Research Article

Wojciech Lewicki*

Technical and economic aspects of starting a selected power unit at low ambient temperatures

<https://doi.org/10.1515/eng-2021-0059>

received October 27, 2020; accepted February 22, 2021

Abstract: The article presents research on the impact of a 359 compression-ignition engine starting at low ambient temperatures. This engine is used in vehicles such as STAR 200, 244, and 226. The purpose of these tests was to determine the amount of wear depending on the ambient temperature and the number of starts, as well as to compare the wear at start-up with the wear occurring during tests on the dynamometer (long-term test for reliability) and wear occurring during the operation of the engine in the vehicle, and the impact of the number of starts and ambient temperature on diesel engine for the life of the vehicle to be repaired. The results of the author's research showed that a minimum of the number of starts at low ambient temperatures has an impact on the number of kilometers driven by the car during operation to replace the cylinder liners (engine repair). Apart from the Polish armed forces and armies of other countries in which this type of vehicle is still used, the direct recipients of the research results are also other entities from the logistics transport sector for which further use of this power unit especially at low ambient temperatures is of fundamental economic importance.

Keywords: exploitation, engine starting, low temperatures

1 Introduction

As the literature on the subject indicates, both modern transport and logistics are closely related to the use of specific means of transport. Undoubtedly, heavy-duty vehicles are one of the dominant means of transport. Observations of market reality indicate that, despite significant technological progress, heavy-duty vehicles with

propulsion units developed at the end of the twentieth century are still in use (armed forces of individual countries or other entities). The problems associated with starting diesel engines, as well as the wear of the components of these engines, especially at low ambient temperatures, make the starting problem still current [1–5]. An analysis of the available literature showed that despite numerous publications related to start-ups, including accelerated wear of compression-ignition engine components, there are no studies related to the wear of the piston–cylinder system [6–11]. The authors of the article decided to carry out tests on the piston–cylinder system wear in a compression-ignition engine of the 359 type, which was used in STAR vehicles (200, 244, and 266). The tests are an attempt to answer the question of how the number of starts and ambient temperature can in practice affect the lifetime of the vehicle's power unit. In connection with the plans to modernize and further use these vehicles of the Polish Armed Forces, the issue of the impact of diesel engine start-ups at low ambient temperatures is of fundamental economic importance. It is worth noting that the available literature on the subject lacks such interdisciplinary analyses and studies, which justify the justification of undertaking this research subject in the light of academic considerations.

The presented research results may find their practical industrial application (Polish armed forces and other countries, entities from the transport and logistics sector) and may be helpful in further development works on extending the lifetime of the tested propulsion unit.

2 Subject of research, low temperature chamber

The engine under examination was placed in a cooling chamber. The cold store was equipped with two aggregates. The refrigerant was freon. The electric control system provided automatic temperature control and maintained a constant temperature during the tests. The recording

* Corresponding author: Wojciech Lewicki, The Faculty of Economics, West Pomeranian University of Technology, Szczecin, Poland, e-mail: Wojciech.Lewicki@zut.edu.pl

device allowed us to record the temperature of the coolant, engine oil, air, rotational speed, etc. In addition, there was the possibility of direct visual and acoustic observations of the engine.

2.1 Research object

The tests were carried out twice on a 359 compression-ignition engine. These engines were installed in STAR trucks (200, 244, and 266) manufactured at FSC Starachowice. It was a direct injection engine with a combustion chamber in the piston crown.

Technical data of the 359 engine are as follows: arrangement of cylinders – in line, vertical, number of cylinders – 6, cylinder diameter – 110 mm, piston stroke – 120 mm, displacement – $6,842 \text{ dm}^3$, compression ratio – 17, ignition order – 1–5, 3–6, 2–4, rated power – 110 kW at 46.7 s^{-1} (150 HP at $2,800 \text{ min}^{-1}$), torque – 440 N m at $30\text{--}36.87 \text{ s}^{-1}$ (44 kG m at $1,800\text{--}2,200 \text{ min}^{-1}$), idle – 8.3 s^{-1} (500 min^{-1}), maximum speed – 52.5 s^{-1} ($3,160 \text{ min}^{-1}$), minimum specific fuel consumption – 62 g MJ^{-1} ($165 \text{ g km}^{-1} \text{ h}^{-1}$), injection pressure – 22–23 MPa ($220\text{--}230 \text{ kG cm}^{-2}$), static injection advance time – $0.322 \pm 0.017 \text{ rad}$ ($18.5 \pm 1^\circ$), injection acceleration angle – 0.192 rad (11°), and suction and exhaust valve clearance – 0.3 mm.

Before the test and after each start-up cycle, valve clearances, injection advance angle, and injector operation were checked, and the required service was performed. During the tests, the engine was equipped with an alternator and a compressor, but without exhaust muffler and air filter.

2.2 Method of conducting tests

The micrometric tests included the following measurements: cylinder liners and pistons.

The diameter of the cylinder was measured with a sensor bore gauge with a 0.001 mm increment. The bore gauge was scaled using gauge blocks.

