DETERMINATION OF THE DEPENDENCE BETWEEN THE WORKING PROCESS AND THE MECHANICAL EFFICIENCY OF I.C. ENGINES

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Introduction

The mechanical and friction losses of the i.c. engines have about the same value as the internal (indicated) losses, so their effect is not to be neglected concerning the characteristics of the actual (losing) engine.

The aim of this paper is to show the thermic dependence of mechanical loss that is efficiency, and the most important characteristics of the working process. In dosing it the experimental data of the i.c. engines now in work and having up-to-date construction and technology are considered.

1. Problems of examination of mechanical losses and efficiency

The main difficulty in determining the mechanical losses, and the arising mechanical medium-pressure p_m lies in the fact, that it can be exactly determined only by the difference of the indicated medium-pressure p_i got from the indicator diagram and the effective medium-pressure p_e got from the data of braking of the engine.

$$p_m = p_i - p_e \,. \tag{1}$$

The determination of p_m in such a way supposes a motor supplying a useful output in real working and in real working process.

A deeper analysis of frictional conditions is considerably aggravated by the circumstance above mentioned and by the fact that the value of p_m

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is given by the difference of two relatively large values and so it can be determined only inexactly.

Owing to the measurement difficulties, several processes differing from the principle aforesaid have been developed in order to determine the mechanical losses. The best-known of these are [1—6].

a) The Willians-procedure. Its essence is to extrapolate from the measurement results of an engine having the same revolution per minute and changing load to the working conditions and the mechanical losses of an engine without combustion having the same revolution per minute. The basic inexactitude of principle comes from the supposition that the frictional medium-pressure is considered to be independent from the indicated medium-pressure, i.e. from the working process, and this is against the reality.

b) The Morze-procedure determines the frictional medium-pressure by the help of the output decrease, when the combustion process of some cylinders of the multicylinder engines is shut down.

The basic problem of this procedure is equal with that of the Willians-procedure: the frictional medium-pressure in cylinders with or without combustion is supposed to be the same, the change of the exhaust pressures are neglected.

c) The running-out procedure concludes to the frictional conditions from the H.P. decrease of the engine. The problem corresponds to the former two procedures, the frictional medium-pressures of the engine in real work and running out can't be the same. In addition, during the running out an instable lubrication state develops that changes the friction medium-pressure relative the engine working at constant R.P.M.

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The running-out procedure, notwithstanding the inevitable decrease of the friction medium-pressure, doesn't give a right result but at the moment of the running-out, in accordance with the consideration aforesaid.

d) The separate-drive procedure is the most suitable for determining the frictional medium-pressure of the i.c. engines. According to the considerations of the author, such procedures give results fitting in with the facts when the actual working conditions are truly simulated and the results got by this way are carefully analysed. The separate-drive procedures used till now haven't assured just the working conditions important from the thermomechanical point of view of the engine at the required degree. The obtained overall losses haven't been analysed, (the mechanical frictional losses are only a part of them) and last but not least the processus of the coming into existence of the frictional losses hasn't been connected with the working process of the engine first of all not with its most important thermic characteristics.

2. The possibility of determining the dependence between the working process and the mechanical efficiency

The frictional loss or the frictional medium-pressure (p_{fr}) isn't independent of the characteristics of the working process of the engine.

According to the research and experimental results of the author, the formation of the frictional medium-pressure is first of all function of the average pressure p_a of the working process [7, 8]. The average pressure of the i.c. engines can be defined as the quotient of the area of the indicator diagram developed as a function of the stroke by the base of the diagram (Fig. 1).

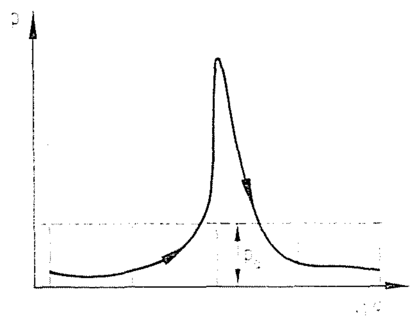


Fig. 1

As referential bases, the angular displacement of the crankshaft as well as the stroke can be used. In this case the values of the average pressure are modified in a certain rate.

The idea of the average pressure and indicated medium-pressure must be distinctly separated. This appears best in the case of the engine realising a working process without dissipation heat transfer where we get a definite magnitude of average pressure in case of zero or little negative indicated average pressure.

