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PREDICTING THE DURABILITY OF THE PISTON-RINGS-CYLINDER ASSEMBLY OF A DIESEL ENGINE USING A PISTON RING PACK MODEL

PROGNOZOWANIE TRWAŁOŚCI UKŁADU TŁOK-PIERŚCIENIE-CYLINDER SILNIKA O ZAPŁONIE SAMOCZYNNYM Z WYKORZYSTANIEM MODELU USZCZELNIENIA TPC *

The article presents a new method for predicting the durability of an internal combustion engine, which uses results of wear measurements of components of the piston-rings-cylinder system and computer simulations of the piston ring pack. In contrast to traditional methods, the method proposed here does not require previous knowledge of wear limits, which, though crucial for precise prediction, are difficult to determine reliably in modern structures. In the method presented here, wear limits are determined on the basis of an analytical model of the piston ring pack. The article shows an example of the application of the proposed method for predicting the durability of a motor-vehicle compression-ignition engine.

Keywords: *combustion engine, durability prediction, wear, blowby, cylinder liner, piston ring.*

W artykule przedstawiono nową metodę prognozowania trwałości tłokowego silnika spalinowego, wykorzystującą wyniki pomiarów zużycia elementów układu tłok-pierścienie-cylinder oraz komputerową symulację uszczelnienia TPC silnika. W przeciwieństwie do tradycyjnych metod, proponowana metoda nie wymaga wyprzedzającej znajomości zużycia granicznego, kluczowego dla dokładności prognozy, a którego wiarygodne określenie dla nowych konstrukcji jest trudne. W prezentowanej metodzie zużycie graniczne wyznaczane jest na podstawie analitycznego modelu uszczelnienia TPC. W artykule przedstawiono przykład wykorzystania metody do prognozowania trwałości samochodowego silnika o zapłonie samoczynnym.

Słowa kluczowe: *silnik spalinowy, prognozowanie trwałości, zużycie, przedmuchy spalin, tuleja cylindrowa, pierścień tłokowy.*

1. Introduction

The piston-rings-cylinder (PRC or piston) assembly is the basic functional system of an engine, and its most important function is to seal the combustion chamber in a tight and mobile manner. Due to the conditions under which they operate, the elements of the PRC assembly cannot be fitted too tightly and so there are clearances between them. Consequently, the sealing is not fully tight, allowing gas from the combustion chamber to pass into the crankcase and lubricating oil to flow into the combustion chamber. As the components of the engine wear out, the clearances grow larger and tightness decreases. Some good measures of the decrease in the tightness of the PRC assembly include increased blowby and elevated consumption of lubricating oil. Increased blowby and oil consumption have an adverse effect on the engine as they reduce engine power, increase the consumption of fuel and motor oil (resulting in elevated toxic emissions), accelerate quality wear of motor oil and wear of engine components, and decrease start-up performance of diesel engines [1, 9, 10]. Repair of a worn PRC assembly is costly and time-consuming and, if done at all, it is usually done as part of a complete overhaul. For many engine types, especially smaller ones, such repair is economically unjustified. Thus, excessive wear of the PRC system usually affects the durability of the entire engine or, in justifiable cases, may determine the necessity of carrying out a complete overhaul.

Methods used for pre-determining the durability of the piston assembly reduce the time and the costs of testing. In classic durability prediction methods, the courses of wear of selected components of the PRC assembly are assessed on the basis of shortened tests and then extrapolated to determine the time after which wear reaches a limit value (fig. 1).

To obtain reliable results when predicting durability, one has to accurately determine the courses of wear and know the value of the wear limit. The first of these conditions is usually satisfied if the operating conditions during tests do not cause
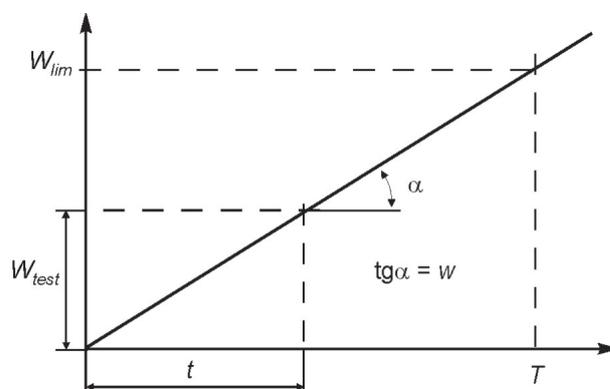

Fig. 1. The principle of predicting durability

wear that differs qualitatively from that occurring during actual operation of the engine and if the courses of wear is determined from measurements taken on a run-in engine. Experience shows that the courses of wear after completion of run-in have a linear character (the intensity of wear w is constant), especially in the case of the cylinder liner [7, 11], and engines are withdrawn from operation before the period of accelerated wear of components begins.