Eight ranges of measurements distant from the top edge of the cylinder were determined:

- L1: 10 mm – corresponded to half the distance of the first sealing ring from the upper edge in ZG.
- L2: 20 mm – corresponded to the position of the first sealing ring in ZG.
- L3: 35 mm – corresponded to the position of the second sealing ring WZG.

L4: 40 mm – corresponded to the position of the third sealing ring in ZG.

L5: 80 mm – corresponded to half the distance of the first sealing ring between turning points.

L6: 140 mm – corresponded to the position of the first sealing ring in ZK.

L7: 235 mm – corresponded to the position of the second sealing ring in ZK.

L8: 245 mm – measurement 5 mm distant from the bottom edge of the cylinder liner.

The diameters of the piston guide parts were measured in a plane perpendicular to the piston pin axis. Measurements were made using a micrometer.

To measure oil, engine coolant and air rhodio-platinum, -platinum thermocouples and a 12-stage temperature recorder were used.

3 Discussion and results

3.1 Cylinder and piston wear when starting a diesel engine at low temperatures

According to Bernhardt [12], corrosion of the cylinder liner occurs primarily during engine start-up at low temperatures, since then the inevitable condensation of harmful compounds on the liner walls occurs. Such active compounds are, above all, acids: formic, acetic, nitric, carbonic, and sulfuric. The highest wear of the sleeve occurs in the upper part of it, because in this zone the upper piston ring is subject to the highest combustion pressure, which presses it against the finish. It causes that it leaves behind a minimal layer of oil, which is easily washed off by fuel or destroyed by corrosive substances – chemical corrosion of the finish occurs. In addition, the upper piston ring pressed against the finish strips away corrosion products and exposes further layers of metal, exposing them to damage.

The author of the work believed that piston group wear has the characteristics of a conglomerate of types of wear. This is oxidation wear in combination with abrasive wear, occurring on the surface of the cylinder, piston, and rings. The piston group is lubricated by splash and the oil is distributed by rings. Cold oil gives less splash performance and less even distribution of oil over the friction surface. A reciprocating movement does not allow the formation of a permanent lubricating film. Dust much harder than metal causes microcutting of

friction surfaces, especially rings and piston. Regardless of this, the proportion of corrosive wear is quite significant, especially in the upper zones of the cylinder (around the contact of the first ring with the cylinder in ZG). This is caused by the influence of hot exhaust gases facilitating both the abrasion process due to the high temperature of the surface layer and causing corrosion of the material of the cylinder, piston, and piston rings.

According to the study by Bernhardt et al. [13] in compression-ignition engines in normal operation, there is mainly sliding friction. At low temperatures due to the high internal friction of the lubricants (high viscosity), the speed of the engine components cannot be as high as for engines operating at normal temperatures. This causes work with dry friction due to the lack of sufficient oil outflow from the oil channels.

W. Balist claims that typical wear of a cooled engine shows extreme values only around the upper and lower return positions of the piston ring. Mikulin in his work presented different opinions of researchers regarding the amount of cylinder wear when starting a cold engine [14]. And so, according to R. W. Kugel one start-up at an ambient temperature of 283 K equals cylinder wear, which occurs after 50 km of mileage, at 273 K – 80 km, and at 263 K – 150 km. J. Pawłowski believes that starting the engine at an ambient temperature of 253 K is equal to wear after a mileage of about 1,000 km, and D. M. Levin believes that one start and warm up the engine at a cylinder wall temperature of 255 K is equal to the effects of 210 km, and at a temperature of 278 K – 80 km. According to D. P. Vilkanova every cold engine start after a night stop in the cold causes wear such as driving a car from 180 to 200 km. D. J. Demjanow believes, however, that one start-up and warm-up is synonymous with a mileage of 15–17 km [7]. According to Lindl and Schmitz [10], during one cold start, engine components were worn as in 4 h and 50 min of operation under normal conditions. The same source states that the consumption at cold start and warm up of the engine is 60% of the total consumption qualifying the engine for major repair. According to US data, engine wear generated during cold start is approximately 45% of total operational consumption.

F. S. Łosavio in his article described the research on the impact of low-temperature starting on cylinder liner wear. Work was carried out on the JaMZ-204 compression ignition engine. The whole study was carried out in three cycles. The first series of experiments was carried out on a cold engine with an average temperature of 258–253 K. The start-up was carried out using the NIAT PŻ-25 starting liquid. A total of 100 starts were carried out (with breaks between starts 6 and 17 h), while at the start of

the cold engine it was heated by idling at 16.6 s^{-1} to 308–313 K. The working time was 5 min.

The second series of experiments involved carrying out the same number of starts at an air and oil temperature of 258–253 K, but with a pre-heated hot water engine block to 298 K and running it for 5 min at the same idle speed at 320 K.

