Five-stroke Internal Combustion Engine - yesterday, today and tomorrow

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Abstract. The article presents an overview of nowadays and historical internal combustion engines, in which additional expansion of exhaust gases in a separate cylinder was used, presently often called five-stroke engines. This operation is oriented towards maximizing the energy recovery of exhaust gases in order to increase the efficiency of an engine. Engines of this type developed at the end of the 19th century by constructors such as Gottlieb Daimler, Nicolaus Otto, Rudolf Diesel or Fernand Forest did not fully meet the hopes placed in them and the concept of additional expansion of exhaust gases was abandoned at that time. This returned in a turbocharged version at the beginning of the 21st century with engines constructed with the participation of Gerhard Schmitz. A similar engine was also built with a substantial contribution of the author of the article in 2011-2013 at the Cracow University of Technology on the basis of the existing four-cylinder spark-ignition engine. The article presents the advantages and disadvantages of a five-stroke engine and the main differences between modern solutions. The directions of development of this type of design and potential areas of its practical application were also presented.

1. Introduction
Emissions of toxic components and CO₂ and the depletion of fossil fuel resources cause almost certain that in the near future internal combustion engines will be replaced in road vehicles by an electric drive. This is not an easy way, because despite the undeniable advantages, such as the reversibility of the electric machine operation and the possibility of regenerative braking [1], many difficulties arise in the development of electromobility. The main problem is the relatively low energy density of currently available batteries causing serious problem with available range of vehicle [2] [3], another issue is the time of charging [4]. This means that at least the next 20-30 years, internal combustion engine will be still used to drive vehicles. Undoubtedly, more and more often in combination with an electric machine in a hybrid propulsion system, which allows for a significant reduction of fuel consumption by vehicles, especially in urban traffic. In any case, there is a constant need to develop this propulsion source, especially in the context of reducing CO₂ emissions and toxic exhaust components.

The piston combustion engine, refined to a form reminiscent of nowadays designs of this propulsion source, was made in 1876 in Germany [5]. As it is commonly known, it was never a device that was characterised by notably high efficiency of energy conversion coming from with fuel combustion. For this reason, the desire to increase the efficiency was the goal of many constructors and inventors working on the development of the internal combustion engine almost from the creation of the first designs that found application for drive of various machines. There are many methods and means to improve the energy conversion efficiency of fuel combustion to mechanical work of an internal combustion engine.
It can be mentioned here, for example, reduction of engine mechanical losses [6], decreasing of thermal losses [7] [8], reduction of pumping losses in the spark ignition engine [5], the use of alternative fuels, among others waste fuels, the use of which modifies the engine combustion system that it allows the increase of its effective efficiency [9] [10] [11], or the use of equipment for the waste heat recovery [12]. Among these methods and means, a quite special place belongs to increasing the expansion ratio of the working medium with reference to classical spark-ignition engines as well as with compression-ignition engines [13].

2. Methods of increasing the engine expansion ratio

Increasing the expansion ratio of the cylinder charge allows for the recovery of a larger portion of energy obtained during fuel combustion than it takes place in a classical engine. This issue was the subject of many theoretical studies [14], model-based research [15], as well as a large number of experimental studies conducted on real engines, for example [16].

At least four methods to increase the expansion ratio of the medium over its compression ratio in a piston engine are known:

- differentiation of the piston stroke length in the intake and compression strokes, comparing to the power and exhaust strokes - James Atkinson's engines [17],
- shortening of the effective length of the intake stroke by closing the intake valve before bottom dead centre (BDC), which, besides increasing the expansion ratio over effective compression ratio of an engine, also means internal cooling of the cylinder charge in a supercharged engine - Miller's idea [18],
- shortening the effective compression stroke length by delaying the closing of the intake valve far after BDC - modern piston engines, referred to as Atkinson cycle engines [19],
- the use of additional expansion of exhaust gases in a separate cylinder - a concept already known in the nineteenth as a compound-engine, or from the German Verbund-motor [20].

The concept of using additional expansion of exhaust gases came from steam engines. In the second half of the 19th century, some applications used steam engines with even triple expansion of the working medium. In relation to currently developed combustion engines with additional expansion of exhaust gases in a separate cylinder, the name of a five-stroke engine can be most often found.