It is more difficult to establish wear limits, because there is no linear relationship between the value of wear of components and the reduction in the tightness of the PRC assembly. That is why wear limits for engine components are most often determined using statistical methods on the basis of measurements of similar objects already withdrawn from operation. Use of such empirical models of the limit state, however, may be burdened with considerable error associated with the different impact that wear of components has on the operation of the assembly, even in similar structures. This follows from the complexity of the mechanisms governing the sealing action of the piston assembly, in which even small changes in design may cause considerable changes in efficiency. Moreover, it has to be born in mind that usually the limit state is determined in this way using engines at least one generation older than the ones for which durability is being predicted.

The article presents a new method for predicting the durability of the PRC assembly of an IC engine, in which wear limits for the components of this assembly are determined using an analytical model of the piston ring pack describing the cause-and-effect relationships between the size of the individual clearances and the rate of blowby. It should be emphasized that analytical models of the piston ring pack have already been applied for some time in the design of piston assemblies [2, 12, 13, 14, 15]. Also, the applicability of the model used in the present work for the assessment of operational changes in the tightness of the PRC assembly has been confirmed in previous studies [5, 8].

2. The piston ring pack model

The tests were carried out using an integrated model of gas flow through the clearances in the piston assembly and displacement of piston rings within piston grooves. In the gas flow model, the piston assembly was treated as a labyrinth seal comprising a series of volumes connected by choke orifices. The volumes of the labyrinth were formed by inter-ring and behind-ring volumes, while the choke orifices were created by piston ring gap clearances and clearances between the side faces of the rings and ring grooves (fig. 2). The instantaneous values of the labyrinth volumes and cross-section areas of the choke orifices were determined as a function of crank angle, taking into account thermal deformation and wear of components. The cross-section areas of the clearances between the side surfaces of a ring and a groove are most strongly dependent on the instantaneous position of the ring within the groove. Axial positions of rings within grooves were determined by taking into account the forces acting on the rings: gas pressure, inertia, and friction against the cylinder. Gas pressures and gas temperatures in the individual volumes of the labyrinth were determined using the laws of energy and mass conservation and the equation of state. Gas flow rates through the individual choke passages were calculated assuming isentropic flow and taking into account cases

of subcritical and critical flow and the empirical discharge flow coefficient. The model had been described in detail in earlier articles [3, 5].
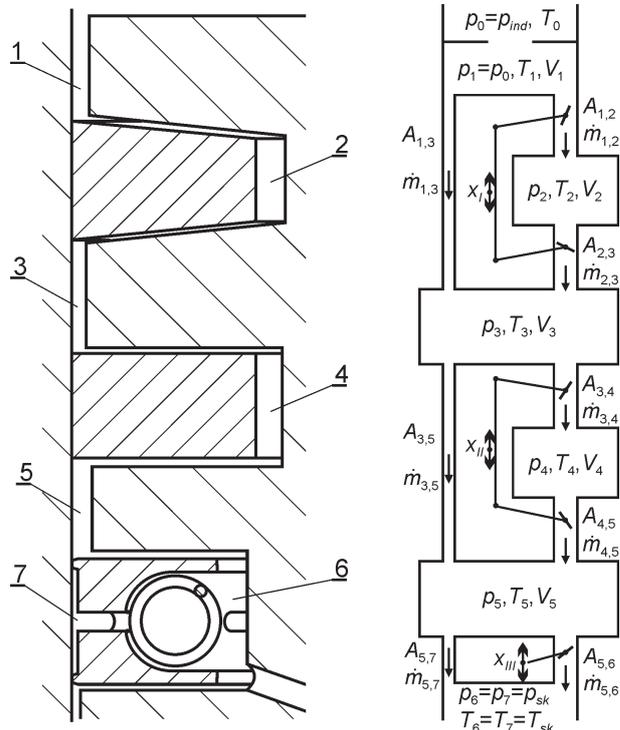

Fig. 2. *Schematic diagram of the piston-ring pack and a corresponding model of a labyrinth seal (p_i, T_i – pressure and temperature of gas in the i-th volume, $m_{i,j}$ – gas flow rate from volume i to volume j, x_I, x_{II}, x_{III} – axial positions of the top, second, and oil ring, respectively) [5]*

Calculations done using a numerical application of the model yield results, among others, for pressure courses in the individual volumes of the labyrinth, displacement of rings within grooves, and instantaneous rates of gas flow through the individual clearances as a function of crank angle (fig. 3). By integrating the instantaneous flow rates through the oil ring gap and the clearance between this ring and groove flank (m_{5-7} and m_{5-6} in figs. 2 and 3), the rate of blowby is obtained.