In the third series of experiments, including 100 starts, cold engine start-ups were carried out at a temperature of about 253 K. After starting, the engine worked only for 10 s until constant speed appeared. Comparison of the amount of wear of the first and third cycles revealed the dynamics of the process of wear of the cold engine during direct start-up, and then independent operation after heating it at idle. This allowed us to determine in which of these two periods the engine components were most worn.

The maximum wear of the cylinders in the first cycle was $30\text{ }\mu\text{m}$, the average wear was $12.3\text{ }\mu\text{m}$, and the average maximum wear in the upper part of the cylinders during 100 cold starts was $25.8\text{ }\mu\text{m}$.

The wear of JaMZ-204 self-ignition engine cylinders qualifying it for major repair was $500\text{ }\mu\text{m}$. The car with such consumption reached mileage up to 70,000 km. Assuming that the temperature 258–253 K will persist for 4 months throughout the year, during this period the wear of the cylinder liner during start-up will be 8% of the total value of the engine wear.

The results of the second test cycle after 100 starts with a pre-heated hot water engine block showed that the maximum cylinder wear was $12.8\text{ }\mu\text{m}$, the average wear was $4.4\text{ }\mu\text{m}$, and the average maximum wear at the top of the preheated engine was $8.3\text{ }\mu\text{m}$. Thus, the starting wear of a partially warmed up engine turned out to be about three times less than the starting wear during starting and warming up of a cold engine [7].

The test results obtained in the third cycle of experiments after 100 cold engine starts without further warming it up at idle showed that the maximum cylinder wear was $18.9\text{ }\mu\text{m}$, the average was $9\text{ }\mu\text{m}$, and the average maximum of the upper part was $12.2\text{ }\mu\text{m}$. A comparison of starting wear of the engine during the start-up and warm-up period at idle (first cycle) with the wear, during the only start-up period (third cycle) shows that about half of the wear falls on the start-up period, i.e., $12.9\text{ }\mu\text{m}$ from the total consumption of $25.8\text{ }\mu\text{m}$.

Tests on the ZD-6 compression-ignition engine carried out by the author also showed a significant impact of air temperature on wear of parts during start-up. In this work, the intensity of piston-cylinder steam consumption during start-up and heating was determined by the

method of iron content in oil. Oil was taken at various ambient temperatures from 245 to 305 K, 1, 3, and 5 min after the start of the engine. After starting, the engine warmed up at 20 s^{-1} for 15 min. A total of 160 subsequent starts were carried out in summer and winter conditions.

Research has shown that the piston rings located higher are wearing more than the rings located lower. Consumption in summer conditions is about 3–4 times lower than that in winter conditions.

L. A. Surikov presented the wear tests during start-up and warm-up and compared them with the wear arising during the start of the engine with warm preparation (filling the cooling system with hot water). The tests were carried out on a D12A-375A engine at an ambient temperature of 233–253 K. The wear of engine parts was assessed by iron content in engine oil. Oil samples were taken from the lubrication system, incinerated, and the iron concentration determined by colorimetry. Start-up and warm-up wear was evaluated using samples taken before and after 20 starts. Consumption at 233 K was twice as high as at 248 K. In an engine whose cooling system was filled with hot water, the consumption was about 20% less than in an engine without heat preparation [15].

According to Grigoreva and Pavliskiy [16], cylinder wear at one cold engine start in general wear is as follows:

- for a 6-cylinder diesel engine with a capacity of 11.15 dm^3 : from 8.5 to 12.7% of total operational consumption, which corresponds to the wear of these parts in the winter after 63.6 km,
- for an 8-cylinder diesel engine with a capacity 11.15 dm^3 : from 8.9 to 13.4% of total operational consumption, which corresponds to the consumption during the course of 63.4 km in winter.

Completely different results regarding the wear of the piston–cylinder assembly were obtained by Belousov [7]. In the years 1975–1978, the author conducted operational tests of two MTZ-80 tractors equipped with an electric starting system in order to ensure a guaranteed start-up of D-240 engines to a temperature of 243 K, without prior heating.

The tractors were equipped with a starter device with an easily igniting liquid in an aerosol container and ZST-225ER accumulator batteries with improved voltage and current characteristics. The lubrication system was filled with concentrated winter oil type M-4z (6 W M6Wz), and the cooling system with M-40 anti-freeze. In June 1978, technical tests were carried out to check the condition of the parts and their wear after operation. Examination of

the surface of the cylinder liners and pistons showed their normal technical condition. There were no burrs or scratches, and the sealing and scraper piston rings were movable. The results of the micrometer of the cylinder liners showed that their dimensions in different planes do not go beyond the tolerance range of the nominal dimension, which is $110 + 0.6\text{ mm}$.

The measured outside diameter of the pistons did not go beyond the tolerance limits. As a result of the inspection and micrometer of pistons, cylinder liners, piston rings, and other engine components, it was found that starting diesel engines in winter conditions without prior heating in operating conditions maintains the reliability, wear resistance, and durability of parts.