Among the above methods, the article focuses on the so-called five-stroke engine, where increasing the expansion ratio consists in using the process of additional expansion of exhaust gases in a separate cylinder. Most often, these engines were built in a three-cylinder, in-line version. In two external cylinders of such an engine a four-stroke cycle is carried out. They are usually called high-pressure cylinders (HP), and that combustion occurs in them, also with the term fired cylinders. The shift of the working phase between HP cylinders is usually 360° of crank angle. Exhaust gases from the fired cylinders in the exhaust stroke are not released to ambient, but they get through properly made channels to the middle low-pressure cylinder (LP) with a significantly larger volume. As the crank of the central low pressure cylinder is rotated 180° in relation to the crank of the working cylinders, in this cylinder additional expansion of exhaust occurs - in the HP cylinder the piston moves upwards and in the larger cylinder LP downwards. The last one works in a two-stroke mode, receiving exhaust gases alternating from the outer HP cylinders. This arrangement of the engine cylinders (2xHP + LP) gives full use of the additional expansion cylinder, what in the two-cylinder version (HP + LP) would not be possible, although these engines were also known. When doubling the three-cylinder configuration, it is also possible to develop a six-cylinder in-line engine or a boxer engine.

The term "five-stroke engine" comes from the additional expansion of the charge in a separate cylinder, during which the energy recovery process takes place, and in a classic engine would be dissipated in the ambient. A simple addition of the number of strokes per working cycle in both engine cylinders (HP then LP) gives the result 6, however, it should be remembered that the stroke of the additional expansion of charge in a LP cylinder occurs at the same time as the exhaust stroke in a fired cylinder.
3. Historical engines with additional expansion process

The following part of the work presents some of the best-known historical solutions of internal combustion engines, where additional exhaust expansion has been applied. Their main features have been described, the available operating parameters or places of application are given. Modern five-stroke engines and an engine with additional exhaust gas expansion designed and still developed by the author of this work at the Cracow University of Technology are presented in the following sections of the article.

3.1. Deutz "Verbund-motor"

One of the first known internal combustion engine, which used double expansion of exhaust gases, was developed in 1879 in the Deutz company. The originator and engine designer was most likely Gottlieb Daimler, although in the book [21] the authorship of the design of this engine was attributed to Nicolaus Otto. The English patent, which protected the described solution, had the designated Daimler as the creator. At the initial stage of his engineering career, from 1861 to 1863, Gottlieb Daimler worked in England at a factory where machines and various types of machine tools were manufactured. Undoubtedly, during his practice in English machinery, he had to meet with a double expansion steam machine. The concept and the first copy of such a single-acting device was developed in England in 1781 by Jonathan Hornblower. In the Hornblower's machine, after the first expansion process in a smaller, high-pressure cylinder, steam underwent a second expansion process in a lower-pressure cylinder with a larger volume. Such an approach resulted in significantly higher efficiency of the steam engine. Hornblower did not develop his idea more, mainly because of intellectual property disputes with James Watt. Several decades later, it was done by Arthur Woolf, who developed many steam engines with two-stage expansion, both single- and double-acting. Woolf machines have spread in English factories and for this reason Gottlieb Daimler practicing, among others, at the factory in Manchester, could had opportunity to meet them.

The engine presented in figure 1 was built in the most common three-cylinder configuration, with two outer fired cylinders - a1 and a2 and a central, larger cylinder for additional expansion - b. In the diagram of part (a) of Figure 1, it can be seen that cranks for individual cylinders are arranged as described in a Section 2 of this work. HP cylinders operate with a 360° offset, while LP cylinder operation is offset by 180° relative to both HP cylinders.

![Figure 1. "Deutzer Verbund-Motor", a) scheme of the engine, b) general view](image)
a1, a2 - fired cylinders(HP), b - additional expansion cylinder(LP), c - bevel shaft for driving valves, d1, i d2 - exhaust valves of HP cylinders, e - exhaust valve of LP cylinder.

The engine was used to drive machinery in a sugar plant in town of Elsdorf, whose shareholder was Eugen Langen. The engine worked there for several years. The technical details of this design are not available. It is only known that the engine power was about 59 HP, while the specific consumption of light gas reached 1.0 m³/kWh. At the time, it was an average value for engines of this size, and the
greater degree of complication did not encourage for further development of the design. In 1884, the engine was returned from the sugar plant to the Deutz factory, where it was sent to the factory museum. Unfortunately, it was scrapped in 1925, when the museum was moved to the newly built building.

