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RESEARCH PERFORMANCE OF NOVEL DESIGN OF DIESEL ENGINE

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Abstract

Certain results of the comparative studies of the high-speed Diesel engine V-12 of the "W" series were presented in the article. The engine was modernised in regard of possibilities to achieve better performances at specific fuel consumption, smaller exhaust emission, smaller scavenge, lower noise and better thermal stability. The subject of this work is the piston cast of novel composite silumin. The development of novel composite silumin (aluminium-silicon alloy), which contains a little more Copper and Nickel, and the introduction of novel alloyed elements, such as Chromium, Molybdenum, Tungsten, increases the strength of the alloy and its thermal stability during successive heating and cooling. The pistons made of this alloy may have a little bigger outside diameter than the pistons made of PA-12 standard alloy, and a smaller clearance between the piston and cylinder liner. The pistons made of standard and novel alloy were mounted successively in the "W" engine. The full load and part load curves were determined. The lubrication oil consumption, fuel consumption, exhaust emission, blow-by and noise were determined too. The article presents the results of the above-mentioned research. The novel composite alloy enables further engine modernization because the engine should operate at higher pressure and temperature in the combustion chamber.

Keywords: *internal combustion engine, Diesel engine, engine piston, composite alloy, thermal stability*

1. Introduction

Since the invention of piston combustion engines, there has always been a continuous strive for obtaining an engine with the biggest power output from an engine displacement unit and a mass unit, with the least fuel consumption and good functional properties, which is expected by users, and the smallest flue gas emissions, which is required by the legislature [1-2]. Developing a new engine is a very difficult task, burdened with a high risk of failure. Therefore, more and more often we are looking for a way to increase engine performance through modernization, since it allows a more reliable achievement of the goal. Engine users report a need for engines of greater power, since they strive for better and better operational effectiveness, and in addition, they would like to combine more devices into blocks. The S12-U engine, which was the subject of the research, is an engine on mainly military application. Among others, it is used to power tanks. Tank users require the tanks to have high manoeuvrability and, apart from that, their weight is increasing, since additional devices are being installed, which improve the crew's performance and the effectiveness of the operations [9, 10]. Hence, the need for engine modernization. One of the problems, which required a solution, was the development of new pistons, which would be characterized by a higher strength and better dimensional stability [13, 14, 15]. Furthermore, the idea was to facilitate piston-manufacturing techniques, namely, changing the manufacturing method from forging to casting of semi-finished piston products.

The work involved developing a new material, which would meet the aforementioned requirements. As a result of comprehensive studies, composite silumin was developed, which is characterized by better dimensional stability and higher strength, over a wide range of engine operating temperatures. This article presents the most interesting results related to these studies. Next, a series of pistons was made from the developed material, and used in engine testing. Improvement of dimensional stability of the piston material enables a decrease of the operating clearance between the piston and the cylinder. As a result, the following could be expected: lower consumption of lubrication oil, lower scavenge to the crankcase, lower operating noise of the engine, decreased exhaust toxicity, and most of all, lower hydrocarbon (HC) emissions. In addition, the engine power slightly increased and the unit fuel consumption decreased. The development of the novel composite silumin allows further modernization of the engine, aimed at increasing the power, since the material has better strength at growing piston operating temperature.

2. Study aim and object

The aim of the study was to determine the differences in the engine′s performance and operating parameters, after the installation of pistons cast from the new composite alloy, in comparison to an engine with pistons forged from the AK12 alloy, which were by default used in engines of the ″W″ series [5, 6, 7, 8, 11, 12, 16, 17]. The new aluminium-based composite alloy is characterized by a greater Cu and Ni content and the introduction of previously unused elements, such as Cr, Mo, W. The Mg content however was decreased in comparison to standard aluminium cast alloys. The composition of the previously used AK12 alloys and the new composite alloy are given in table 1.