The input data necessary to carry out calculations using the numerical application of the model include, among others, the dimensions of engine components and pressure course in the combustion chamber as a function of crank angle. The dimensions of the components are established on the basis of technical documentation or direct measurements. In the case of key dimensions, i.e. those that determine the cross-section areas of clearances and the labyrinth volumes, the values entered into a computational software program should account for thermal deformation of the components. Thermal deformations are calculated for the given operating conditions of the engine using FEM. The deformation values determined in this way are added to the dimensions given in the documentation or those established on the basis of measurements of cold components [4]. Optimally, the course of combustion chamber pressure to be used in the calculations should be determined from measurements done on an actual engine.
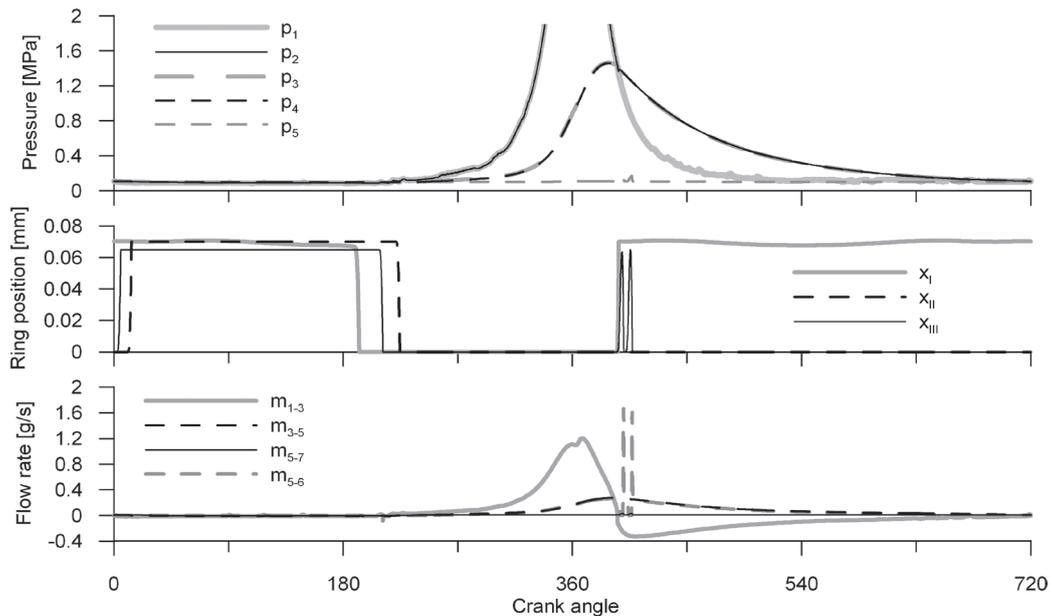
Fig. 3. Pressures in the volumes between and behind the rings, axial displacements of rings within piston grooves, and gas flow rates through ring gaps and the clearance between oil ring side face and groove as a function of crank angle, determined using the piston ring pack model

The geometrical dimensions entered into the calculations can consider the wear of the individual elements of the piston assembly, analogically to the way thermal deformations are taken into account. This allows one to estimate how an increase in wear affects the tightness of the piston assembly. The possibility of using the presented model for the assessment of the effect of wear on blowby was confirmed earlier by comparing results of numerical calculations with blowby measured in actual engines [5, 6, 8].

3. The durability prediction method

According to the proposed method, an engine should be run in before the durability of its PRC assembly is assessed. The time of engine operation in that period (t_0 in fig. 4) should be such that the unstabilized tribological processes associated with run-in have definitely been completed.

The principal part of the experimental tests starts with an assessment of the initial tightness of the PRC assembly done by measuring blowby flow rate B_1 and by determining initial engine wear W_1. Wear is estimated through measurements of the components of the PRC system after prior disassembly of the engine.

As a next step, the engine should be allowed to operate for time t to enable assessment of the rate of wear of its components, having in mind that a longer operation time allows obtaining more precise results. The engine in that period may be run either in a vehicle or on a test bed. The operating conditions, however, should not diverge too far from those intended for its normal operation. Once this testing stage is completed, measurements of blowby flow rate B_2 and engine wear W_2 have to be done analogically to the way in which blowby flow rate B_1 and initial engine wear W_1 have been measured.