3.2. Rudolf Diesel's "Compound-Motor"
Rudolf Diesel, attracted by the positive effects of the multiple expansion in the steam engine, also built an internal combustion engine with a double expansion of the working medium. Diesel assumed the exceptionally high working pressure in its machine, which was to reach up to 250 bar. It caused that the idea of a double expansion of working medium seemed to be promising. The possibility to apply double expansion of exhaust was enrolled by Diesel in his first patent application from the end of 1891. The engine with a double exhaust expansion was built at the Maschinenfabrik in Augsburg since the beginning of 1896. The work did not proceed particularly fast, but eventually the engine was mounted on the test bench on July 20, 1897. A general view of Rudolf Diesel's Compound engine was presented in Figure 2.

![Figure 2. "Compound-Motor" developed by Rudolf Diesel.](image)

The Rudolf Diesel Compound engine arrangement was basically similar to that of the Deutz engine. The differences were that the fired cylinders worked simultaneously, without a 360° shift, what made that the low-pressure cylinder received exhaust for additional expansion one time only for two revolutions. The lower side of the piston in the LP cylinder was used for pre-compression of the air which then goes to the fired cylinders.

All pistons worked with a stroke of 400 mm. The bore of the additional expansion cylinder was 510 mm. Both fired cylinders had a bore of 220 mm (according to other sources 200 mm). The assumed nominal speed was 150 rpm. Diesel was hoping to get 148 HP. The first engine start took place on August 24, 1897. There were numerous engine problems requiring intervention. Longer, two and a half hour tests were carried out on November 3, 1897. Unfortunately, this engine did not live up to its hopes. The obtained power was significantly lower than Diesel assumed at the beginning - it did not exceed 98 HP. The specific fuel consumption was approximately 712 g / kW · h. This result was more than twice worse than that obtained by a single-cylinder ordinary Diesel engine. Significant energy losses occurred at the valves and in the channels between the cylinders, where the combustion occurred and the cylinder in which the additional expansion of the exhaust occurred. For relatively trouble-free operation, this part of the engine required efficient cooling, which drastically reduced the effects of additional exhaust expansion. Serious doubts are also raised by the fact that the HP cylinders are working simultaneously what caused most likely an idle run of the LP cylinder in one of the engine crankshaft revolutions.

For the last time, Rudolf Diesel's Compound engine worked at the end of 1897. Diesel was counting on using it to test components for other engines he was developing then, but Compound was soon scrapped. Diesel recalled in the following years that he was very disappointed, that he had to abandon
plans to improve the efficiency of the internal combustion engine with the use of additional exhaust expansion.

3.3. Forest and Gallice "Moteur Compound"
Fernand Forest was a French inventor and constructor of internal combustion engines of the second half of the 19th and beginning of the 20th century. He is not a figure particularly well known in the history of development of internal combustion engines, but it should be mentioned that it was one of the pioneers in the field of multi-cylinder internal combustion engines, but also the use of electric ignition. Forest constructed his engines mainly for the purpose of propelling boats [23]. Many innovative solutions were found in them, such as a mechanism for changing the direction of rotation of the motor shaft without stopping it. Among the many designs by Fernand Forest, there is also an engine with additional exhaust expansion. This engine was developed and then patented with Georges Gallice in 1888. The engine, the diagram of which is shown in figure 3, was built in in-line configuration, used petrol and equipped with an innovative at that time spark ignition system.

![Figure 3. Scheme of the "Moteur Compound" developed by Forest and Gallice [23].](image)

The engine has a total of four high-pressure cylinders and one cylinder for additional expansion. The fired cylinders are grouped two on each side of the additional expansion cylinder. The HP cylinder connecting rods of each group (left and right) are connected to the common crank pins of the shaft. Unlike the Deutz engine, but also differently than in the Diesel engine, the cylinder of the additional expansion was double-acting, i.e. the exhaust from the fired cylinders A and B, on the left side of the LP cylinder went to the bottom side of its piston, and the exhaust gas from cylinders C and D - to the top side of the piston of the LP cylinder.