Tab. 1. The comparison of the aluminium alloy composition for the tested pistons at % Wt

	Si	Cu	Mg	Ni	Fe	Ti	Cr	Mo	W	V	Mn	Zu	Other total
1	10.5 -12.5	0.5 -1.5	0.8 -1.8	0.5 -1.5	≤0.7	≤0.1	-	-	-	-	<0.2	<0.2	≤0.15
2	11.5 -12.5	3.0 -4.0	0.3 -0.6	4.0 -5.0	≤0.5		0.05 -0.08	0.05 -0.08	0.05 -0.08	0.05 -0.08	0.20 -0.35	-	

(Comparison of the chemical composition of near-eutectic silumin for pistons)

1. AK12 silumin for forged pistons
2. Tested composite silumin

Prior to executing new pistons with the use of the novel composite material, comprehensive material tests were performed, involving:

- strength testing in ambient and increased temperatures (up to the temperature increasing the operating temperature of piston engines);
- dimensional stability testing of the alloy after cyclic heating and cooling of the material samples;
- heat treatment testing (single and multi-phase);
- seizure resistance testing.

Dimensional stability studies were particularly important in relation to piston material testing, since they enabled decreasing oil consumption; scavenge to the crankcase and the mission of toxic exhaust components – mainly hydrocarbons. The tested samples of the new composite silumin showed the same values of the thermal expansion coefficient during heating and cooling of the alloy, in the temperature range from 20°C to 350°C (which can be seen in fig. 1). Samples cut out from pistons made from the AK12 alloy show big differences in the thermal expansion coefficient during heating and cooling (fig. 2). It causes the occurrence of larger piston deformation during the engine operation and the need to maintain larger clearances between the piston and the cylinder.

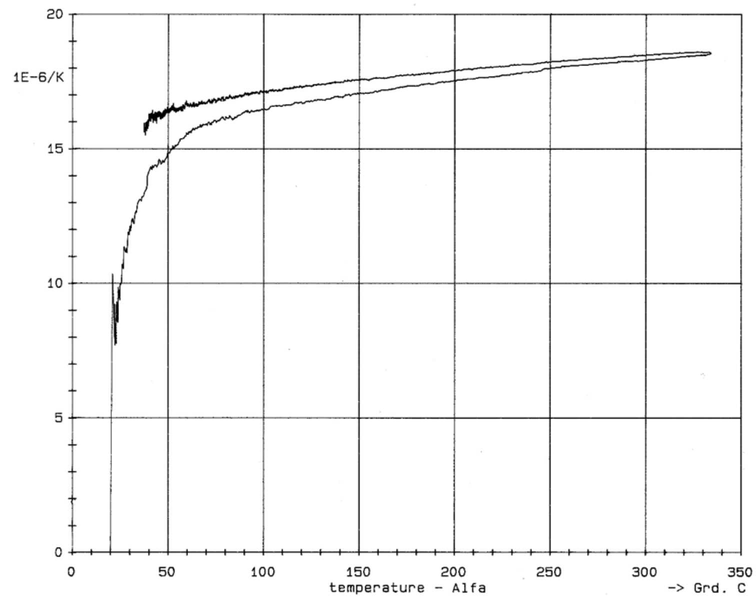

Fig. 1. Thermal expansion coefficient as a function of temperature from ambient temperature to 350°C during heating and cooling of the novel composite alloy

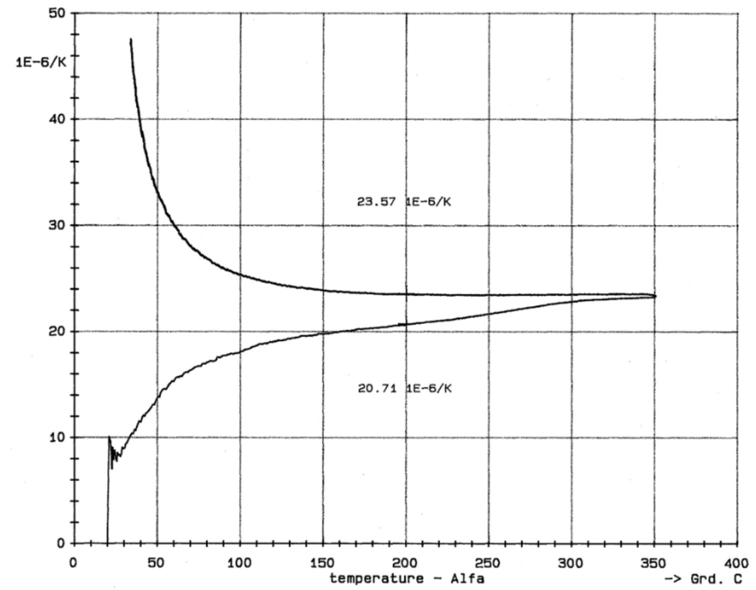

Fig. 2. Thermal expansion coefficient as a function of temperature from ambient temperature to 350°C during heating and cooling of the forged piston PA alloy

