ON THE INDICATED EFFICIENCY

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Abstract

Full Text

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HEAT ENGINEERING

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ON THE INDICATED EFFICIENCY

OF AN INTERNAL COMBUSTION ENGINE

In the present work we shall find an expression for the indicated efficiency of an engine.

Figure 1 gives the indicator diagram of an engine over two working strokes with a constant amount of working substance in the cylinder. The expansion and compression lines from the beginning of exhaust and from the end of intake are extended to the lower dead point (L.D.P.) in logarithmic coordinates as straight lines. As the working substance we take the combustion products, to which heat is supplied from outside in such a way that the working substance describes the actual cycle 1—*a*—*c*—2 (Fig. 1). In this case the cycle can be closed by cooling the working substance from point 2 to 1 with rejection of heat Q_2 to the cold source. Let along the path 1—*a*—*c*—2 heat Q_1 (active heat) have been supplied to the working substance, and let the indicated work, equivalent to the area of the diagram, be equal to L_i; then

Fig. 1. Cycle No. 1—the actual cycle 1—*a*—*c*—2; cycle No. 2 (dashed)—the cycle 1—3—*d*—4—2, equivalent to cycle No. 1

$$\eta_t = 1 - Q_2/Q_1 = AL_i/Q_1 = AL_i/(AL_i + Q_2); \tag{1}$$

$$\eta_i = AL_i/H_u = \xi\eta_t, \qquad Q_1 = \xi H_u, \tag{2}$$

where η_t is the thermal efficiency; η_i is the indicated efficiency; H_u is the heating value of the working mixture; ξ is the coefficient of release of active heat.

If another working substance with heat capacity c_v' described the cycle 1—a—c—2—1, then, in order to preserve η_t, it would be sufficient to have

$$Q_2 = \int_1^2 c_v dT = \int_1^2 c_v' dT, \qquad R = R',$$

where R is the gas constant.

For the case $c_v' = \text{const}$ and $c_v = a + bT$, we find

$$c_v' = a + 0.5b\,(T_2 + T_1). \tag{3}$$

The law of heat supply to the working substance along the path 1—a—c—2 for $c_v' = \text{const}$ and $c_v = \text{var}$ will be somewhat different. The discrepancy in the amount of active heat supplied to the working substance is found from the equation

$$d(Q_{\text{ak}}' - Q_{\text{ak}})/d\varphi = (c_v' - c_v)\,dT/d\varphi,$$

where φ is the angle of rotation of the crankshaft. The maximum discrepancy occurs at $T_{\text{avg}} = 0.5(T_2 + T_1)$, when $c_v = c_v'$. In this case we obtain

$$\frac{|Q_{\text{ak}}' - Q_{\text{ak}}|_{\max}}{Q_1} = \frac{T_2 - T_1}{9[a/\theta + T_{\text{avg}}]} \cdot \frac{Q_2}{Q_1},$$

which amounts to no more than 2% of Q_1. Taking hereafter as the working body a gas with constant heat capacity c_v', we shall preserve the value η_t and almost not change the law of heat supply. Let our new working body describe (Fig. 1) the cycle 1—3—d—4—2—1 (cycle No. 2), consisting of the combustion line 3—d—4 and two adiabats 1—3 and 4—2. Let, on the combustion line in cycle No. 2, heat continue to be supplied in the amount Q_1, and let the rate of heat supply with respect to the angle of rotation of the crankshaft be $dQ_2/d\varphi = \text{const}$. The thermal efficiency of cycle No. 2 will obviously be equal to the thermal efficiency of the cycle 1—a—c—2 (cycle No. 1). At the same time, each position of point 3 must correspond to its own constant value of the rate of heat release, so that, in passing from the adiabat 1—3 to the adiabat 4—2, exactly the heat Q_1 would be supplied. We choose the position of point 3 so that the rate of heat release is minimal. We note that in the actual cycle No. 1 the supply of the greater part of the heat occurs at an almost constant rate, while the beginning of heat release is regulated in order to obtain the maximum η_i, which, as we shall see below, is equivalent for cycle No. 2 to the minimum of the rate of heat release.

Thermodynamic cycles Nos. 1 and 2 are, as having the same η_t, equivalent, and we shall seek the thermal efficiency of cycle No. 2, estimating the law of heat supply in cycle No. 1 by the value of the minimum rate of heat release of cycle No. 2. We take the first law of thermodynamics in the form

$$(k-1)\frac{dQ}{A}v^{k-1} = d(pv^k) \tag{4}$$

and, applying it (clockwise) to cycle No. 1 or 2, find:

$$\oint \frac{k-1}{A}\,dQ \cdot v^{k-1} = 0 = \int_1^2 \frac{k-1}{A}v^{k-1}dQ - (k-1)\frac{Q_2}{A}v_1^{k-1},$$

whence, for $\varepsilon = v_1/v_0$, we have

$$(1-\eta_t)\varepsilon^{k-1} = \int_1^2 \frac{dQ}{Q_1}\left(\frac{v}{v_0}\right)^{k-1}; \tag{5}$$

for cycle No. 2 we obtain

$$(1-\eta_t)\varepsilon^{k-1} = \int_3^4 \frac{dQ}{Q_1}\left(\frac{v}{v_0}\right)^{k-1}. \tag{6}$$