The engine was used by Forest for propulsion of yacht Jolie Brise built by its business partner, Georges Gallice. Then it was replaced by a different engine. This is probably one of the main reasons that the engine has been preserved to the present. This engine can be seen at the Musée des Arts & Métiers in Paris - figure 4 [24].

In 1890, Forest and Gallice engine tests were carried out in the Brest fortress. During tests, the engine obtained power of about 14.7 kW (~ 20 HP) at 193 rpm and specific consumption of petrol of about 626 g/kWh [25]. Forest himself in his book [23] wrote that the idea of using additional expansion of exhaust did not bring him, admittedly, the expected benefits, but nevertheless he assessed his design as refined, well-balanced and maintaining stable run.
3.4. Other similar designs of the turn of the 19th and 20th centuries

In the pioneering years of development of internal combustion engines, at the turn of the 19th and 20th centuries there was a relatively large interest in engines with double exhaust gas expansion. Many constructors wanted in this way, modelled on the steam engine, to improve effective efficiency of engine. An exceptionally extensive combination of engines with additional exhaust gas expansion developed at the end of the 19th century and at the beginning of the 20th century can be found on the website [24]. Some of these designs did not go beyond the concept of patent, some were used to drive various machines, some were built as single prototypes without a known practical application, while there were designs among those engines that found practical use, including propulsion of road vehicles. A good example is the engine of John H Eisenhuth, which was used in Compound passenger cars produced by his company. Vehicles (figure 5) of this brand participated in the competition for the smallest fuel consumption in 1905, National Economy Test obtained quite good results 16.1 mpg.

Compound cars were probably the only in history powered by engines with additional exhaust expansion. Due to the fact that they were expensive, their sales did not reach too high a level. Finally, in 1907, the Eisenhuth Horseless Vehicle Company was taken over by another company and the production of Compound cars was ended.
4. Concept of Gerhard Schmitz and five-stroke engine by Ilmor engineering

Gerhard Schmitz, a Belgian engineer and inventor, dealt with the problem of an engine with an additional exhaust gas expansion at least from the 80s of the last century, what is documented by a patent [26] granted to him for a combustion engine with multiple exhaust expansion. The second patent, where the name of the five-stroke engine was already used, was granted in 2003 [27]. As it is known now, the concept of an internal combustion engine with a double exhaust expansion was no longer new, but G Schmitz added some innovative assumptions to the known solution. His invention consisted in using a high boost using a turbocharger to obtain high performance and combine it with the benefits of a prolonged expansion of working medium. To achieve this, the compression ratio of the HP cylinders is relatively low (~ 7), which ensures no knock combustion problems. On the other hand, a high overall expansion ratio (~ 14) increasing the overall efficiency of the engine was obtained by applying additional expansion in a separate, larger low-pressure cylinder. Gerhard Schmitz established cooperation with the British company Ilmor Engineering specializing in the construction of engines for motorsport, which resulted in the construction of a five-stroke engine prototype in 2007. Its essential technical data and performance obtained in the testing phase are presented in table 1.

| Parameter                          | Value                                      |
|------------------------------------|--------------------------------------------|
| No. of cylinders, configuration    | 3 (2xHP, 1xLP),                           |
| Bore x stroke                      | HP - 78x73 mm, LP - 106.09x88mm            |
| Engine capacity (HP cylinders)     | 698 cc                                    |
| LP cylinder capacity               | 778 cc                                    |
| Compression ratio                  | HP - 7:1, LP - 25:1                       |
| Overall expansion ratio            | 1:14                                       |
| Maximum torque                     | 166 Nm at 5000 rpm                        |
| Maximum power                      | 97 kW at 7000 rpm                         |
| Lowest BSFC                        | 226 g/kWh                                  |

The general view of the five-stroke engine prototype built by Ilmor Engineering and its 3D model is presented in figure 6.

![Figure 6. Five-stroke engine demonstrator made by Ilmor a) 3D model, b) general view [28].](image)

As it is visible in the table, the engine obtained very promising results, especially the brake specific fuel consumption (BSFC) has a very favourable value, but the design of the five-stroke engine in this form has not been further developed. In 2008, Ilmor continued the development and testing of the five-stroke engine, but without the originator's involvement [28]. In 2009, Mr. Schmitz was involved as a consultant in the project of one of the German automotive concerns to develop an engine with "extended exhaust gas expansion". It is known that some simulation studies were conducted with promising results,
but there is no information about the construction of a demonstrator and its possible experimental research as a result of these works.