Even in this case we have frictional losses just as in the case of a working engine, as frictional losses don't depend upon the fact if the gas-pressure that brings them about comes from the positive part (expansion) or the negative part (compression) of the working process.

On the fundamental parameter the frictional medium-pressure is influenced, besides the average pressure, also by other characteristics of the working process and the engine, although to a lesser degree. These are:

a) The nature of the working process. It is basically defined by the two or four stroke operation of the engine. Here our research is limited to four stroke engines.

b) The relation between maximum and minimum pressure. According to observations, its effect doesn't seem to be essential.

c) The calorific condition of the engine determined first of all by the temperature of the cylinder-wall and the lubricating oil.

d) The average rate of the R.P.M., i.e. of the piston. This needs a detailed and very precise test, because some authors [9] consider as mechanical frictional losses even the gas change and other hydraulic losses depending greatly upon R.P.M., and having no mechanical character at all, but being a part of the indicated losses. This explains why, according to certain authors, the frictional medium-pressure changes in the function of the R.P.M. in a different way, contrary to the reality, depending upon the fact whether it is a precombustion chamber or a direct-injection engine.

e) In any way the construction or better the output of the engine or its cylinder capacity modifies the absolute value of the frictional average pressure within certain limits, without influencing essentially the qualitative running off of the process.

So the frictional medium-pressure can be given as follows:

$$p_{fr} = f(p_a;\ p_{max}/p_{min};\ n;\ \text{caloric condition};\ \text{constr.}) \tag{2}$$

The functional relationship (2) can be determined empirically by the means of separate drive of the engine, as it will be shown later. By the means of the average pressure p_a introduced and defined in the paper as basic parameter, a relationship can be established between the frictional loss and the originary working process. Namely, an essentially unambiguous relationship can be set up between the medium-pressure p_i and the average pressure p_a of the actual working process got by combustion process by means of the working process and the following thermal and mechanical characteristics of the engine:

a) compression relation (ε),

b) air ratio (m),

c) degree of loading (λ),

d) atmosphere characteristics (T_0 ; p_0),

e) R.P.M. (n),

f) calorific condition influencing first of all the quantity of heat leaving upon cooling,

g) dissipation heat transfer taking into consideration the quantity of heat leaving upon cooling.

$$p_i = f(p_a;\ \varepsilon;\ m;\ \lambda;\ T_0;\ p_0;)$$

caloric condition; dissipation heat transfer (3)

The theoretic and experimental problems of the actual working processes can be taken as essentially solved at least in this sphere of question, making use of the possibilities given by electronic computers [10—18]. A relationship can be set up between the frictional medium-pressure and the indicated medium-pressure by the help of the relationships (2) and (3), that in the overwhelming majority of the cases can only be obtained from diagrams.

$$p_{fr} = f(p_i; \varepsilon; m; \lambda; T_0; p_0; m;)$$

caloric condition; dissipation heat transfer (4)

The mechanical efficiency η_m, unequivalent function of p_{fr}, p_i and p_{aux}.

$$\eta_m = \frac{p_i - p_m}{p_i} = \frac{p_i - (p_{fr} + p_{aux})}{p_i} = f(\varepsilon; m; \lambda; T_0; p_0; n;$$

caloric conditions; law of dissipation heat transfer (5)

where p_{aux} is the medium-pressure corresponding to the rate of power input of the auxiliary plants.

By means of the process given, the influence of the working processes and of the engine characteristics on the mechanical efficiency can be examined, in order to analyze the mechanical-frictional losses and to define the characteristics of the working process assuring the maximum mechanical efficiency. The idea of the relation between average pressure and frictional medium-pressure as it is explained in this paper can be well used even in order to perfectionate the Willians, Morze and the running-out procedures for defining the frictional average pressure, as the basic theoretical inaccuracy of theses processes lies in the fact that the frictional medium-pressure is supposed to be independent of the working process. A deeper study of the frictional processes is indispensable also for the sake of the thermic analysis of the working processes of the engine, of the exact establishment or examination of the heat transfer factor and the quantity of heat penetrating the cylinder-wall.

3. Determination of the frictional medium-pressure as a function of the most important engine and working-process characteristics

3.1. *The principle of the procedure, the building up of the experimental appliance*

According to available records, the value of the frictional medium-pressure can be stated in the most exact way by separately driving the engine operated as in a plant. In order to approach as perfectly as possible the working conditions of an actual engine, an artificial working-process must be brought about in it, assuring a mechanical load equivalent to the original working process.

