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Original scientific paper

INNOVATIVE DESIGN STRATEGY FOR AN INTERNAL COMBUSTION ENGINE WITH IMPROVED OUTPUT CHARACTERISTICS

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Abstract. *The paper describes the concept of a new internal combustion engine. Presented IC engine concept possesses a variable displacement, variable compression ratio, combustion at constant volume, improved intake and exhaust processes, as well as more complete expansion of the working fluid. A comparison of some performance of this new concept with conventional IC engine and electric motors is provided. The results indicate that the performance of IC engine can still be improved. The achieved efficiency of the engine is over 40%. The Ricardo Wave program was used for simulating the characteristics of the engine. CAD model of concept engine was made with CATIA V5.*

Key words: *IC engine, Concept, Efficiency, Variable displacement, Constant power*

1. INTRODUCTION

When in 1877 Otto, in collaboration with Gottlieb Daimler, designed and patented the four-stroke internal combustion engine on German soil, he probably had no idea what role his invention would play in the future development of technology and society. Compared to the steam engines and their performance, especially when it came to efficiency which was around 2%, Otto's engine appeared quite superior to all technical solutions of that time. Today, almost 150 years later, it can be said that it is difficult to imagine the perception of the modern world without the use of such engines. The problems brought about by these engines are more than obvious and have become very relevant in recent years. The issue of improving the efficiency of IC engines is highly relevant today, both in theoretical research and in practical and experimental work. There's a noticeable increase in the use of sophisticated software packages for analyzing engine processes and predicting their

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performance, such as one-dimensional gas dynamics programs like Ricardo/WAVE, AVL BOOST, and GT POWER. Alongside the development of these programs, their verification through experiments has also progressed. Many authors described the application of WAVE in the early stages of engine design. Meanwhile, some authors presented the calculation and optimization of variable intake valve opening using 1D-CFD (one dimensional-computational fluid dynamics) code. As for simulating the efficiency, performance, and emissions of the engine-vehicle system, it was presented in [1]. Apart from basic modules for detailed engine process analysis, some authors have gone further to simulate GTDI engine with the intention of maximizing the engines efficiency and minimizing the emission [2]. Comprehensive simulations and accurate predictions intended for highly stressed engines have also been carried out in references [3].

As different software solutions have evolved, the idea of integrating two or more software packages for more comprehensive and precise analysis of complex phenomena in the intake and exhaust systems of IC engines has emerged. Such integration of numerical codes has enabled the connection of 1D software with 3D analyses of individual engine model segments, allowing for detailed monitoring of fluid flow effects in specific engine components. The results of these simulations aim to optimize the observed components better. Simulations of air path systems and intake manifold problems are presented in references [4, 5]. Simulations of flow through the intake manifold of a V6 engine were described in [6] coupled with 3D CFD VECTIS code. There are several papers where 1D code for simulating engine model processes was linked with PROMO 3D CFD code, and intake manifolds, coolant flow, and exhaust manifolds were subjected to simulation to observe the advantages between one-dimensional and three-dimensional process observations. Simulation of a turbocharged engine also was carried out in many publications.

From the aforementioned research and research that can be found in worldwide literature, it is evident that all significant aspects of the classic engine concept have been simulated, with many publications successfully verifying these results through experiments. However, all research conducted so far has focused on engine operation based on a predetermined kinematics i.e. in CFD code programs a characteristic law of volume change or piston motion was not provided, only the geometry of elements defining the change in engine displacement of the conventional piston mechanism was defined. This practically means that, with knowledge of piston stroke length, piston diameter, crankshaft radius, and crank mechanism deaxiality if it exists, the program deals with volume change at any given moment. From a theoretical perspective of studying thermodynamic cycles in engines, numerous publications critically review volume changes in conventional piston motion. Primarily, research in finite time thermodynamics repeatedly demonstrate heat addition at constant volume as the most efficient method of heat addition [7, 8], such heat addition has been specifically studied in the Otto cycle [9]. Then, variable compression ratio as a modernization of piston mechanism kinematics is well known and explained from various aspects [10, 11]. Similarly, the advantages and efficiency of variable displacement engines are detailed in [12]. Not to be forgotten are the significant drawbacks of working fluid discharge resulting from conventional piston motion, inevitably leading to premature expansion process interruptions [13, 14]. Likewise, the classic piston mechanism kinematics leads to increased pumping work and efficiency degradation [15].

From all this, the authors believe that there is a lack of analyses in the field of IC engine efficiency that would describe the output parameters of engine operation to some extent when using a modified piston motion law. All previous research has been extensively conducted, with expected results proven on test benches and documented in the mentioned publications. Therefore, in addition to their experimental research, the authors rely on certain principles verified by numerous eminent researchers in the analyzed field. However, the emphasis in this study will also be on simulating engine operation in the case of unconventional piston motion laws. In this paper the integration of modified piston motion laws was performed by inserting the laws into the CFD code of the 1D Ricardo/WAVE program. The modified piston motion laws aim to achieve variable engine displacement and variable compression ratio, as well as the peculiarities of piston rest in TDC (top dead center) and BDC (bottom dead center).

2. New Concept of IC Engine

The basic components of the new IC (internal combustion) engine concept with certain similarities and differences to today's engines will be presented. It should be noted that the illustrations presented are merely a basic description of the appearance and elements that are there to essentially describe the mechanism, rather than provide insight into the complete technical documentation of the engine.