5. Engine developed by the team Kéromnès, Delaporte, Schmitz, Ailloud and Le Moyne
In the context of the five-stroke engine Mr. G Schmitz appears for the second time in studies [29] [30]. The originator of the five-stroke engine in a modern form joined the team of French engineers and scientists. They together developed a five-stroke engine with a power of about 40 kW designed to drive a generator for range extender of electric vehicle or to a serial hybrid drive system for a C-segment passenger car. General view of the engine of Kéromnès, Schmitz et al. and the view of its 3D model are shown in figure 7.

![General view (a) and 3D-model of the five-stroke engine developed by Kéromnès, Schmitz et al. [28].](image)

As can be seen in the diagram on figure 8, the engine was equipped with three camshafts in the cylinder head. One shaft controls the opening of the engine intake valves, the second - valves opening exhaust gas flow between the fired cylinders and the low pressure cylinder, while the third shaft controls LP cylinder exhaust valves.

![Scheme of the engine developed by Kéromnès, Schmitz et al. [29].](image)

One of the characteristics of the engine is the replacement of the classic waste-gate valve upstream the turbine by an additional exhaust valve of the additional expansion cylinder whose outlet channel bypasses the turbine. This valve, called the "smart wastegate", opens and closes a bit later than the main
exhaust valve controlling the inlet to the turbine. In combination with the use of a phase change system for this camshaft, this gives the option of adjusting the boost pressure. The main purpose of this unconventional method of regulating the boost pressure was, on the one hand, the desire to use high energy of exhaust gases in the turbine in the initial phase of exhaust stroke, and, on the other hand, the desire to reduce backpressure in the further part of the piston movement to the top dead centre (TDC). This approach increases the efficiency of the work of cylinder of additional expansion. Unfortunately, the authors did not provide details on the timing of both exhaust valves and the range of its variability. Another interesting solution is a shifting of the HP cylinder axis and the cylinder axis LP relative to the crankshaft axis. Firstly, this results in the possibility of shortening the channels transferring exhaust gases from HP to LP cylinders. Secondly, in this way a specific synchronization of the cylinders’ work has been achieved - the TDC of the LP cylinder falls out slightly earlier than the BDC of the fired cylinders, which improves the process of additional expansion of exhaust gases.

Compared to the first demonstrator built by Ilmor, the engine built by the Kéromnès team, Schmitz et al. has a significantly lower maximum power. The authors of the design based on an analysis assumed that the engine to a range-extender of the C-segment car should have a power of about 40 kW. The engine also has a lower capacity. A bore/stroke ratio was also changed to a certain extent. The basic technical data of the engine of Kéromnès, Schmitz and others is summarized in table 2.

Table 2. Technical data of the five-stroke engine developed by Kéromnès, Schmitz et al. [29].

| Parameter                               | Value                        |
|-----------------------------------------|------------------------------|
| No. of cylinders, configuration         | 3 (2xHP, 1xLP), in-line      |
| Bore x stroke                           | HP - 71x64 mm, LP - 85x80 mm |
| Engine capacity (both HP cylinders)     | 506 cc                       |
| LP cylinder capacity                    | 464 cc                       |
| Compression ratio                       | HP - 8:1, LP - 30:1          |
| Overall expansion ratio                 | 1:12.7                       |
| Maximum torque                          | 95 Nm at 3500-4250 rpm       |
| Maximum power                           | ~40 kW                       |
| Lowest BSFC                             | 226.4 g/kWh                  |

This time, the additional expansion cylinder has a displacement slightly lower than twice the volume of each of the fired cylinders.

The authors of the described solution emphasize that the obtained value of BSFC is extremely low, especially for the engine with such a small capacity of the fired cylinder. In the perspective there is a further improvement in the effective efficiency of the engine. It should be remembered that this engine has only two valves per fired cylinder and multi-point indirect injection system. Certainly, the use of four valves per cylinder or direct injection system would increase the efficiency of the engine, but would nevertheless increase its cost. Unfortunately, there is no current information on whether the engine now still developed. The last publication [29] gave a hope for that, but the author of this work could not find newer information.