According to other authors [17,18], during the analysis of work devoted to bench tests on the wear of engine parts during start-up at low temperatures, it was found that those tests in which large equivalents of wear at start-up were obtained were carried out by the method of not predicting lapping after each start-up of microbarbs. This means that after the start-up, the engine was not heated by its independent operation, which would cause microbarbs to reach. Starting the engine in the presence of unbroken microbarbs on rubbing surfaces will cause wear on these surfaces 5–11 times greater than normal wear. Therefore, the main danger to the durability of the engine lies not in the start-up, but in the long-term start-up of the engine in an unheated condition.

The effect of engine load after starting at low temperatures on its wear was tested by A. M. Golovina [11]. The quoted author of the study ran on a compression-ignition engine type A-41. The cooling system was filled with M-40 anti-freeze, and the oil in the oil sump was diluted with A-72 gasoline. The tests were carried out at average ambient temperatures of 263 and 253 K. Self-heating the engine after start-up to a temperature of 323 K was carried out at idle and under a load equal to 75% of the nominal. The nominal rotational speed of 29 s^{-1} was determined in all tests. The wear was determined by the method of artificial bases, which were applied to the sleeves and upper piston sealing rings. The markings on the sleeves were scored in four zones. The research showed that wear in the first zone around the cylinder circumference in the process of starting and warming up the engine at idle and with a load of 0.75% of nominal at 263 and 253 K ambient air is uneven. This nature of the distribution of wear in the upper zone can be explained by the fact that in the warm-up start-up process, the temperature of the sleeve around the periphery is different and the rings rotate. Analysis of the cited data indicates that consumption at start-up and

heating under load is 2–2.5 times lower than at start-up and idle: at 263 K and at 253 K. Moreover, wear at start-up and heating under the load at 253 K is less than the wear at start-up and idle at 263 K. The quoted results show that heating the engine under load significantly reduces the wear of the rings compared to heating the engine at idle. The rings and the upper zone of the sleeves wear out when the engine is under load at 253 K less than when idle at 263 K.

The dependence of the rate of wear on the time of engine operation was investigated by Bryzik and Henein [9]. The tests were carried out on an SW 680, compression ignition engine. The piston–cylinder group wear was determined by means of iron concentration in oil samples. The ambient air temperature during the tests was 286–290 K. The high wear rate that occurred in the initial start-up period began to decrease at the end of the first minute. The wear rate increased when the intervals between starts were increased from 15 min to 3 h. A fairly quick reduction in the wear rate is explained by the fact that the start-ups were carried out at positive air temperatures and the intervals between subsequent start-ups were small. Under such conditions, due to the low viscosity of the oil during start-up, the intensity of its introduction into the piston–cylinder group at $20 \text{ s}^{-1} = \text{const}$, reached $0.11\text{--}0.13 \text{ g s}^{-1}$ for 30 s after start-up.

At this stage of consideration it is worth noting that other authors, [4] although dealing with this research issue in relation to much more technologically advanced propulsion units, emphasize the significant impact of engine start-ups at low ambient temperatures on the economic exploration period.

In domestic and foreign literature [9,10,12,17], there is a widespread belief that wear during engine start-up and warming up accounts for 50–75% of the total wear and tear, especially consumption at low temperatures of ambient air. This article presents a number of views of various authors on the wear of basic engine components during start-up and warm-up at low temperatures.

When testing the wear of parts of internal combustion engines, the classification used for this type of objects by researchers [10,12,15,19] can be used, according to which mechanical, mechanical–molecular, and mechanical–corrosive wear are distinguished. In each of these types one can distinguish a number of sub-types of wear, characteristic of the cooperation of various engine components. Mechanical wear can be divided into abrasive wear (in the presence of mechanical impurities), wear due to plastic deformation, fatigue wear. Abrasive wear accompanies the work of many engine parts during its operation. In this case, wear products

and other abrasive particles inevitably get in between the surfaces of the rubbing parts together with the contaminated air or lubricant. These hard particles deform the friction surface of the parts, creating on them scratches of varying width and depth, and even places where material crumbling occurs.

Mechanical–molecular wear, accompanied by phenomena of transferring metal particles from one cooperating surface to another, often occurs with the cooperation of the surfaces of various engine parts, especially in places of insufficient lubrication. This type of wear includes heat consumption associated with high heating of the friction surface at high pressures and high sliding speeds of the mating parts. The molecular interaction increases with increasing temperature. Its size is affected by the structure and hardness of the materials associated with the surface. These types of wear occur when the pistons interact with the cylinder liner.

Mechanical–corrosive wear can be divided into wear due to oxidation and wear under aggressive environments. It is mechanical wear compounded by corrosion phenomena. It occurs among others on the cylinder walls. Each of these types of wear can occur as leading or associated depending on the operating conditions of the engine.

In addition to the types of wear mentioned, there are others that are generally considered as independent types of wear: cavitation, erosive [2,5,20,21]. In engines, cavitation wear occurs in cylinder liners, main bearings, the atomizer, and other components. Erosive wear is manifested in the separation of material particles from the surface as a result of movement relative to these surfaces and contact with them by liquid or gas medium. Erosive wear occurs among others in engine piston rings.