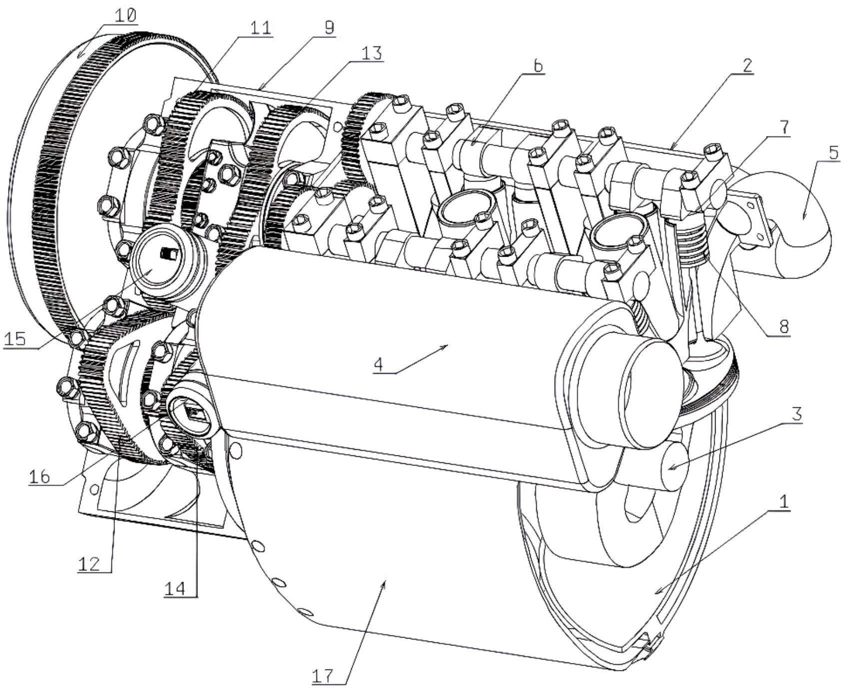


Fig. 1 Basic components of a new concept IC engine

In Fig. 1, the basic components of the engine assembly are presented. Some elements can be observed that are present in modern automotive internal combustion engines, as well as elements that appear for the first time as part of the IC engine mechanism. The following elements are shown in the indicated positions: 1-torsional block, 2-engine head, 3-torsional piston, 4-intake manifold, 5-exhaust manifold, 6-camshaft, 7-valve, 8-valve spring, 9-motion generator housing, 10-flywheel, 11-14-non-circular gears, 15-electric motor for changing engine displacement, 16-electric motor for changing compression ratio, 17-crankcase. To provide a clearer and more comprehensive understanding of the concept and the formation of the toroidal combustion chamber, Fig. 2 is presented below.

In addition to the mentioned elements in the previous figure, the following are shown: 7-camshaft of exhaust valves, 8-exhaust valve, 18-camshaft of intake valves, 19-intake valve, 20-engine head cover. It is clearly observed how combustion chamber is formed, limited by elements 1 (torsional block), 2 (engine head), 3 (piston), 8 (intake valves i.e., intake valve heads) and 19 (exhaust valves i.e., exhaust valve heads). The analogy of piston movement through the cylinder in a standard engine is here similarly executed with a toroidal piston and toroidal engine block through which the piston moves. Several factors determine the size of the toroidal section, the first being that the ratios of piston stroke and diameter remain within the limits used today in conventional engines. Another important aspect is undoubtedly the ability to perform too large stroke of the piston through the toroidal section. It is observed from Fig. 2 that in the described case, a toroidal section of about 100 degrees is chosen. It could be said that this size also represents almost maximum values, because by increasing the size of this section, it would be very difficult to construct an intake manifold.

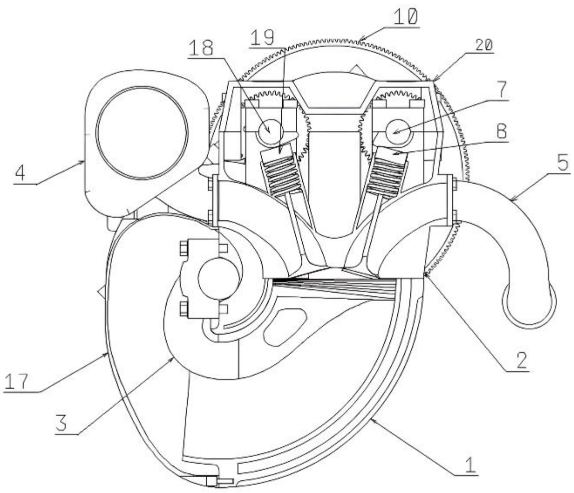


Fig. 2 Engine cross-section (formation of the toroidal combustion chamber)