6. Five-stroke engine developed at Cracow University of Technology

The research project of National Science Centre of Poland No. N N509 559040 was carried out in the years 2011-2013 at Cracow University of Technology (CUT). The material effect of the project was the development of an engine with additional expansion of the exhaust gas in a separate cylinder. The essential difference with respect to the engines described in the article so far is that this engine was not developed from scratch, but was constructed on the basis of an existing four-cylinder spark-ignition engine. The most important modifications concerned the engine head - figure 9 a). The general view of the engine on the test bench is shown in figure 9 b).
In the engine developed at Cracow University of Technology, combustion of mixture takes place in the cylinders 1 and 4, while the cylinders 2 and 3, internally connected through a channel drilled in a combustion chamber wall are a common volume in which the process of additional expansion of the gases takes place. Then, the exhaust gases are removed through a total of 4 exhaust valves to the exhaust manifold, and from there to the turbocharger. The engine was developed basing on a EA113-family engine of the VAG company. Unlike in the case of engines of Ilmor or team of Kéromnès, Schmitz and others, this engine is made in a four-valve technique and is equipped with a direct injection system. It is also important that the oil pump, coolant pump, high pressure fuel pump and alternator are driven by the engine. The engine also has its autonomous electric power supply system, and from it the control system with injectors and ignition coils and a low pressure fuel pump is powered. In this situation, the power measured on the shaft and the brake specific fuel consumption are real net values. In the previous two solutions, basically all external systems (excluding valvetrain system) were driven from an external source, which meant that the BSFC actually obtained, and this is the most important parameter, was somewhat underestimated in relation to reality. The basic technical data of the five-stroke engine developed at the Cracow University of Technology is shown in Table 3.

| Parameter                              | Value                                         |
|----------------------------------------|-----------------------------------------------|
| No. of cylinders                       | 4 (2xHP, 2xLP combined into one volume)       |
| Configuration of cylinders             | in-line                                       |
| Bore x stroke                          | 82.5x92.8 mm                                  |
| Engine capacity (HP cylinders)          | 992 cc                                        |
| LP cylinder capacity                   | 992 cc                                        |
| Compression ratio                      | 10.5 in HP and LP cylinders                   |
| Overall expansion ratio                | 21                                            |
| Maximum obtained torque                | 162 Nm at 3600 rpm and boost 0.9 bar (KP39)   |
| Maximum obtained power                 | 66 kW at 4800 rpm and boost 0.9 bar (KP39)    |
| Lowest obtained BSFC:                  |                                                |
| - naturally aspirated                  | 261 g/kWh at 2600 rpm                        |
| - with KP39 turbocharger                | 239 g/kWh at 3000 rpm and boost 0.3 bar       |
| - with BV35 turbocharger (VNT)          | 241 g/kWh at 2400 rpm and boost 0.7 bar       |

In comparison to Schmitz engines, the engine developed at the Cracow University of Technology has a significantly higher capacity. It is also a undersquare engine (bore < stroke), both designs developed with the participation of Schmitz had both HP and LP cylinders made as oversquare (bore > stroke). Another significant difference is the clearly higher compression ratio of the HP cylinders, but this allows
the direct injection applied in the engine. On the other hand, the volumetric compression ratio has not been modified (increased) in LP cylinders, and it should be remembered that the entire volume of the chamber over the LP cylinder piston set in TDC in such an engine should be treated as a parasitic volume. The use of pistons of the LP cylinders with specially shaped fillers in crowns would certainly improve the ratio of energy recovery in the additional expansion cylinders. Modification of the former combustion chambers in the cylinder head for these cylinders would be much more difficult. Another difference compared to engines developed with the participation of G. Schmitz is a use of two camshafts driven by a toothed belt with a 2:1 gear ratio. In Schmitz engines, the camshaft controlling the exhaust valves of the LP cylinder has a 1:1 gear ratio with the crankshaft. In the engine developed in the CUT, this solution is not possible because one camshaft is responsible for controlling the intake valves for both HP cylinders (4-stroke mode) and for controlling all LP (2-stroke mode) cylinder exhaust valves. In order to enable the correct operation of the engine, the part of camshaft for the exhaust valves of additional expansion cylinders has doubled cams. This means that all 4 exhaust valves of LP cylinder open simultaneously in each revolution of the engine crankshaft.