Parts of internal combustion engines are therefore subject to various, most often comprehensive types of wear, characteristic of their materials and operating conditions.

Test results and theoretical considerations indicate that the majority of mechanical losses in piston engines are caused by friction in the piston–ring–cylinder assembly, and among these losses the vast majority comes from the friction of the piston rings on the cylinder liner.

Similarly, according to Bernhardt et al. [13], the corrosive wear of the cylinder liners occurs primarily during engine start-up at low temperatures; since then the inevitable condensation of harmful compounds on the cylinder walls occurs. Such active compounds are primarily: formic, acetic, carbonic, and sulfuric acids.

Stouffer et al. [3] considered electrochemical corrosion in conditions of insufficient lubrication as the main

Table 1: Maximum values of cylinder liners wear (own study)

Number of starts	Cylinder number						Average
	1	2	3	4	5	6	
	Maximum wear of cylinder liners (mm)						
Before the test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
150	0.050	0.035	0.040	0.040	0.055	0.040	0.043
150–300	0.020	0.015	0.010	0.015	0.015	0.025	0.017
300–450	0.013	0.008	0.028	0.09	0.014	0.019	0.015
450–600	0.016	0.012	0.019	0.015	0.013	0.014	0.015
600–750	0.066	0.049	0.025	0.045	0.057	0.068	0.052

reason for the phenomenon of wear during start-up at low temperatures. In addition, water accumulated in the oil pan has a large impact on consumption. It causes coagulation and hydrolysis of other inhibitors contained in the oil, which worsens its lubricating properties. In addition, this leads to clogging of oil lines as a result of precipitation. When starting at 263 K, cold oil reaches the top of the cylinders up to 180 s, and at 253 K up to 230 s. The review shows that the assembly of piston rings at low temperatures is subject to both mechanical and corrosive wear.

3.2 Tests of piston–cylinder system wear at low ambient temperatures

This section presents tests on cylinder and piston wear at low ambient temperatures. The tests consisted of five series of 359 engine starts at 268 K, 150 starts in each series. The engine after warming up worked to reach maximum speed, from idle speed to maximum speed. The test duration was 3–5 min. The thermal condition of the engine was determined on the basis of the engine oil temperature (measured in the oil sump), the temperature of the cooling liquid (measured in the water collector), and the ambient temperature (air in the low-temperature chamber). Further start-ups were carried out after obtaining the same temperature of engine oil, coolant, and air.

The tests were carried out using IZ-35 diesel oil and Selektol Super Plus motor oil. The cooling system was filled with Borygo antifreeze. After each series of starts, the engine was disassembled and the parts were subjected to detailed examination and micrometric measurements. Before each series of starts, the injectors were checked, whose injection pressure was set in accordance with the standard. The results are summarized in Table 1 and are shown in Figures 1 and 2.

Figure 1 shows the backlash characteristic of the piston–cylinder combination. The characteristic clearance is defined as the difference between the cylinder dimension and the piston dimension measured 12.5 mm from the bottom edge of the piston in a plane perpendicular to the axis of the crankshaft.

The border clearance for the 359 engine was 0.3 mm. As can be seen from the figure, the clearances after 750 starts are within 0.115 mm for the second cylinder to 0.17 mm for the sixth cylinder, i.e., they have not reached the limit value. Figure 2 shows the average wear of cylinder liners after 750 starts. This consumption ranges from 0.038 mm for the second cylinder to 0.058 mm for the sixth cylinder. The average piston wear after 750 starts is shown in Figure 3. It ranged from 0.03 mm for the fourth and sixth pistons to 0.12 for the second piston.

In the case of the second engine cylinder, there was an accelerated wear of the cylinder liner surface as a result of an uncontrolled breaking of the oil film continuity between the upper sealing ring and the cylinder surface. It is closely related to the course of the combustion process and the increase in the average working pressure in this cylinder. Six-cylinder in-line engines are fully balanced in terms of first- and second-order

Figure 1: Characteristic loose piston–cylinder pair after 750 starts.

Figure 2: Average wear of cylinder liners after 750 starts.

Figure 3: Average piston wear after 750 starts.

forces and moments of inertia. Therefore, taking into account the coordinate measurements of the geometry of the main engine assembly and the high accuracy in terms of the machined working surfaces and roughness topography, it can be said with high probability that the intensification of the wear of the two cylinder liners was influenced by the rapid course of the combustion process. This fact was confirmed by measurements of fuel doses of all cylinders fed to the combustion chamber, which indicates an over 10% increase in the supplied amount of fuel for cylinder 2. Such a change in engine operation parameters leads to an increase in pressure working in this cylinder and uneven distribution of unit pressure of sealing rings to the cylinder surface. This fact is confirmed by measurements of material structures and shape stereometry. The existence of such operating conditions allows us to assess the influence of the increase in the working pressure of the medium in the combustion chamber on the increase in the wear of the cylinder liner

and other mechanisms of the main engine assembly. In the long run, this will lead to a non-linear spike in wear and damage to the motor.