The wear rate w of components is determined on the basis of the measurements of W_1 and W_2 in accordance with the following relationship:

$$w = \frac{W_2 - W_1}{t} \qquad (1)$$

A second area of work on durability assessment using the proposed method is associated with investigations of the model of the piston ring pack. Working in this area, one should first determine all the input data necessary for the calculations, including the results of the earlier measurements of wear of components of the piston assembly. Next, tightness calculations should be done for input data corresponding to the initial engine wear W_1 and for input data corresponding to the final wear W_2 measured after the engine durability tests. A comparison of the calculated and observed increases in the blowby flow rate caused by wear allows one to assess the adequacy of the model. If the results of simulations concur with the results of measurements, further simulations should be done for higher values of wear of the PRC assembly, assuming that the wear rates for the individual components are those determined in the experimental tests. The aim of those calculations is to find such a value of wear W_{lim} for which the increase in blowby rate will reach an assumed limit value B_{lim}. The value of wear W_{lim} determined in this way is the wear limit. The limit blowby flow rate is determined taking into account the negative effects of blowby on engine operation and previous experiences from engine durability tests.

The predicted engine durability t_{lim} at a given wear rate w and the limit value of wear W_{lim} is

$$t_{lim} = \frac{W_{lim} - W_1}{w} + t_0 \qquad (2)$$

A schematic diagram for predicting engine durability on the basis of measurements of blowby flow rate and wear of the components of the PRC assembly is shown in fig. 4.
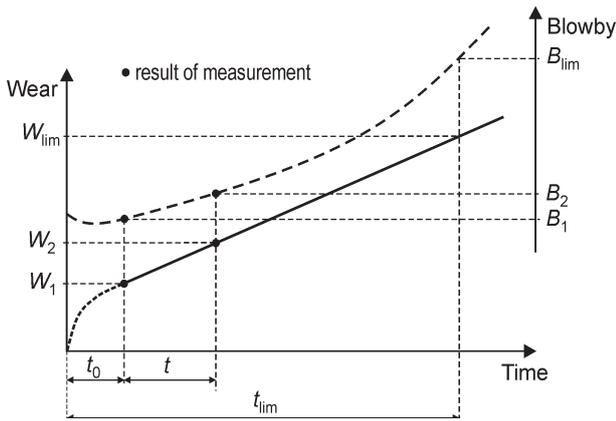
Fig. 4. The durability prediction method

4. A computational example

4.1. Determination of the courses of wear

The test object was a six-cylinder compression ignition engine with a capacity of 6.8 dm^3 and rated power of 110 kW at the speed of 2800 rpm. The engine was equipped with wet, cast iron cylinder liners with the nominal inside diameter of 110 mm. The piston travel was 120 mm.

To avoid errors related to the deviation of a single engine from the average of a population, the tests were conducted on 5 engines mounted in trucks of medium loading capacity and a gross vehicle weight of 12 Mg. All the vehicles were the property of one transport provider and were used under similar conditions, with an average monthly mileage of 10 000 km. The engines were lubricated with the same CE/SF SAE 15W/40 class oil.

The tightness and wear of the PRC assembly were measured after 50 000 km of travel. This amount of travel guaranteed full run-in of the engines. The blowby flow rate was measured at idle run. Next, the engine was partially disassembled to measure the wear of its components. After removal of the heads the cylinder diameters were measured by the micrometric method using a Carl Zeiss two-point bore gauge with the minimum graduation of 0.002 mm. The cylinder diameters were measured in two directions, parallel (A-A) and perpendicular (B-B) to

the main axis of the engine, at four levels: 20 (top dead center TDC of the top ring), 35 (TDC of the second compression ring), 50, and 95 mm from the head face. Then the assembled engines were operated under pre-disassembly conditions. Once the engines had reached a mileage of 150 000 km, blowby flow rate and engine wear were measured again in the same manner as at 50 000 km.

The results provided a basis for determining mean values of wear of the components of the PRC assembly for all five test vehicles. Since the piston ring pack model does not provide for deviations from circularity of the components of the PRC assembly, the results for directions A-A and B-B, i.e. parallel and perpendicular to the main axis of the engine, respectively, were averaged. The results are shown in fig. 5a. Next, the wear courses were extrapolated on the assumption that they were linear (constant wear rate w, fig. 5b).