The original working process can best be approached by the working process without heat transmission, but identically to the original one in other characteristics, as shown in Fig. 2.

The draft of the experimental appliance is seen in Fig. 3. The engine absorbs from one of the air tanks, and back-fires to the other. The two tanks

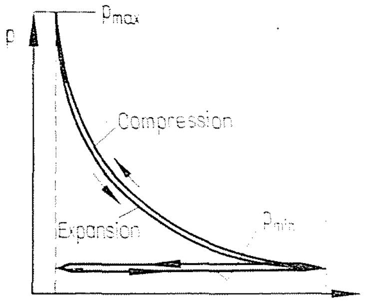


Fig. 2

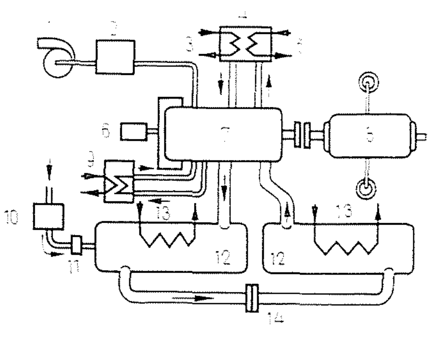


Fig. 3. Legend: 1 suction-ventillator: 2 measuring of filtering gas; 3 heating; 4 oil boiler; 5 cooling; 6 stroke-giver for indicating; 7 experimental engine; 8 balance engine; 9 lubricating oil cooling; 10 air compressor; 11 pressure regulator; 12 air-tank; 13 cooler; 14 air orifice

are connected by a piping with an orifice to determine the quantity of medium flowing through the engine. The initial pressure of the working process can be adjusted by changing the pressure in the airtanks. The gear-case gas leakage due to piston untightness was measured by a gasmeter or by a special Pitot-tube assuring always a constant atmospheric pressure in the crank case. In the cooling apparatus of the engine hot oil was circulated instead of water. This was given the required temperature in a combined cooling-heating system. The temperature of the lubricating oil was controlled in a similar way in the cooling apparatus.

By changing the initial pressure, the compression relation, the cylindric wall, the temperature of the oil, and the R.P.M. every actual working condition of the engine has an equivalent working condition brought about by an artificial working-process and being on a par with the original one from the point of view of friction.

The experiments were made partly on the Type JAFI Pl—406 engine assisted by the Institute of Vehicle Development [19], partly on the type

D 414 Csepel Auto engine helped by the Csepel Autógyár (Csepel Motorcar Factory) [20].

The all-loss p_{al} of the engine rotated from outside, to create on artificial working-process, expressed in medium-pressure can unambiguously be determined from the data of the balance-engine revolving the engine.

According to the studies up to now, however, this all-loss p_{al} isn't identical with the frictional-mechanical loss of the engine, but is the sum of the following part-factors:

$$p_{al} = p_{fr} + p_{be} + p_{chi} + p_{aux} + p_{coi} + p_{unti} \ [\mathrm{kp/cm^{32}}] \qquad (6)$$

where p_{fr} actual frictional loss, accounting for a great part, about 50 to 60% of the all-loss;

p_{be} own loss of the balance-motor;

p_{chi} medium-pressure with negative sign of the gas-change process;

p_{aux} medium-pressure necessary for eventual auxiliary plants to be driven by the engine under test;

p_{coi} indicated medium-pressure, always negative in practically important cases, owing to the heat transmission between the working medium and the wall and established at the main working-process (compression-expansion);

p_{unti} an always negative medium-pressure established in the main working-process, due to leakage (untightness) between piston and pistonring and the cylindric wall.

3.2. *Determination of some partial losses, calculation and experimental results*

The own-loss of the balance-engine p_{be} can directly be measured or verified from the characteristic curves.

The indicated medium pressure of the gas-change process p_{chi} can be determined from the diagram of the indicator provided with weak springs. Such a use of the diagram of the indicator with weak springs for the examination of the frictional medium-pressure gives an inaccuracy one order of magnitude less than the same method, if the frictional medium-pressure would be to be determined from the difference between the indicated and effective medium-pressures. According to the survey data the value of p_{chi} increases considerably in function of R.P.M. and the initial pressure. The considerable increase of the gas-change loss compared to the actual working conditions is due to the caulking convection losses on several parts of the system.