Table 1 shows the maximum values of cylinder liner wear for subsequent series of starts. The highest wear of the cylinder liner occurs in the fifth start-up cycle and is 0.052 mm.

In quantitative terms, the average of the maximum consumption is the highest for the 600–750 start-up series. It was respectively for individual temperatures: 0.078 mm for a temperature of 258 K, 0.052 mm for 268 K, and 0.046 mm for a temperature of 273 K. Five series of 359 engine starts were also carried out at temperatures of 273, 268, 263, and 258 K with 150 starts in each series. The tests were carried out as described previously for a temperature of 268 K. The results are shown in Figure 4. Simulation models will be included in further research.

The lowest wear occurred on the central cylinders.

Comparing these values with the average of the cylinder liner wear (not presented in the article), it was observed that the correctness remained. The increase in the number of starts caused an increase in the amount of wear, and a decrease in the temperature of the start caused the amount of wear to increase. Only the consumption values changed. The average of the maximum consumption of cylinder liners ranged from 18.9% for the first series of 150 starts at 258 K to 36.8% for 750 starts at 273 K.

Also in other cases, the conclusions based on the analysis of wear values for the average of the average cylinder liner wear were confirmed by the analysis of the average maximum cylinder liner wear. General relationships did not change despite the change in individual numerical values.

3.3 Approximation of the cylinder surface wear graph

Using the amount of wear after 750 starts (intervals of 150 starts), the number of starts at limit consumption was calculated. The course of the graph showing cylinder wear as a function of start-ups was approximated by the classic least squares method. Calculations were carried out using a computer program. Among the polynomials tested, the best approximation was obtained using the fifth degree polynomial. Approximate results of approximation are shown in Figure 5. In the case of average cylinder liner wear, the wear graph in the

Figure 4: Average of the maximum wear of cylinder liners.

Figure 5: An approximate approximation of the average cylinder liner wear as a function of start-ups (wear limit $x = 963$, $y = 0.16$) at an ambient temperature of 268 K.

function of start-ups was approximated and then interpolated to the limit wear value. The limit value for the piston–cylinder combination clearance provided by the manufacturer for the 359 engine was 0.30 mm. Assuming that the average wear of the pistons was 0.00 mm and the average mounting clearance was 0.140 mm, the wear

limit value of the cylinder liner was 0.160 mm. The wear of the cylinder liner 0.160 mm corresponded to 963 starts.

The graphs of average cylinder liner wear were approximated.

As shown in Figure 5, it is possible to notice two lines of inflection of the average values of the wear waveforms

of cylinder liners. The first range covers the initial run-in period of the assembly, the flank of the piston, the sliding surface of the piston rings, and the running surface of the cylinder running surface. Intensification of initial wear results from a large share of mixed friction in the initial period of running-in of selected kinematic pairs. To reduce this, a lubricating oil with increased dynamic viscosity can be used, with a simultaneous increase in internal friction resistance in the oil film in the entire operating temperature range. The initial run-in period was completed with approximately 150 run-in cycles. Then you can see a slight wear pattern of the working surface of the cylinder running surface until about 400 starting cycles. After this period of operation, the wear of the cylinder liner suddenly increases. It is mainly related to the build-up of axial play and angular increase displacement of the piston axis. As a result, there are increased angular tilts of the piston rings in the piston grooves. The effect of these changes is a sudden reduction in the thickness of the oil film especially on the upper sealing ring at the end of the compression stroke and the beginning of the expansion stroke. This results in a further increase in the proportion of mixed friction and wear of the working surfaces of these assemblies. A sudden increase in the wear of the working surface of the cylinder occurs as a result of an increase in the clearance of the piston pin and an increase in the effect of gas forces in the labyrinth spaces of the piston rings. Therefore, there is a rapid wear of the side and rear piston rings and rapid increases in pressure of working gases in the working spaces. In extreme cases, this causes turbulent gas flow and sudden changes in the position of the rings in the piston grooves. This results in rapid wear of the cylinder lining and loss of tightness in the combustion chamber. Therefore, to reduce the effects of these activities, great attention should be paid to the construction of the main engine assembly and the geometry of these assemblies should be designed in such a way as to maximize the thickness of the oil film. It should be remembered that any attempt to reduce the friction losses of this assembly leads to a decrease in the thickness of the oil film and an increase in the share of mixed friction in the entire engine operation cycle. For comparison, cumulative trend lines were made for the subsequent start-up cycles, a large share of the boundary friction can be seen. For comparison, several model-based simulations were performed [22–25]. They consisted in the assessment of the wear rate depending on the angular changes in the position of the piston, comparable to the experimental tests. All engine outputs were substituted according to the experimental model.