During the work carried out so far, the engine was tested in the naturally aspirated version, then with turbocharger controlled by waste-gate valve, and more recently with turbocharger with variable-nozzle turbine (VNT). The latter modification, by increasing the resulting boost pressure, brought about a significant improvement in engine performance at lower engine speed, but on the other hand, it was not possible to achieve brake specific fuel consumption as low as previously. The result of this is the increase of turbine flow resistance in comparison to the classic turbocharger with waste-gate, what worsens the energy recovery in the cylinders of additional expansion. As it was presented in the table, the application of turbocharging allowed to significantly reduce the value of the minimum brake specific fuel consumption. The use of supercharging reduced the frictional losses in the overall energy balance of the engine and intensified the process of energy recovery in the cylinders of additional expansion. In addition to the research and development work, theoretical considerations on the thermodynamic cycle of the engine with additional exhaust expansion were also carried out [34] [35].

In recent months, the author of the article has been researching various catalytic reactors for the described five-stroke engine. Its characteristic feature is the relatively low temperature of exhaust gases leaving the turbine [35], what may hinder the efficient operation of the reactor, especially at low engine load.

7. Summary and conclusions

The initial interest in the internal combustion engine, in which additional expansion in a separate low-pressure cylinder was applied, resulted from the earlier successful application of an analogous solution in steam engines used in particular for the propulsion of large vessels. The use of two-stage expansion in the combustion engine was motivated by the desire to increase the efficiency of the engine in relation to the classic solution with single expansion. Unfortunately, the different characteristics of the working medium (comparing to steam) caused that the use of additional charge expansion in the internal combustion engine caused more problems than benefits in the engines from late nineteenth. Rudolf Diesel found it most painful, the design of whose showed significantly higher fuel consumption than his classic engines. The problems were mainly caused by the high temperature of exhaust gas, what introduced a very large heat load of the valves between fired cylinders and additional expansion cylinder. This forced the need for efficient cooling of these engine parts, which resulted in significant heat losses that significantly reduced the efficiency of the exhaust energy recovery process in the cylinder of additional expansion.

The interest in the engine with additional expansion of exhaust gases returned at the end of the 20th century. There were already available materials for valves that allow them to work at significantly higher temperatures. In addition, it was possible to apply a turbocharging system to such an engine, which significantly contributes to improving its effective efficiency.

During the development of the engine, it has been shown that the use of additional exhaust expansion is only reasonable at high load [13]. At low load, it may be that the indicated power in the cylinder of
additional expansion has a negative sign, which means that the cylinder instead of giving extra power to the shaft requires a drive (become a load). In the load range from low to medium, indicated power in the cylinder of additional expansion may have a positive sign, but low enough that after taking into account the mechanical losses of this cylinder, it turns out that the profit is very small or even zero. For this reason, an engine with additional exhaust expansion is not suitable for use in a classic vehicle drive system, where it would be the only source of propulsion. It is suitable for propulsion of generator for stationary use, for a hybrid drive system or as a range-extender for a pure electric vehicle, under special conditions also for a series-parallel hybrid system. Everywhere there the work of an internal combustion engine is mainly carried out with a high load, and in such a regime the engine with additional expansion of exhaust gases repays with high efficiency.

The engine with additional expansion of the exhaust gases also has features that, depending on the place of application, may prove to be an advantage, but also a disadvantage. One of such features is the relatively low exhaust gas temperature. It may cause some problems with the operation of a classic catalytic reactor that would require, for example, preheating. On the other hand, a low exhaust temperature could be very desirable for military applications, for example for auxiliary power unit for an infantry fighting vehicle or a tank. The low thermal footprint is highly beneficial in military use due to the reduced ability of the enemy to detect the vehicle.

In summary, the problem of the engine with additional exhaust gas expansion is an interesting issue, and, above all, still giving development and optimization opportunities to obtain a high value of the effective efficiency of internal combustion engine. In any case, the author of this work declares the development of the described construction, in the near future in terms of validation of exhaust aftertreatment system based on a three-way catalytic converter.

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