4.2. Determination of the limit state and durability of the engine

Input data for the calculations with the use of the piston ring pack model were established. Geometrical data were established on the basis of technical documentation and measurements. Thermal deformations were determined using FEM and added to the dimensions established for a cold engine. Measurements of indicated pressure were carried out on an engine test bench.

Calculations were done for dimensions of the components corresponding to the mileages of 50 000 km and then 150 000 km. The input data for the calculations at the different mileages differed only in the dimensions of the components which had been changed by wear. The calculations took into account wear of the cylinder liner (fig. 5a), wear of the running faces of rings, and wear of the side faces of rings and piston grooves. The value of blowby determined in the numerical calculations at 150 000 km of travel was 22% higher than at 50 000 km. Because the simulated change in blowby matched the actual one, further numerical calculations were done for higher mileages. Wear values (dimensions) of the individual components at higher mileages were established on the basis of the previously determined courses of wear (an example for a liner is shown in fig. 5). The calculations were done with a view to finding a mileage at which blowby would reach a limit value. Since the investigated engine was not a new model, specimens withdrawn from opera-
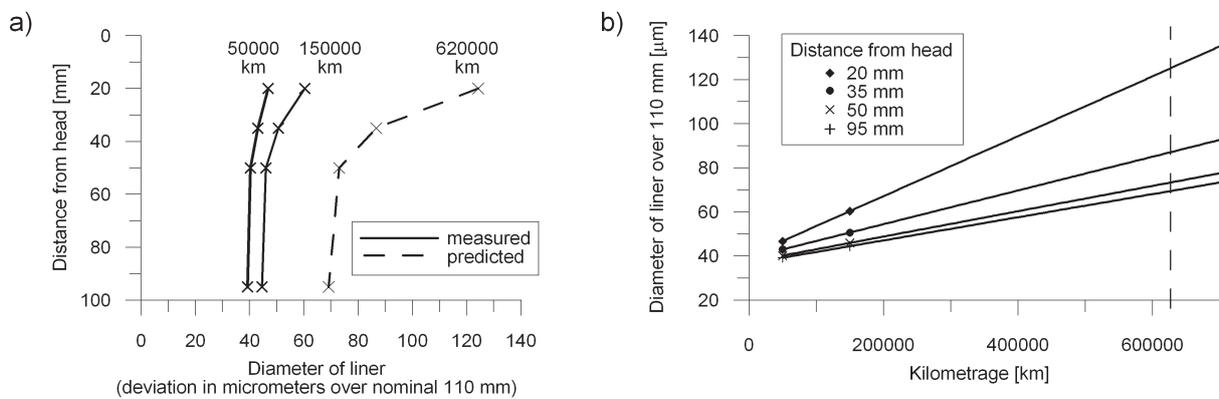

Fig. 5. Experimentally determined diameters of cylinder liners at different distances from head (a), assumed courses of cylinder liner wear at different distances from head (b), and predicted limit state of the cylinder liner –liner diameters at 620 000 km of travel – determined as described in section 4.2 (a)

tion could be used to establish limit blowby values. They turned out to be 2.5 times higher than the values obtained in the test engines at 50 000 km of travel. Hence this increase in blowby was assumed to be the limit increase. In numerical calculations, a 2.5-fold increase in blowby rate was obtained for predicted wear at mileages of over 620 000 km. This mileage defines the durability of the engine as predicted by the proposed method. The predicted liner wear profile for this mileage, which is at the same time the predicted wear limit, is shown in fig. 5a. The actual mileages achieved by engines of the investigated type have been in the range between 500 and 800 thousand km.

5. Conclusions

The proposed durability assessment method is based on experimentally determined wear rates for the components of the PRC assembly and on results of numerical studies of an analytical model of the piston ring pack. Wear rates can be determined from measurements of engines tested either on a test-stand or in a vehicle [9-10]. The proposed method has the advantage of not requiring prior knowledge of the wear limit. In traditional durability prediction methods, the adopted wear limit determines the adequacy of the obtained results. Unfortunately, this value is difficult to specify reliably in modern engine structures. By contrast, the new method described in this article does not require previous knowledge of the wear limit because wear limits are determined here on the basis of an analytical model of the piston ring pack. This, however, requires the knowledge of the permissible decrease in the tightness of the PRC assembly. The permissible decrease in tightness may be adopted on the basis of assumed permissible decrease in the efficiency and eco-friendliness of an engine.

The applicability of the proposed method for predicting the durability of a motor-vehicle compression-ignition engine has been verified in the study reported here. An additional merit of the discussed analytical model is that it can be directly used in work on improving the design of the PRC assembly.

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