During the strength testing of the new composite silumin, the impact of different alloy elements on the tensile strength and hardness of silumin in ambient temperatures and increased temperatures up to 350°C was comprehensively studied. The suggested alloy composition (table 1) showed the best properties, both, at ambient temperature, as well as in increased temperatures up to 350°C. Fig. 3 shows the relationship between the tensile strength in the temperature function of alloys containing different amount of tungsten. The difference in tensile strength in ambient temperature was 30% and in 350°C was about 75%. The highest strength over the entire temperature range was demonstrated by an alloy with tungsten content of 0.7%. The effects in terms of dimensional stability and strength of the alloy were achieved through the introduction of a large number of alloy elements, about 22% wt. (19.2%-22.77%). In the case of previously used pistons, about 15% (12.4%-17.3%). In the case of the new piston silumin, we can also notice a smaller interval between the minimum and maximum content of additives in alloy series.

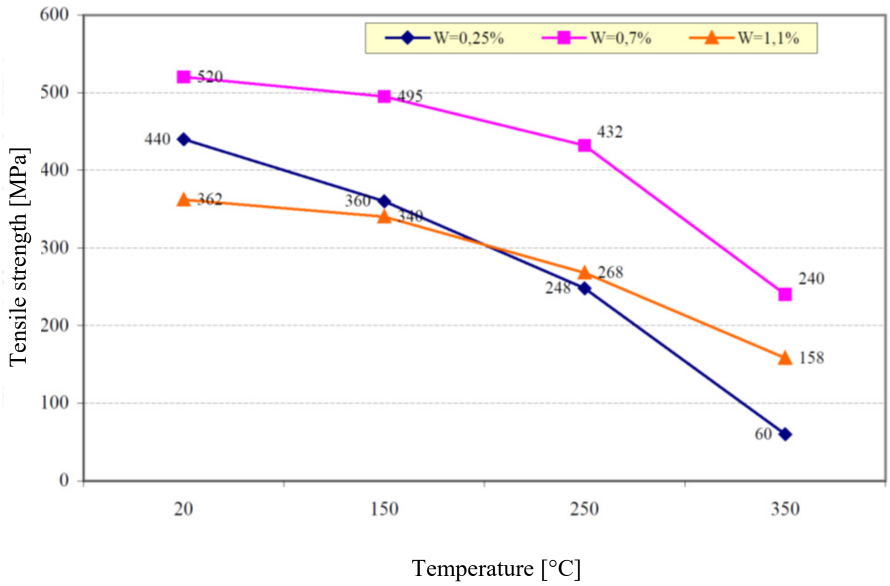

Fig. 3. The relationship of tensile strength in the temperature function of alloys containing different amount of tungsten

The comparative studies of engine pistons were performed on the Wola "W" engine. It is a V-12, four-stroke engine with compression ignition, direct injection, liquid-cooled with mechanical supercharging. The engine is presented in Fig. 4. Engine data: cylinder diameter 150 m, displacement 38.88 dm^3, nominal power 625 kW at 2000 RPM, maximum torque 3360 Nm at 1350 RPM. The engine is mainly used to drive military vehicles (tanks) but can also be used for construction and industrial machines. Due to the application, less attention is being paid to such issues as the wear of consumables and exhaust toxicity, although they are also very important factors.