Fig. 4 illustrates the process of establishing a *negative medium-pressure due to the heat transmission between the medium of work and the wall* at main working process. In course of compression, the medium is colder than the cylindric wall until the adiabatic point, so the medium takes heat from the cylindric wall, by this way its entropy grows. After having reached the adiabatic point the medium being warmer than the cylindric wall transmits heat, so its entropy decreases. The situation is similar during the expansion, at the beginning of the expansion the entropy of the medium decreases, then after having reached the adiabatic point it grows. If the process is closed with the initial specific volume line, a visibly negative working-process comes into

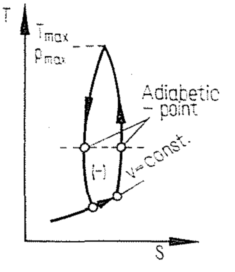


Fig. 4

being. The indicated medium-pressure of this negative working-process can't be determined in practice by evaluating the indicator diagram, as the fault of the indication is about the same as the value of the indicated medium-pressure sought for.

The calculation of the indicated medium-pressure of the working process is the following: the process of the polytropic compression (just as the expansion) can be considered as a series of elementary processes consisting of iso-

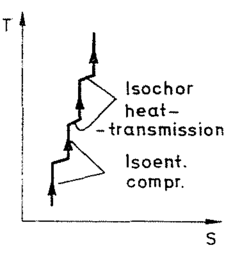


Fig. 5

sion) can be considered as a series of elementary processes consisting of isoentropic compression and isochor heat transmission (Fig. 5). The heat quantity at constant volume equals that penetrating through the wall. In our calculation the Sitkei—Woschni heat transmission formulas were applied [21, 22]. By knowing precisely the real compression and expansion curves, the indicated medium-pressure can be determined as well. Calculation was made by an electronic computer, sorry to say the survey of the details of the computation surpasses the frames of this paper, the calculation has made in function of the initial pressure and initial temperature, the degree of temperature of the cylindric wall, the compression-relation and the R.P.M. The value of p_{coi} grows as a function of compression-relation and the initial pressure, a fact related first of all to the increase of the heat transmission factor. With the increase of the initial temperature and with the decrease of the wall temperature the value of p_{coi} grows as well, as the difference of temperature grows in both cases between the medium of work and the cylindric wall. By decreasing

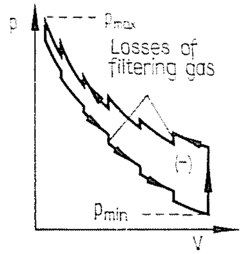


Fig. 6

the R.P.M., the value of p_{coi} gets ever increasing negative values as the time of heat-transmission increases. The maximum value of p_{coi} negative medium-pressure got from cooling is about 0,8 kp/cm^2. To neglect it would give a considerable fault in determining the frictional medium-pressure.

The real change of condition *owing to the untightness between the piston and the cylindric wall* can be got also from elements of isoentropic compression or expansion and from pressure decrease processes coming about from medium-escape when the cylindric volume remains constant (Fig. 6).

The pressure and temperature decrease due to the effect of medium quantity ΔM that flows out during time Δt from a given cylinder capacity and covers a piston-course ΔS has been stated on the principle that the decrease ΔU of the inner energy of the medium in the cylinder equals the enthalpy ΔI of the leaking medium quantity ΔM. Supposing a laminar isothermic convection between the cylindric wall and the piston as a first approximation, the medium quantity penetrating in unit time is linearly related to the pressure in the cylinder as a good approximation. The medium-quantity leaking during the whole working process has been determined by measuring the gear-box-gas. According to the calculations the value of p_{unti} increases considerably in function of compression relation ε and the initial pressure, as the absolute value of the gear-box-gas increases as well, besides by the increase of the pressures, the decisive part of the gas-loss appears near the upper dead-centre, increasing considerably the negative medium-pressure originating from it. Here again the decrease of R.P.M. causes to increase the value of p_{unti} the maximum being $0.2-0.3$ kp/cm³.

The rate of power input of eventual auxiliary plants driven by the engine in test (generally it is only a built-in oil pump) expressed in medium-pressure can be unambiguously stated from the characteristics of the auxiliary plants and the operational data of the test engine.