3.4 Comparison of the average wear of the 359 engine cylinders after the cold store tests with the wear values obtained after a long-term test on a dynamometer

In order to compare the consumption of low temperatures obtained in the chamber after 750 engine starts at 268 K with engine wear after a test of 550 h of work on the dynamometer, the following formulas were used. The average wear of cylinder liners after 550 h of engine operation on the dynamometer was 0.018 mm, while after a series of 750 starts, 0.046 mm.

Consumption was calculated, which corresponded to 1 h of engine operation on the dynamometer:

$$\frac{0.018}{550} = 33 \times 10^{-5} \text{ mm h}^{-1}. \quad (1)$$

Consumption after 750 starts was equivalent to consumption after 1,394 h of engine operation on the dynamometer

$$\frac{0.046}{3.3 \times 10^{-5}} = 1,394 \text{ h}, \quad (2)$$

$$\frac{1,394}{750} = 1.86 \text{ h}. \quad (3)$$

So one start corresponded to 1.86 h of work on the dynamometer.

Reitz (2013) stated on the basis of tests that one start-up at 258 K is equivalent to the consumption of 2–3 h of forced dynamics.

3.5 Comparison of type 359 engine wear after refrigeration tests with wear values occurring during the operation of the engine in a car

The tests also made it possible to determine the course of operation (in the scope of normal operation of the engine in a car) corresponding to one start-up.

In order to compare the wear occurring during start-ups in the cold room with the wear and tear, calculations were made taking into account the average wear of the cylinder liners. After 750 starts (at 268 K ambient temperature), the average cylinder liner wear was 0.046 mm, and after 550 h of engine operation on the dynamometer 0.018 mm. One start caused wear such as after 1.82 h of work on the dynamometer. Assuming the average engine wear of the 359 after a long-term test (550 h) on the dynamometer is the same as after a car mileage of

30,000 km, it was calculated that one start-up and warm-up of the engine at 268 K causes wear like after a mileage:

$$\frac{1.82 \times 30,000}{550} = 99.2 \text{ km.} \quad (4)$$

Results of the authors' research mentioned in the works [2,3,10,16,18].

R. W. Kugel – one engine starts at 273 K wear such as after 80 km and at 263 K – 150 km.

D. W. Lewin – one start-up at a temperature of 255 K caused such as after 210 km.

D. P. Vilkanow – one start-up after a night's stop in a cold caused engine wear, such as after driving a car 180–200 km.

M. A. Grigorev – one start in winter caused wear over the engine, such as after driving a car 63.6 km.

L. J. Demianov – one start-up in the winter and warm-up was synonymous with the effects of a car 15–17 km.

S. B. Stouffer – one start-up temperature at 263 K corresponded to the same consumption as after driving 10 km.

From the research presented above, the authors show that the data of S. B. Stouffer and L. J. Demianova deviate from the norm.

The results obtained in this work were in good agreement with the results of tests previously carried out (presented above).

Considering that one start-up and warm-up of the engine at 268 K corresponds to a mileage of 99.2 km, and about 1,000 starts (average cylinder wear) would qualify the cylinder liners for replacement ("wet" cylinder liners), it would mean that the car could run about 100,000 km to replace the cylinder liners. Referring to economic aspects in 2020, the cost of replacing cylinder liners with respect to the 359 engine unit is estimated at PLN 660 net of spare parts price (furthermore parts resulting from the technological repair process in the amount of PLN 200) and PLN 1,600 net of labor costs.

4 Conclusions

The presented own research allowed us to formulate the following conclusions:

1. The initial layer of engine oil retained on the TPC friction surfaces (piston–rings–cylinder) did not provide sufficient lubrication during engine start-up at negative ambient temperatures.

2. After starting the engine, a certain amount of time was needed to supply a sufficient amount of lubricating oil to the TPC parts. This time depended on the oil properties, starting method, and lubrication system design solutions.
3. The rate and amount of wear of engine components during start-up and warming up in negative temperatures was always higher than in positive temperatures, despite the same number of crankshaft revolutions at idle or the same load.
4. Consumption could be reduced by creating the right starting conditions. This was achieved by using appropriate engine oils and using methods that allow easier engine starting at low temperatures.
5. The technical condition of the piston–cylinder assembly parts after 750 starts and engine warm-up at 268 K is generally satisfactory.
6. It was found that the cylinder wear after tests (750 starts) did not exceed the values given by the vehicle manufacturer.
7. The typical character of cylinder liner wear was found, i.e., maximum wear in the area of the first sealing ring in the head turn (ZG).
8. It was calculated that the wear of the 359 cylinder liner after one start-up at 268 K corresponds to the wear after the engine has been running on the dynamometer for a period of 1.82 h (reliability test) and wear as after driving 99.2 km in normal operation.
9. Using approximation and then interpolation of the graph of cylinder liner wear, it was found that the border wear of the cylinder liner, i.e., 0.160 mm, will occur after 963' starts-up at 268 K.
10. Considering only start-ups at 268 K, they would indicate that the car could run about 100,000 km to replace the cylinder liners.
11. The number of starts at low ambient temperatures affects the number of kilometers driven by the car during operation to replace the cylinder liners (engine repair).
12. The cost of replacing cylinder liners with respect to the 359 engine unit is estimated at PLN 660 net of spare parts price and PLN 1,600 net of labor costs.