Since it is a variable displacement and variable compression ratio engine, the piston will move through the torus with different angular displacements. This practically means that at low active volumes, the piston will oscillate, i.e., angularly move in the upper parts of the toroidal section, while for example, at very high volumes it will move through almost the entire toroidal volume. Of course, if it is about regimes that require large displacement and small compression ratios the piston will not reach the top of the torus because that part of the space will be reserved for the compression volume. Today there are engines that change displacement not by changing the piston stroke, but by deactivating cylinders. In such engines, regardless of deactivation, the piston continues to move through the cylinder, only fuel combustion does not occur in it. Therefore, even though the cylinder is not active, it still incurs certain mechanical losses. When changing the engine volume due to changes in piston stroke, there will not be unnecessarily much greater piston movement as is the case with cylinder deactivation, thus reducing losses will be influenced. It is known that there are many different concepts of internal combustion engines, and for many there is a challenge in designing the combustion chamber sealing due to the piston different shape. In this concept, sealing is not an issue because the piston rings are cylindrical in shape. The torus itself represents a kind of cylinder, i.e., the cylinder would be a special case of the torus where the diameter of the tube tends to infinity. In Figs. 1-3, an approximate appearance of an unconventional engine with variable piston motion is shown. All basic elements and mechanisms of the engine can be observed on the same images. The engine flywheel serves as an energy accumulator, as in a classic engine, only it is connected to the piston mechanism through the motion generator with two pairs of non-circular gears. In the shown case, such a transmission ratio is implemented that the flywheel rotates three times about its axis during one working cycle. In contrast to a classic engine where the flywheel rotates as many times during the working cycle as the crankshaft, i.e., twice in four-stroke engines and once in two-stroke engines. The basic setup of the system for the distribution of working fluid, exhaust system, and intake system can be observed on the same image. The most demanding mechanism highlighted is the motion generator with non-circular gears, all other engine elements are more or less similar to the elements of today's engines. The described concept is not presented to provide a final image of the engine assembly, but only to outline a rough picture of the new mechanism and the possibilities of realizing such an engine. The presented mechanism can be realized in several ways, for example, by adding another section of pistons, or by a different execution of the complex mechanism with non-circular gears in order to better withstand high torques.

The phase of the two pairs of non-circular gears is crucial for achieving the required angular oscillation, with an increase in the phase shift the amplitude of oscillation increases but not the frequency. To increase the frequency of oscillation, it is necessary to increase the angular velocity of the non-circular gears or the flywheel. For easier understanding of the way the phase shift is formed, two cross-sections of the engine are presented in Figs. 4 and 5. The used sections are outlined in Fig. 3, where certain elements are removed for better clarity. Although of a complex profile, it is observed that the engagement of the presented pairs of gears always occurs at points lying on the line of the shortest distance from the axes of rotation of the non-circular gears. It has been observed that two adjacent, identical, non-circular gears overlap within the mechanism. This design feature enables the piston to stop at both the Bottom Dead Center (BDC) and Top Dead Center (TDC) positions. As a result, the combustion process occurs with a smaller change in volume, closely approximating an isochoric heat addition. Furthermore, this configuration allows for the later opening of the exhaust valve, which facilitates a more complete expansion of the working fluid.

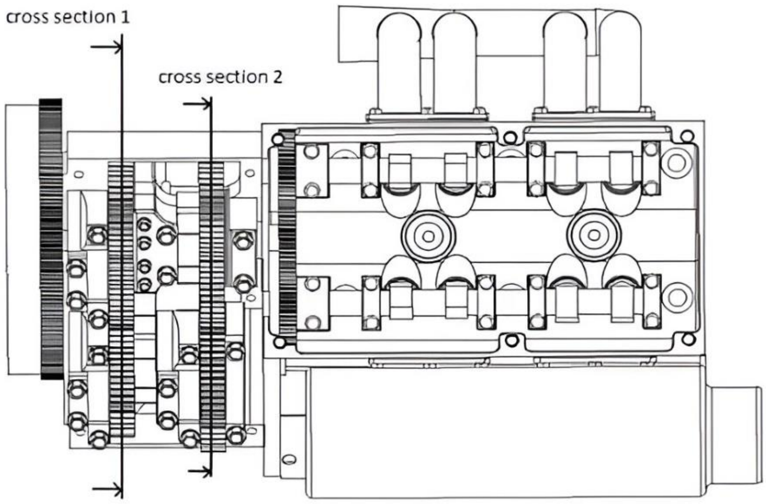


Fig. 3 Approximate appearance of an unconvetional IC engine with marked cross sections (electric motors 15 and 16 shown in Fig. 1 are removed here)

Electric motors 15 and 16 (Fig. 1) are connected through gears and levers and can control two important parameters: the compression ratio and the volume. Electric motor 15 is responsible for changing the engine displacement (by adjusting the oscillation angle of the piston), while electric motor 16 is responsible for changing the compression ratio.

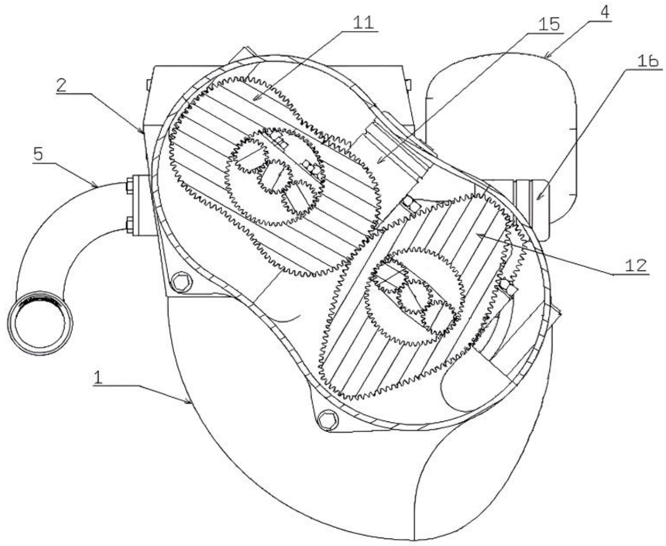


Fig. 4 Cross-section of the first pair of non-circular gears (cross-section 1 from Fig. 3)