The frictional medium-pressure p_{fr} can be determined by substracting the non-frictional losses dealt with formerly from all-loss p_{al} by means of the experimental device seen in Fig. 3.

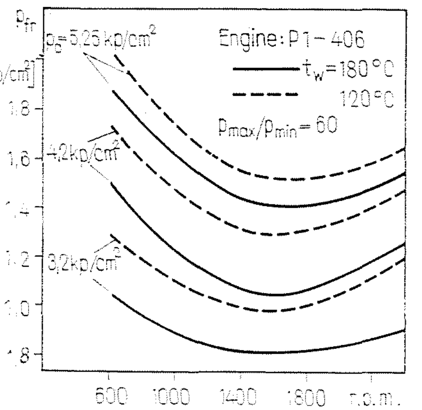


Fig. 7

Fig. 7 illustrates the change of the frictional medium-pressure in function of the R.P.M. with different average pressures p_a and cylindric wall temperatures. The value of p_{fr} increases considerably with increasing average-pressure, in agreement with the considerations. According to measurement results that are not published here, as a first approximation and within the limits examined, the value of p_{fr} is independent of the changes of the maximum and minimum pressures. With the increase of the R.P.M. the frictional medium-pressure increases after having reached a minimum. By increasing the wall temperature and the oil temperature, the value of p_{fr} decreases in the field examined. The tendencies above could be observed in the whole field of measurement with approximately the same character.

4. Examination of the mechanical efficiency as a function of the characteristics of the working process

The relation between the characteristics of the mechanical efficiency and working process can be stated according to the basic relationships (2), (3), (4), (5) as follows:

a) The change of the frictional medium-pressure is to be determined in an experimental way mainly in function of the average pressure. Such a relationship can be seen in Fig. 7 presented above.

b) The relation between the indicated medium-pressure and average pressure must be determined by calculating in function of the different working-process characteristics. The calculation of real working processes was done by an electronic computer. The working-process calculation method used was that by Ass.-Prof. Dr. István KALMÁR (Budapest Technical University). The combustion process was approached with the VIBE combustion-law. In

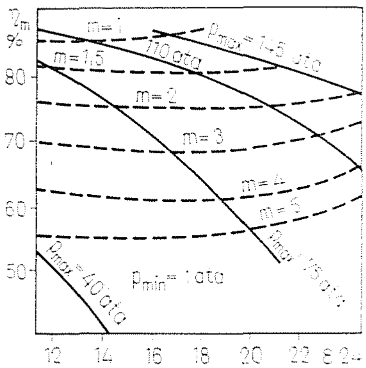


Fig. 8

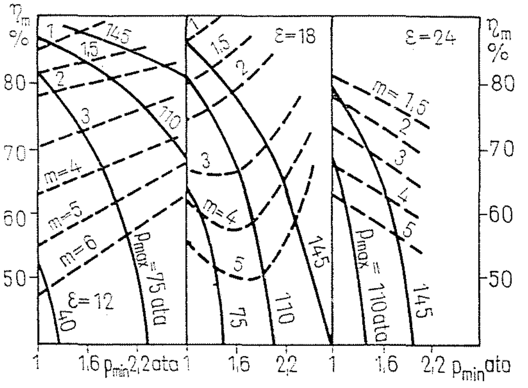
order to determine the heat quantity penetrating through the wall, the Pflaum heat transmission factor has been used. In order to make the relationships to correspond better to the reality, the negative gas-change work of the uncharged engine and the fact that this gas-change work turned positive with charged engines was taken into consideration.

In Fig. 8 the change of the mechanical efficiency based on the experimental data of the Type JÁFI Dl—406 can be seen in the case of a suction engine as a function of compression relation ε, peak pressure and air ratio. With constant air ratio the value of η_m rises by about 2—3% after a minimum initial decrease when the compression relation of the engine is increased, but it may be considered as practically unchanged between the limits $m = 1-3$. Although the indicated medium-pressure rises when the compression-relation is increased, as the constant air ratio means at the same time a liberated heat quantity of constant value, the average pressure, or the mechanical load of the engine, rises too, in proportion to p_i.

In the reality, corresponding to the considerations mentioned above, the specific consumption doesn't improve indeed when the compression relation is exceedingly increased.

