):

$$p_v = \Delta P_{grill} + \Delta P_{chan.} + \Delta P_{coll.} + \Delta P_{guard} + \Delta P_{conf.} + \Delta P_{rad.} + \Delta P_{diff.} + \Delta P_{outlet} - \rho_2' \frac{v_a^2}{2}, \quad (5)$$

where: ΔP_{grill}, $\Delta P_{chan.}$, $\Delta P_{coll.}$, ΔP_{guard}, $\Delta P_{conf.}$, $\Delta P_{rad.}$, $\Delta P_{diff.}$, ΔP_{outlet} – loss of the air flow energy correspondingly in a facing grill, channel, collector, guard, confusor, radiator, diffuser and at the outlet, Pa; v_a – car speed, m/s; ρ_2' – air density at the radiator inlet, kg/m^3.

As generally fan systems are tested in the same section with a collector, guard and confusor, the resistance in these sectors of the aerodynamic channel is considered in the characteristics of the fan system itself and there in no need to calculate it in the equation (5). Son the equation (5) changes to:

$$p_v = \zeta_{0-I}\rho_2' \frac{v_a^2}{2} + \zeta_{I-II}\rho_2' \frac{v_{2fr}^2}{2} + \zeta_{V-VI}\rho_{2av} \frac{v_{2fr}^2}{2} + \zeta_{VI-VII}\rho_2'' \frac{v_{2fr}^2}{2} + \zeta_{VIII}\rho_2'' \frac{v_{2fr}^2}{2}\left(\frac{F_{2_{fr}}}{F_{2_{VIII}}}\right)^2 - \rho_2' \frac{v_a^2}{2}, \quad (6)$$

where: v_{2fr} – air velocity in front of the radiator, m/s; ρ_2'' – air density at the radiator outlet, kg/m^3; $\rho_{2_{av.}}$ – average air density in the radiator, kg/m^3; ζ_i – coefficient of resistance of i-element of an aerodynamic channel; F_{2fr} – area of radiator front, m^2; F_{2VIII} – area of cross-section at the outlet, m^2.

In the equation (6) the air velocities levels in front of the radiator ($v_{2_{fr}}$), as well as the air density in front of the radiator (ρ_2') and behind it (ρ_2'') are determined by the heat calculation. The indeterminate in this equation is pressure (p_v), produced by the fan, necessary for overcoming the resistance of the aerodynamic channel.

So, the energy calculation of a cooler unit in a car engine is held for estimating the efficient parameters of radiator design (its surface, passed by the air); heat transfer fluids' temperatures at the radiator outlet; air velocity in front of the radiator (that must be produced by the fan); fan operating mode; power input for driving the fan.

The scientific principles of cooler unit calculation in a car engine, taken into consideration, enable to present the following calculation scheme:

1. Defining the cooling surface of the radiator from the fluid and air sides:

- from the fluid side

$$F_1 = \left(\pi \cdot a_0 + 2(b_0 - a_0)\right) \cdot l_{tube} \cdot z_{tube}, \text{ m}^2, \quad (7)$$

where a_0 – inner tube section width, m; b_0 – inner tube section length, m; l_{tube} – tube working length, m; z_{tube} – number of tubes, pcs;

- from the air side

$$F_2 = F_{2_{fin}} + F_{2_{tube}} = \frac{2 \cdot l_{tube}}{t_{fin}}\left[B_{fin} \cdot L_{fin} - z_{tube}\left(a\left[a + b - \frac{\pi \cdot a}{4}\right] + \left[b - a + \frac{\pi \cdot a}{2}\right] \cdot \left[\frac{l_{tube}}{z_{fin}} - \delta_{fin}\right]\right)\right], \quad (8)$$

where: F_{2_f} – cooling surface of the radiator's fins, m^2; $F_{2_{tube}}$ – cooling surface of the radiator's tubes, m^2; l_{tube} – tube working length, m; t_{fin} – pitch distance between fins, m; B_{fin} – fin working length, m; L_{fin} – fin working width, m; z_{tube} – number of tubes, pcs; a – tube section width, m; b – tube section length, m; z_{fin} – number of cooling fins, pcs; δ_{fin} – fin thickness, m.

2. Defining the cross-sections for cooling fluid and air flow:

- cross-section for fluid flow:

$$f_1 = \left(\frac{\pi \cdot a_0^2}{4} + \left(b_0 - a_0 \right) \right) \cdot z_{tube} \text{, } \mathbf{m^2}; \tag{9}$$

- front section for air flow:

$$f_{2_\phi} = l_{tube} \cdot B_{fin} \text{, } \mathbf{m^2}, ; \tag{10}$$

where: B_{fin} – fin working length, m.

3. Defining cooling fluid velocity in radiator tubes:

$$v_1 = \frac{V_1 \cdot z_{str}}{3600 \cdot f_1} \text{, m/s, ;} \tag{11}$$

where: V_1 – cooling fluid's pump rate, m^3/h; z_{str} – number of cooling fluid strokes in the radiator.