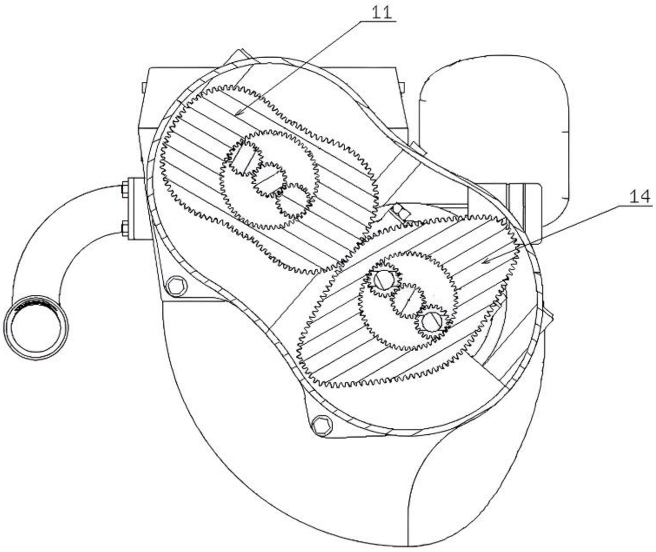


Fig. 5 Cross-section of the second pair of non-circular gears (cross-section 2 form Fig. 3.)

3. Simulation Model

In the following section the most important input data for the engine model will be presented. First and foremost, basic data given in Table 1 should be mentioned. It is observed that the data are very similar to those of a standard engine. When it comes to the valve mechanism, it is almost exactly the same as in a conventional engine. Although this involves a toroidal-shaped piston, the piston stroke actually represents the mean diameter of the toroid, and it is therefore expressed in millimeters, even though it would be more accurate to express this quantity in terms of an angle. Also some values of valve lift are diffirent in order to optimize the fluid flow.

Table 1 Main engine data

Engine type	Otto four stroke
Number of cylinders	2
Number of valves per cylinder	4
Piston bore	120 [mm]
Piston stroke	30-177 [mm]
Intake valve diameter	44 [mm]
Exhaust valve dimaeter	40 [mm]
Valve lift	15 [mm]
Exhaust valve open duration (EVDUR)	235 [deg]
Iintake valve open duration (IVDUR)	230 [deg]
Exhaust valve maximum open point (EVMP)	253.3-245 [deg]
Inteake valve maximum open point (IVMP)	479.3-471 [deg]
Compression ratio	8-16

It is also noted that the valve lift lengths defined by the previous table are very similar to the values of conventional engines. This is a result of the alignment of the kinematics of the valve mechanism and the piston mechanism. In addition to the classic parameters, it is observed that the compression ratio in this model is represented within certain limits. Since this is a variable compression ratio engine, this value must also be defined within the limits where it changes during the simulation process. The engine displacement, as well as the compression ratio, represents one of the variable parameters, and therefore the stroke is also defined within specific limits. The values of EVMP and IVMP actually represent the angle when the valve is fully open. This concept allows for the operation of the engine under variable conditions of displacement and compression ratio, so the analysis of such an engine will result in much more complex outcomes compared to a conventional engine.

For this research the Ricardo/WAVE software package was used for making engine model (Fig. 6). Unlike conventional engine modeling where piston motion is defined using classical kinematic parameters, in this study, piston motion or changes in working fluid volume were defined using the Profile Editor. Results from kinematic analysis were individually inserted into the editor, ensuring accurate distribution of piston positions relative to the crankshaft position. Although the presented concept does not feature a conventional crankshaft, changes in displacement had to be defined relative to a reference angle. Therefore, the traditional crankshaft rotation angle was replaced with the term equivalent angle for easier interpretation of results. So in this study a 720-degree motion profile was used (Fig. 7), even though the flywheel actually rotates three times, not twice.

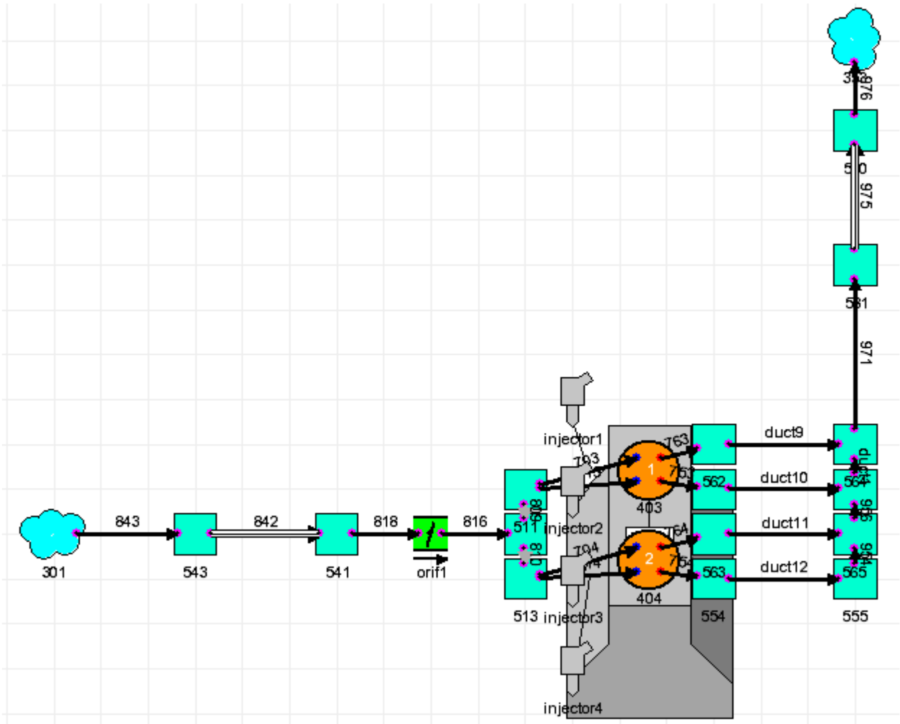


Fig. 6 Engine model

To generate diagrams in the Wave Post processor, the input piston motion law was defined with a step for every degree of crankshaft rotation, requiring 720 points for one complete cycle. This mechanism allows for an infinite number of values of angular displacements of the toroidal piston. One such diagram of possible angular displacements is shown in Fig. 7.