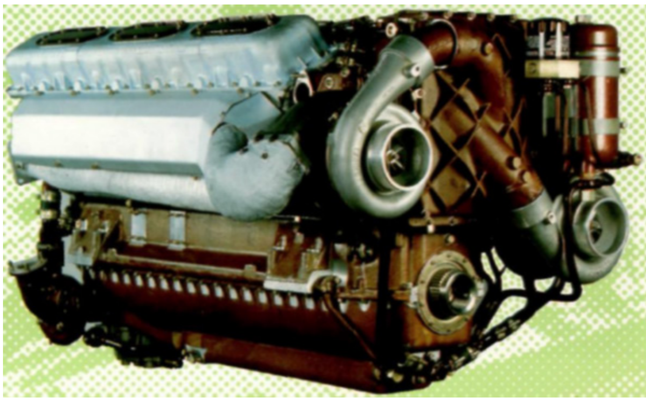

Fig. 4. View of the tested S12-U engine

The study was of comparative nature, thus, the first stage involved testing the engine with previously used pistons, and next, the second stage, involved testing the engine with the new composite silumin pistons. The first, as well as the second, stages of the tests involved the use of new elements cooperating with the pistons, namely: new cylinder liners, new piston rings, new piston pins, as well as new piston slide bearing of the crankshaft and connecting rods. The engine was subject to the same breaking in procedures for 150 min. Next, a factory test lasting 90 min. was conducted, in order to determine the actual engine performance. If an engine met the requirements, and it did in these case, then the next test would commence, which involve the determination of the external characteristics (the relationship of power, torque, unit fuel consumption in a function of the revolution speed of an engine at full load – maximum fuel dosage) and load characteristics (unit fuel consumption in the engine load function). The tests also involved the determination of the maximum pressure in one cylinder and the content of toxic component in exhausts (CO, HC, NO_x and smoke level of exhaust gases).

3. Results of engine tests

The full load performance was determined at the revolution speed of 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 1950, 2000 RPM, after stabilizing the engine operation, from the highest revolution speed to the lowest. Fig. 5, 6, 7 compares selected, most interesting test results – external characteristics of an engine with standard AK12 alloy pistons with the new composite silumin pistons. Fig. 5 compares the engine power waveforms.

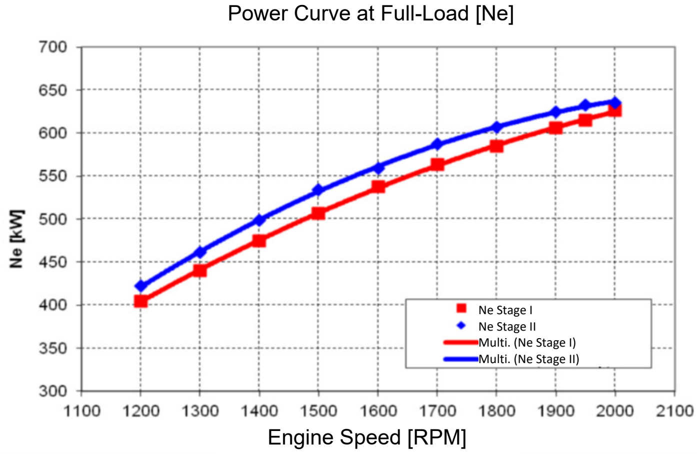

Fig. 5. Comparison of the S12-U power with pistons made of novel composite alloy and PA alloy forged piston

The figure shows that the power of the engine with pistons made of novel composite silumin was larger over the entire engine operating range by 1.5% to 2%. The waveform of the torque of an engine with pistons made from the new composite silumin was also, along the entire range of revolution speeds, higher than the AK12 silumin pistons. Fig. 6 compares waveforms of unit fuel consumption (BSFC). Unit fuel consumption was lower over the entire operating range of the engine by about 4% [3, 4].

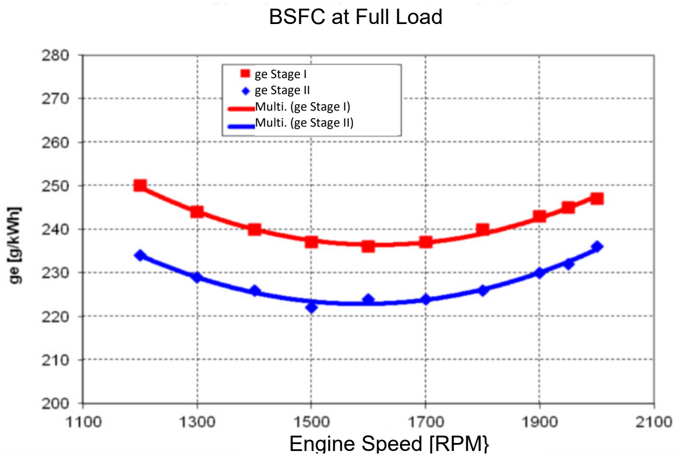

Fig. 6. Comparison of specific fuel consumption (BSFC) as an engine speed function of the tested S12-U engine with pistons made of novel composite alloy and PA alloy forged pistons at full load operation