Summing up the authors' considerations regarding the impact of compression ignition engine type 359 start-ups at low ambient temperatures on the economical exploitation period, they do not fully exhaust the essence of the issue, but are merely an attempt to signal the complexity of the studied problems regarding the further operation of these propulsion units in type vehicles (STAR 200, 244, and 266).

References

- 1 Gunther H. Diagnosing diesel engines. Warsaw: WKŁ; 2018. p. 45–7 (in Polish).
- 2 Reitz RD. Directions in internal combustion engine research. *Combust Flame*. 2013;160(1):1–8.
- 3 Stouffer SB, Lewis AB, Whitney TJ, Drake ML. Diesel cold start improvement using thermal management techniques. University of Drayton Research Institute. Final report. UDR-TR-2000-0013; 2000.
- 4 Zhong L, Gruenewald S, Henein N, Bryzik W. Lower temperature limits for cold starting of diesel engine with a common rail fuel injection system. SAE technical paper 2007010934; 2007.
- 5 Yun H, Reitz RD. Combustion optimization in the low-temperature diesel combustion regime. *Int J Engine Res*. 2005;6(5):513–24.
- 6 Austen W, Lyn WT. Some investigations on cold starting phenomena in diesel engines. *Proc Inst Mech Eng Automob Div*. 1959;13(1):111–23.
- 7 Belousov JS. Analysis of operation of cold diesel engines. Russia: Novosibirsk State Technical University; 1979.
- 8 Biddulph TW, Lyn WT. Unaided starting of diesel engines. SAE technical paper 680103; 1963.
- 9 Bryzik W, Henein NA. Fundamental cold start phenomena within advanced military diesel engines. 19th Army science conference, Orlando, Florida, USA; 1994R.
- 10 Lindl B, Schmitz HG. Cold start equipment for diesel direct injection engine. SAE technical paper 1999011244; 1999.
- 11 Golovin AM. Investigation of the wear of the sleeve-piston group of a diesel engine with a gun-heating in conditions of low ambient temperatures. Diesel engine operation at low temperatures. Irkutsk, Russia 1977 (in Russian).
- 12 Bernhardt M. Internal combustion engines. Warsaw: WKŁ; 1978. p. 23–5 (in Polish).
- 13 Bernhardt M, Dobrzyński ST, Loth E. Car engines. Warsaw: WKŁ; 1987. p. 45–7 (in Polish).
- 14 Mikulin JuV. The possibility of reducing the starting wear of a diesel engine in winter. *Automot Ind*. 1966;6:34–9.
- 15 Licharovic A. Cylinder and piston wear when starting a diesel engine at low temperatures. *J Mech Eng Sci*. 1965;7(3):87–92.
- 16 Grigoriev MA, Pavliskiy VM. Features of cylinder wear during engine start-up and warm-up. *Automot Ind*. 1977;12(3):3–5.
- 17 Bolt AJ, Henein NA. The effect of some engine variables on ignition delay and other combustion phenomena in a diesel engine. *Proc Inst Mech Eng Conf Proc*. 1969;184(10):130–6.
- 18 Henein NA. Diesel cold starting. A phenomenological model. ASME energy sources technology conference. Paper No. 93-ICE; 1993. p. 24–33.
- 19 Annand WJD, Pinfold D. Heat transfer in the cylinder of a motored reciprocating. in automotive engineering congress and exposition. SAE technical paper 800457; 1980. p. 45–55.
- 20 Dempsey AB, Walker NR, Gingrich E, Reitz RD. Comparison of low temperature combustion strategies for advanced compression ignition engines with a focus on controllability. *J Combust Sci Technol*. 2014;186(2):210–41.
- 21 Mukhopadhyay S, Badavath S, Henein N. Direct injection compression ignition engine: cold start on gasoline and diesel. SAE technical paper 2017010699; 1999.
- 22 Wróblewski P. Technology for obtaining asymmetries of stereometric shapes of the sealing rings sliding surfaces for selected anti-wear coatings. SAE powertrains, fuels and lubricants meeting. SAE technical paper 2020-01-2229. SAE International, USA; 2020.
- 23 Wróblewski P, Iskra A. Problems of reducing friction losses of a piston-ring-cylinder configuration in a combustion piston engine with an increased isochoric pressure gain. SAE powertrains, fuels and lubricants meeting. SAE technical paper 2020-01-2227. SAE International, USA; 2020.
- 24 Wróblewski P. Effect of asymmetric elliptical shapes of the sealing ring sliding surface on the main parameters of the oil film. *Combust Engines*. 2017;168(1):84–93.
- 25 Wróblewski P. The impact of the asymmetric shapes of sliding surfaces of sealing rings on the mechanical efficiency of the reciprocating combustion engine. Dissertation. Publishing House of Poznań University of Technology; 2018.