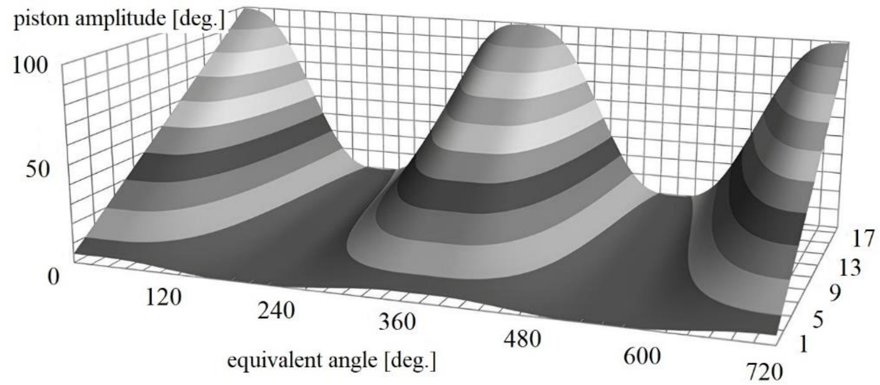


Fig. 7 Complex angular motion of piston (18 cases were examined)

The use of one-dimensional CFD simulation for engines is now one of the most significant tools during the early stages of engine development. Engine design through simulation drastically reduces the time that would otherwise be required for extensive experiments and prototypes as such simulations can predict a large number of experiments. One of the main advantages of this approach to the development of internal combustion engines is the relatively high correlation between simulation results and experiments, which, with proper definition and shaping of all engine components, can achieve accuracy of approximately +/- 5%. The main problem to address in this case is the synchronization of the valve mechanism and the piston mechanism, defining the ignition timing angle, and limiting engine operation due to the risk of knocking, given that this is a virtual engine and there are no predefined values for parameters that have a significant impact on engine performance. In this case, we are dealing with an unconventional piston motion law, so it is crucial to determine the ignition timing angle, which will differ from standard values. The reason for this is the piston position near TDC, which allows possibility of avoiding larger negative work (ignition before TDC). In this concept, the piston is held around TDC for a longer period, which allows the spark to occur later (closer to TDC). This way, negative work is reduced by decreasing pressure buildup before TDC.

The parameter EVMP holds the same significance as IVMP, but in this case, the simulation process is related to the exhaust valves. Although the timing of the intake valves is always marked as having a very sensitive impact on process efficiency due to cylinder charging, it is observed that the timing of the exhaust valve openings also significantly affects efficiency. One of the main reasons for this efficiency trend is that the valves are designed to open only when the piston reaches BDC. Unlike in conventional designs where valves open before the piston reaches BDC, such valve movement is not desirable in the described concept. This approach allows the engine model to achieve greater efficiency by enabling more complete expansion of the working fluid.

Besides the selected engine parameter values, it is necessary to define the wall temperatures that enclose the combustion chamber as initial quantities. The defined values are taken from the Ricardo/WAVE recommendations. These values are presented in Table 2.

Table 2 Combustion chamber temperatures

Wall/border	Temperature [K]
Piston head	520
Cylinder head	500
Cylinder wall	430
Intake valve	450
Exhaust valve	520

When all simulation parameters are defined, the modeling of the engine model segments can begin. Generally speaking, the basic engine model is relatively simple; it consists of the intake system, the fuel-air mixture formation system, the engine itself, the exhaust system, and the working environment. The working environment does not necessarily have to be the same for the intake and exhaust sections, but standard values are usually adopted, which is also the case in this model. The intake system is designed to meet the conditions of minimal losses and to avoid undesirable air flow oscillations that reduce the cylinder filling coefficient. In this analysis, the efficiency coefficient of the coupled gear pair is assumed to range from 0.98 to 0.99, depending on the type of coupling. Specifically, higher values are chosen for internal couplings, as recommended, while external couplings and couplings of non-circular gears are slightly less favorable, with a coefficient of 0.98 adopted for these connections. Using these input values, only a rough estimation of the mechanical losses in the motion generator can be determined. Since the Ricardo/WAVE software includes an option for defining these losses through multiple parameters, it was necessary to align the losses in the new concept with the classical setup. It can be stated that the losses associated with the working fluid distribution mechanism remain unchanged in this new concept. Likewise, the losses in the crankshaft-to-engine block connections can be considered unchanged. For further analysis, a modified Chen-Flynn model was used. This correlation includes several terms, among which one accounts for engine equipment losses, another is a function of cylinder pressure, a third term is linearly dependent on the mean piston speed (calculating hydrodynamic losses), and the fourth term considers aerodynamic losses through a quadratic dependence. Each cylinder contributes to the overall engine losses, which are based on the actual pressure in the cylinder, known to vary from one cylinder to another. By adjusting input parameters, friction losses in the piston assembly can be reduced, while mechanical losses in the piston motion generator may increase. This approach provides an approximate estimation of total mechanical losses. Although not ideal, it represents the only viable method for defining mechanical losses in unconventional designs within the Ricardo/WAVE software.