Fig. 7 compares the waveform of hydrocarbon emissions in external characteristic conditions. In this case, the effects were largest. HC emissions in the case of the engine with pistons made of new composite silumin greater by as much as 24% than in engines with standard pistons. Similar effects were obtained in terms of other test results, involving maximum pressure in the cylinder and other toxic components both, in the case of external characteristics as well as load performance. It needs to be emphasized that absolute test effects are impacted by other factors associated with the engine's operation, mainly, the operation of the fuel equipment and control parameters of the engine. Therefore, a higher number of test results for a larger number of engines is necessary, in order to determine the actual effects of using the new piston material.

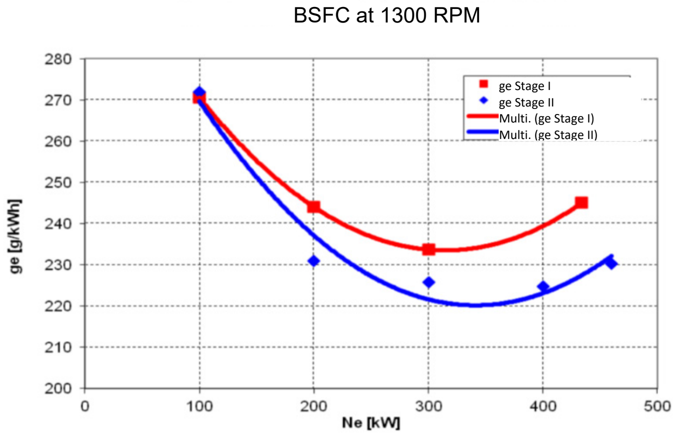

Fig. 7 Comparison of hydrocarbon (HC) emissions as an engine speed function of the tested S12-U engine with pistons made from novel composite alloy

Oil consumption tests were very labour-intensive, since one trial lasted for 300 min., not counting the time of reaching stable operating conditions. It resulted from the need to ensure high measurement accuracy in the case of oil in the oil sump. The tests were conducted according to a specially developed methodology at 800, 1400, 1600, 1800 and 2000 RPM. The engine worked for 20 min. at each revolution speed at 1250 Nm, 1850 Nm and 2450 Nm loads, and between individual loadings, the engine worked for 5 min. at minimum load (0-300 Nm) and a revolution speed of 800 RPM. Therefore, during the measurements, the engine worked for 220 min. under load, 60 min. in idle run and 20 min. in stabilizing run. During the measurements, the engine operated at 1800 RPM and at full load (as in the case of external characteristics), stabilized outlet oil temperature of 95ºC and the cooling liquid engine outlet temperature of 90ºC. Fig. 8, 9 present oil consumption for an engine during the tests of an engine with standard pistons and novel composite silumin pistons.

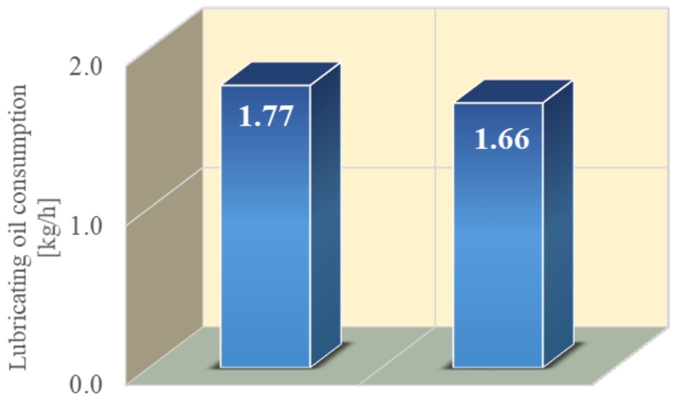

Fig. 8. Hourly consumption of lubricating oil of the S12-U with pistons made of novel composite alloy

When comparing the results, it can be concluded that an engine with pistons made from the new composite material was characterized by lower oil consumption by 11% to 36%, with result dispersion, and in the case of a standard piston engine, as well as pistons from new composite silumin, by about 10%. Decreasing oil consumption, similarly to reducing HC emissions, shows how much of an impact on these parameters (effects) decreasing the clearance between the piston and the cylinder has. Pistons with new silumin had, in fact, a slightly changed outline of the piston jacket and the ring section, due to an increase of certain diameters. Consequently, the clearance between the cylinder and the piston decreased by about 16%. Piston rings have the greatest impact on oil consumption, but in the case of these tests, a set of piston rings was identical, therefore, the difference in oil consumption may be attributed to decreasing the clearance between the cylinder and the piston.