4. Defining density and thermal heat capacity of cooling fluid and air for given temperature and pressure values [Kulikov Yu. A., Gribinichenko M.V., Goncharov A. V. 2006]:

- for cooling fluid (water)

$$\rho_1 = \frac{1005}{0{,}99534 + 0{,}466 \cdot 10^{-3} \cdot t_1} \text{, kg/m}^3, \tag{12}$$

$$Cp_1 = 4205{,}11 + 1{,}36578 \cdot t_1 + 0{,}0152341 \cdot t_1^2 \text{, } \frac{J}{kg \cdot K}, \tag{13}$$

- for air

$$\rho_2 = \frac{0{,}0034839 \cdot P}{t_2 + 273{,}15} \text{, kg/m}^3, \tag{14}$$

$$Cp_2 = 1000{,}5 + 0{,}11904 \cdot t_2 \text{, } \frac{J}{kg \cdot K}. \tag{15}$$

The values of heat transfer fluid density and thermal heat capacity are developed according to average temperature values as a result of heat calculation conducted (with successive approximation method).

5. Calculating coefficients of heat transfer and heat loss for cooling fluid and air by taking into account the distance between radiator fins with the help of the experimental correspondences in parametric and criteria form received [Kulikov Yu. A., Gribinichenko M.V., Goncharov A. V. 2006]:

$$k = C_1 \cdot G_2^{n_1} \cdot \left(\frac{t_{fin}}{L}\right)^{m_1}; \tag{16}$$

$$Nu_1 = \frac{\alpha_1 \cdot d_{eq_1}}{\lambda_1} = 0{,}021 \cdot Re_1^{0,8} \cdot Pr_1^{0,43} \cdot \left(\frac{Pr_1}{Pr_{wall}}\right)^{0,25} \cdot \varepsilon_1; \tag{17}$$

$$Nu_2 = \frac{\alpha_2 \cdot d_{eq_2}}{\lambda_2} = C \cdot Re_2^n \cdot \left(\frac{t_{fin}}{L}\right)^m. \tag{18}$$

6. Conducting heat calculation of a car engine cooling system with the help of numerical scheme (2)…(4), which results in defining heat transfer fluids temperature at the outlet of the radiator, as well as air velocity in front of the radiator, that must be produced by the fan for rejecting the given amount of heat. With the received temperature values the average values of density and thermal heat capacity of cooling fluid and air are developed; the calculation is repeated until the necessary degree of approximation is obtained $\left|t'_{av_1} - t''_{av_1}\right| \le \varepsilon_{t_1}$ and $\left|t'_{av_2} - t''_{av_2}\right| \le \varepsilon_{t_2}$.

7. Calculating with the help of equation (6) of resistance of aerodynamic channel in a car engine cooling system for the value of air velocity in front of the radiator, received in heat calculation.

8. Defining the non-dimensional values of fan capacity (φ), pressure (ψ) and power (λ):

$$\varphi = \frac{V_2}{\frac{\pi \cdot D_f^2}{4} \cdot \frac{\pi \cdot D_f \cdot n_f}{60}}, \tag{19}$$

where: V_2 – air consumption, supported by the fan, m^3/s; D_f – fan diameter, m; n_f – fan blade rotary velocity, r/min;

$$\psi = \frac{p_v}{\rho''_{2_1} \cdot \left(\frac{\pi \cdot D_f \cdot n_f}{60}\right)^2}, \tag{20}$$

where: p_v – fan total pressure, Pa; ρ''_{2_1} – air density with air temperature in front of the radiator (at the outlet of Section I of the radiator (fig. 1)), kg/m^3:

$$\lambda = \frac{\varphi \cdot \psi}{\eta_f}, \tag{20}$$

where: η_f – fan coefficient of efficiency.

9. Defining power input for driving the fan:

$$N_2 = \frac{p_v \cdot V_2}{\eta_f}. \tag{21}$$

CONCLUSION

Therefore, the considered scientific principles of calculation allow to present the main algorithm points, meanwhile the introduction in the algorithm of power calculation of distance between radiator fins t_p helps to choose efficient construction parameters and operation modes of a car engine cooling system: radiator dimensions and weight, fan type and dimensions, power input for driving it.

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НАУЧНЫЕ ОСНОВЫ РАСЧЕТА ОХЛАЖДАЮЩЕГО УСТРОЙСТВА ДВИГАТЕЛЯ АВТОМОБИЛЯ С НАГНЕТАТЕЛЬНОЙ АЭРОДИНАМИЧЕСКОЙ СХЕМОЙ

Куликов Ю.А., Томачинский Ю.Н.,
Гончаров А.В., Верховодов А.А.

Аннотация. Рассмотрены методика и алгоритм энергетического расчета охлаждающего устройства двигателя автомобиля с нагнетательной аэродинамической схемой, позволяющие производить выбор рациональных параметров конструкции и режимов работы блока «радиатор-вентилятор».

Ключевые слова: методика, алгоритм, охлаждающее устройство, нагнетательная аэродинамическая схема, энергетический расчет.