4. Results and Discussion

When it comes to the characteristics of full-load performance for various stroke ratios, the curves obtained can be seen in Fig. 8. It is observed that maximum efficiency is achieved at small stroke values and high engine speeds. Conversely, for large strokes, maximum efficiency is achieved at lower engine speeds. This is primarily due to cylinder charging, excessively large piston strokes cannot achieve effective cylinder charging at higher engine speeds, whereas smaller strokes have the opposite effect. Figure 8 highlights the curve of maximum efficiency as well as the curve for the typical efficiency of conventional internal combustion engines.

In general, it can be concluded that increasing the compression ratio leads to a rise in the maximum cylinder pressure, which is expected. It should be noted that these results applied to cases where the ignition timing and corresponding compression ratio were aligned, and the results clearly indicated that the maximum pressure approached TDC with increasing compression ratio. In Fig. 8, areas of constant efficiency can be identified. It is observed that high efficiency is achieved across all engine speeds but for different stroke to bore ratios or stroke/diameter (S/D). This practically means that the engine can operate very efficiently under full load if the necessary S/D ratios are met. Similarly, it is unrealistic to expect high engine speeds with a large piston stroke. By changing the S/D ratio, the benefits of variable displacement can be achieved with this IC engine [16].

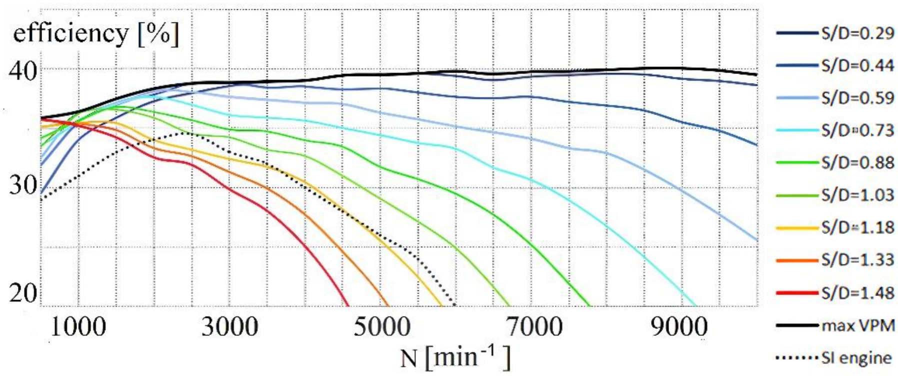


Fig. 8 Engine efficiency in relation to S/D and rpm in comparison to standard SI engine (dotted line)

It should not be forgotten that at very high engine speeds in a conventional engine concept, there is a significant increase in the average piston speed, which negatively impacts mechanical losses. In the case of variable piston stroke, at very small strokes and high engine speeds, the average piston speed does not increase significantly compared to regimes with large strokes and low speeds. This is one reason why the impact of engine speed on mechanical losses is expected to be smaller for engines with variable piston stroke (VPM), as evidenced by the results. Analyzing the obtained results leads to the idea of developing a concept that allows for the realization of maximum power with high efficiency across all operating regimes. This means that the engine can deliver high power at low speeds when using large displacements and high power at high speeds with small displacements. As expected, the engine exhibits exceptionally high power at low speeds (80 kW at slightly over 2000 rpm). Of course, excessively high power at low angular speed of the drive wheels is impractical because it leads to large torque, resulting in significant force on the drive wheels. Such high forces can cause wheel slip, making it inefficient to realize excessively high power at low engine speeds. Finally, the characteristics of full-load power for different S/D ratios can be presented in Fig. 9. It has been observed that a relatively high level of power is reached quickly. Following this initial surge, the power curve increases at a slower rate. This gradual rise is primarily due to the possibility of achieving a slightly higher compression ratio under certain operating regimes.