Fig. 9. Hourly consumption of lubricating oil of the S12-U with pistons made of novel composite alloy PA alloy of forget piston

After conducting full tests on an engine test bench, the engine was dismantled and the pistons as well as cooperating elements, in order to identify deformations and wear, were subjected to visual inspection and micrometric measurements. The appearance of the pistons after the testing, both in the case of standard, as well as the ones made from composite silumin, was similar like in the case of production engines. Carbon deposit accumulated in the areas between the valves and on the right side, looking from the front of the engine. Whereas clear traces of the cooperation between the piston and the cylinder liner appeared on the left side. It is similar in the case of visual inspections of pistons after production engine testing. It could indicate that there is a need to correct the position of the piston pin relative to the piston bottom, since a piston in a reciprocating motion moves revolutionly around the axis of the pin so that one side of the piston is more loaded. As far as the number of deposits on the piston is concerned, it is comparable in both cases. Fig. 10 presents the appearance of the pistons after an engine test, which shows the places of deposit accumulation on the piston bottom and piston jacket. Due to the facts that a piston jacket is graphitic, these traces may seem less clear.

Fig. 10. View of the novel composite alloy pistons after engine testing

Fig. 11 presents a view of a piston after engine testing. We can see visible traces of the cooperation between the piston jacket and the cylinder liner. On the opposite (invisible) side, we can see an increased number of deposits. Fig. 12 shows the appearance of pistons after engine testing, on the side opposite to Fig. 11. We can clearly see an increased number of deposits, while there are no traces of cooperation with the cylinder liner.

Fig. 11. Friction markers formed on a piston surface which appear during engine operation

Fig. 12. View of piston carbon deposits opposite to Fig. 11

Therefore, as a result of extensive studies regarding the piston composite material and engine tests such pistons were developed, which could replace the previously used ones with a benefit for the engine's performance. Nonetheless, there are further possibilities of improving the effects of replacing standard pistons, which requires further studies.

5. Conclusions

Engine tests of pistons made of newly developed aluminium alloy were conducted on a Diesel engine and were of comparative nature. The first stage involved testing and engine with standard pistons, forged from AK12 alloy. Then, in the second stage, an engine with pistons cast from the new composite silumin was tested. These comparative studies allow us to draw the following conclusions:

- The engine with composite aluminium pistons showed slightly more power along the entire full load performance and output load and a bigger torque, smaller unit fuel consumption and less exhaust toxicity than the engine with AK12 forged pistons;

- The engine with pistons made from novel composite silumin showed less fuel consumption in the test according to the standard test methodology for that engine, than the engine with AK12 forged pistons.
- After dismantling the pistons from the engine after the engine tests with new composite silumin pistons, as well as standard pistons, it was found that traces of cooperation between the cylinder liner and pistons rings, and the nature of deposits on the external surface and the bottom of the pistons were similar in relation to both piston types;
- Pistons made from the new composite silumin were characterized by better (higher) dimensional stability than standard pistons, which enabled the increase of certain external dimensions of the piston and decrease the clearances between the piston and the cylinder;
- Decreasing the clearances between the piston and the cylinder resulted in reduced oil consumption of the engine and a decreased scavenge to the crankcase, which is confirmed by the test results;
- The new composite aluminium alloy is characterized by greater strength in ambient temperature, as well as the operating temperature in the engine;
- Decreasing the clearances between the piston and the cylinder in the engine with pistons made from the new composite alloy had a particularly beneficial impact on reducing hydrocarbon emissions (approximately 24%).
- Due to the improved dimensional stability of the pistons, after operating in an engine at different loads and with higher strength of the new alloy, there is a possibility of further engine modernization, aimed at improving its performance;
- In the case of a significant increase of the engine power, it will be, however, necessary additionally to cool the pistons.

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