When the air characteristics increase, the value of η_m decreases unambiguously, a regularity valid in the whole field examined. The conclusion can be therefore drawn, that *changes of the working-process characteristics having an atmospheric initial state and causing the increase of air ratio, decrease the mechanical efficiency.*

A clear-cut and powerful decrease of the mechanical efficiency can be experienced when the compression-relation is increased under constant peak-pressure as the indicated medium-pressure decreases, while the average-



a *b* *c*

Fig. 9

pressure increases. In such a case the air ratio rises too, corresponding to our previous statement, as the possibility of heat transmission is ever decreasing.

A special attention must be paid to the examination of the mechanical efficiency of the charged engines (Fig. 9). In the case of a lower compression relation ($\varepsilon = 12-13$) as shown in Fig. 9/a and under constant air ratio, the mechanical efficiency of the charged engine improves, in the case of medium values ($\varepsilon = 16-17$) as shown in Fig. 9/*b* it remains essentially unchanged, in the case of higher compression relations (Fig. 9/*c*) it decreases. This tendency is absolutely congruent to the reality. It is generally observed that only engines with lower compression relation behave favourably when charged. Under constant peak-pressure when the charge is increased, the mechanical efficiency of the engine deteriorated unambiguously. The deterioration of the mechanical efficiency can be cut by decreasing the compression relation or by increasing the peak pressure. Even these test results taken at random prove that the mechanical efficiency can be really connected to the characteristics of the working-process of the engine using the average-pressure as auxiliary parameter and the working-process optimum from the point of view of mechanical efficiency can be found.

5. Improvement of the Willians, Morze and running-out processes by means of a relationship between the frictional medium-pressure and the average-pressure

Until now, in the processes applicable under actual working conditions for determining the frictional losses, the fact was ignored that each of these processes gave the all-loss p_{al} proportional to the frictional losses p_{fr} only in the case of an engine without heat development. The all-losses for engines without heat development were then identified with the losses of the engine in a real working process. The neglect was twofold. First, the average pressure of the engine with combustion is twice that of the engine without combustion, consequently its frictional loss increases accordingly. In the second place the all-losses measured on the engine at work are put identical with the frictional losses, but they have the components shown in Eq. (6) in the part dealing with the separate driven engine.

The principle of the process is therefore:

The actual frictional losses must be determined from the all-losses p_{al} for engines without combustion and for working motors. The non-mechanical frictional losses can be determined with the calculation and experimental principles as described in point 3.

The frictional losses p_{fr} of the engine working at the given R.P.M. with combustion got by this way must be increased in proportion to the average-pressure grown alongside the combustion. The actual frictional losses of the engine with combustion are:

$$p_{fr} = p_{fr_0} + \Delta Pa \left(\frac{dp_{fr}}{dp_a}\right) \tag{7}$$

where p_{fro} frictional loss of the engine without heat transmission,

Δp_a difference of the average pressure belonging to p_e, the given effective medium pressure of the engine with heat transmission and the average pressure of the engine without heat transmission,

dp_{fr}/dp_a gradient got from the experimental relationship $p_{fr} = f/p_a$ determined by the way of a separate driven engine.

Where the value of dp_{fr}/dp_a largely upon the average pressure, the p_{fr} value must be increased depends at suitably little intervals Δp_a. With the above process the effect of the difference between the engines with and without heat transmission can be taken into consideration, as the change of the frictional medium-pressure in function of the heat condition of the engine (temperature of cylinder wall and of lubricating oil) is known by testing the separate driven engines. Sorry to say, the given size of this paper does not enable the presentation of experimental results even in this matter. The author is ready to make available his experimental results for those showing interest in it. On the basis of what was said it will be certainly clear that the introduction of the average-pressure and the analysis of the all-losses of the engines without heat development renders it possible to closer follow the change of the frictional medium-pressure as a function of different parameters. This helped us to analyse the engine losses more exactly and to give the thermic bases for decreasing the frictional losses.

Summary

The practicability of finding a correlation between the working process and the mechanical efficiency of I.C. pistons is discussed, with a view to find the optimum working process for mechanical efficiency. The main factors determining friction, mean effective pressure are discussed, and a new approach utilizing average pressure p_0 as the most important fundamental parameter for the development of a correlation between working process and mechanical efficiency is presented. In an analysis of the friction loss p_{fr} of the engine, from the overall loss determined by measurement, the losses of non-mechanical character are separated. For their determination a new calculation and test method has been developed.

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