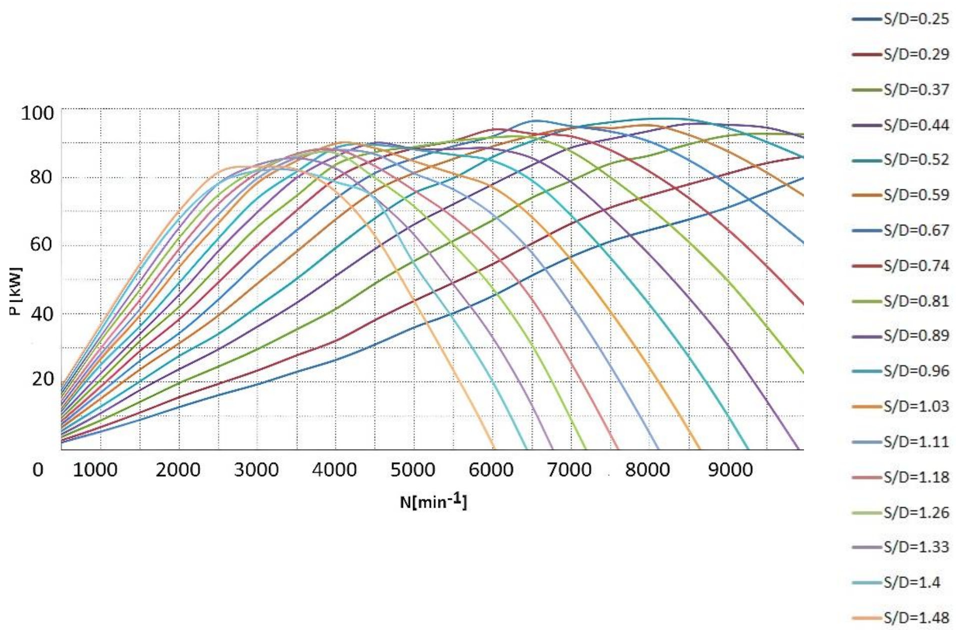


Fig. 9 Engine power in relation to S/D and rpm

It is well-known what the torque curve of a conventional internal combustion engine looks like. When considering a design that has the property of varying the stroke-to-bore ratio (S/D), it is concluded that such an engine possesses a multitude of torque curves corresponding to each specific S/D ratio. This can be illustrated by the results shown in Fig. 10.

Due to this change in torque, it is possible to realize a curve known as the ideal hyperbola of torque. It should be noted that this curve is achieved without compromising power at specific operating regimes, particularly at high engine speeds. The curve of maximum torque over a broad range of engine speeds is a logical outcome of the operational cycle in a variable piston motion engine. From previous analyses it is evident that at high stroke-to-bore ratios, high charging coefficients are achieved at low engine speeds. This positively affects torque and allows for relatively high maximum power to be maintained even at very high engine speeds. As engine speeds increase, the degree of cylinder charging deteriorates with such large strokes, leading to a reduction in torque. Therefore, at medium engine speeds, conditions are created to reduce piston stroke in favor of increased charging efficiency, which helps maintain constant power. If engine speeds were to increase further, the newly established regime would no longer meet the criteria for effective cylinder charging, necessitating a reduction in piston stroke again. In this

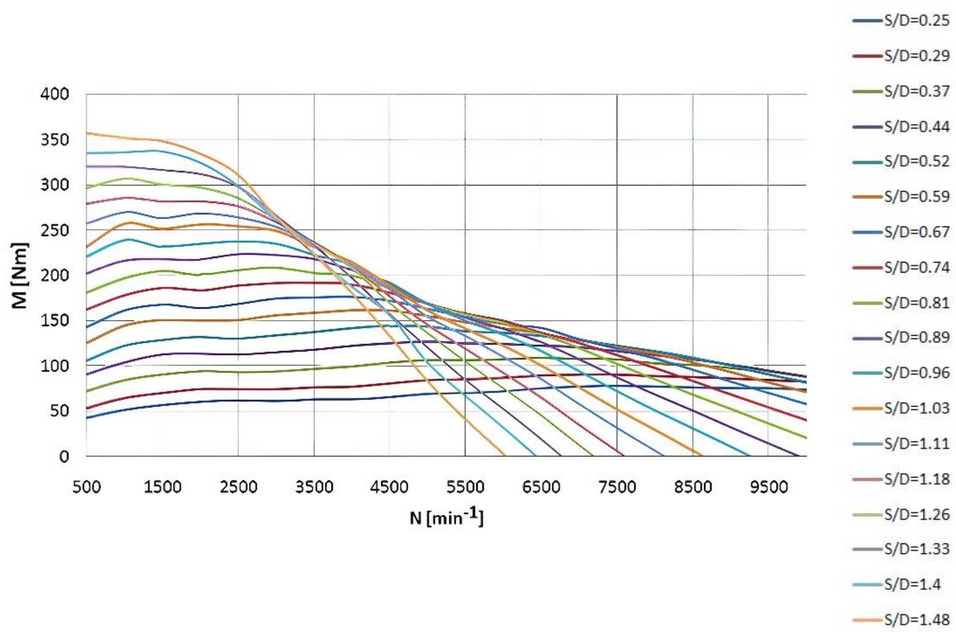


Fig. 10 Engine torque in relation to S/D and rpm

manner,a constant power curve is achieved, or, if considered in terms of torque, this behavior of engine displacement as a function of engine speed will produce an ideal torque hyperbola. An ideal torque hyperbola is not characteristic of conventional internal combustion engines but can be realized in some diesel engines within narrow ranges of engine speeds. However, having a torque hyperbola in a narrow operational range is positive but not sufficient for significant advantages. The concept described here actually offers the possibility of eliminating the need for a traditional gearbox. It is not enough to simply have a torque hyperbola, a sufficient broad range of engine speeds where power remains constant is also necessary. The described concept is capable of meeting both these necessary and sufficient conditions for operating a vehicle without the need to change the current transmission gear. Now we can compare the performance of this concept with an electric motor which is used in electric vehicle. First, the performance of electric motor efficiency is presented in Fig. 11.

To obtain such diagrams, it is necessary to first measure the observed parameters across the entire operating range of the engine, at a sufficient number of different engine speeds and load conditions [17]. In this case, since it is a virtual engine model, the data was obtained by analyzing a multitude of load conditions, which consisted of many operating points. Here, the load refers to the corresponding stroke to bore ratio, or the current engine displacement. As described, changes in displacement can be used to form a power curve that remains constant over a large portion of the engine's operating speeds. Naturally, for well-known reasons, power cannot remain constant throughout the entire range, as at very low speeds, the engine would generate excessively high torque, which would not be practical for transmission to the road surface. Nonetheless, this engine can generate constant power over a wide range of speeds. Finally, we can see the efficiency map similar to those of electric vehicles (Fig. 12).