Introduce a new variable x (for $\varphi \leq 40^\circ$ from TDC)

$$x = \pm\sqrt{\frac{v}{v_0} - 1} \simeq \frac{\sqrt{\varepsilon - 1}}{2}\varphi, \tag{7}$$

where the plus sign corresponds to cylinder volumes after TDC. By the rate of heat release we shall understand the quantity

$$W = \frac{dQ}{dx} \simeq \frac{2}{\sqrt{\varepsilon - 1}}\frac{dQ}{d\varphi}.$$

Noting that W is constant in the interval $x_4 - x_3$, we find from equation (6)

$$(1-\eta_t)\varepsilon^{k-1} = \frac{W}{Q_1}\int_3^4 \left(\frac{v}{v_0}\right)^{k-1} dx \tag{8}$$

and also

$$Q_1 = W(x_4 - x_3). \tag{9}$$

Whether we now, on the basis of equations (8) and (9), seek $W_{\min}$ for $\eta_t = \text{const}$, or, for a given W, seek $\eta_{t\,\max}$, in both cases we find $v_4 = v_3$ and $x_4 = -x_3$ (with

$Q_1 = \text{const}$).
For $v_4/v_0 \leqslant 2.6$ one may, with sufficient accuracy, put

$$\frac{W}{Q_1}\int_{-x_4}^{+x_4}\left(\frac{v}{v_0}\right)^{k-1}dx = \frac{W}{Q_1}\,2x_4(1+x_4^2)^{0.4(k-1)} = \left(\frac{v_4}{v_0}\right)^{0.4(k-1)},$$

and then from equation (8) we find

$$\eta_t = 1 - \frac{1}{\varepsilon_1^{k-1}}, \tag{10}$$

where

$$\varepsilon_1 = \varepsilon(v_0/v_4)^{0.4} = \psi\varepsilon.$$

We shall call ε_1 the reduced compression ratio, and ψ the coefficient of utilization of active heat.

From equation (2) we shall have

$$\eta_i = \xi\left[1 - \frac{1}{(\psi\varepsilon)^{k-1}}\right]. \tag{11}$$

Noting that

$$(k-1) = AR/c'_v = AR/[a + 0.5b(T_2 + T_1)], \tag{12}$$

$$(1-\eta_t) = 1/\varepsilon_1^{k-1} = Q_2/Q_1 = (T_2 - T_1)[a + 0.5b(T_2 + T_1)]/\xi H_u, \tag{13}$$

from equations (12)–(13) we find

$$\varepsilon_1^{k-1} = \frac{\xi H_u \mu(k-1)}{4[2/\mu b\,(k-1) - a/b - T_1]}; \tag{14}$$

where μ is the molecular weight of the combustion products, and T_1 is their temperature at point 1, differing from the temperature of the fresh working mixture T_{1c}, according to the equation $T_{1c} = T_1 R/R_c$. Equation (14) relates ε_1, ξ, and $(k-1)$.

According to equation (11), the indicated efficiency in the most general case is determined by two parameters: 1) the coefficient of liberation of active heat ξ, showing what fraction of the available heat is imparted in the cycle to the working medium, and 2) the reduced compression ratio ε_1, determining the degree of utilization of active heat for work. In this case the heat-utilization coefficient ψ reaches its maximum value $\psi_{\max} = 1$ only in the ideal cycle of rapid combustion (the Otto cycle), provided that the real working medium has a heat capacity independent of temperature; i.e., ψ takes into account (estimates) both the law of heat addition to the working medium and the heat capacity of the working medium.

The coefficients ξ and ψ (when compared with unity) may serve to evaluate the perfection of the working process of an internal-combustion engine. Having taken an indicator diagram from the engine and having found on it T_1, T_2, L_i, we find, from equations (12), (15), and (16), $(k-1)$, ξ, and $\varepsilon_1 = \psi\varepsilon$:

$$\xi H_u = (T_2 - T_1)[a + 0.5b(T_2 + T_1)] + AL_i, \tag{15}$$

$$\varepsilon_1^{k-1} = 1 + \frac{AL_i}{(T_2 - T_1)[a + 0.5b(T_2 + T_1)]}. \tag{16}$$

When designing a new engine, the expected indicated efficiency can be found from equations (11) and (14), if experimental material is available that permits ξ and ψ to be estimated in advance.

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Note: Figure translations are in progress. See original paper for figures.