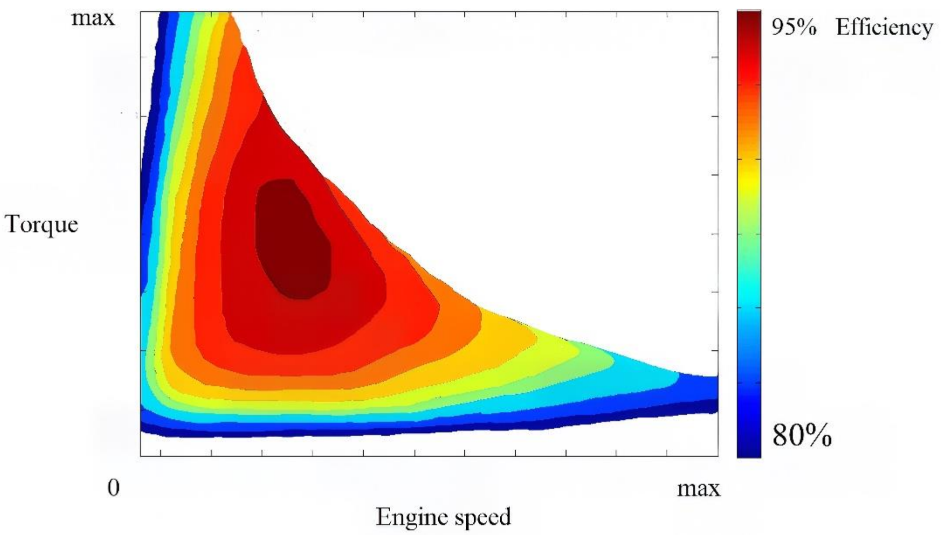


Fig. 11 Electric motor efficiency map

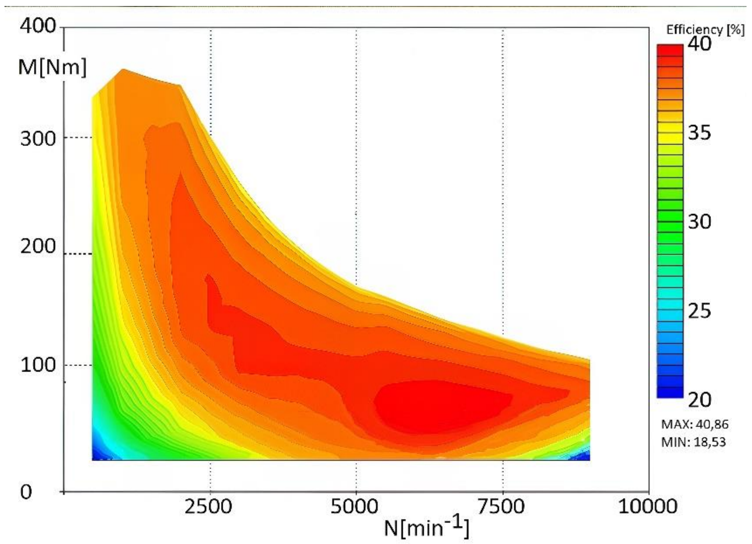


Fig. 12 Efficiency map of unconvetional IC engine

It is interesting to compare this unconventional engine with a conventional engine (Fig. 13).

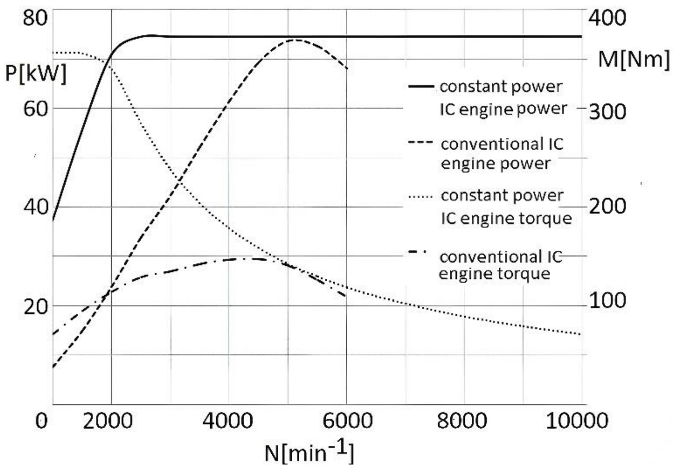


Fig. 13 Comparison of power and torque between the conventional and unconventional IC engine

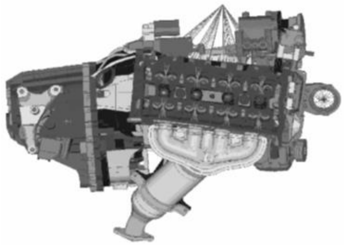
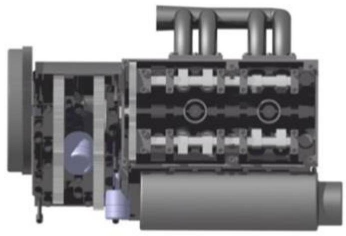
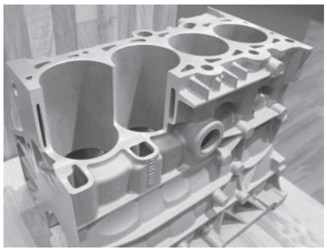
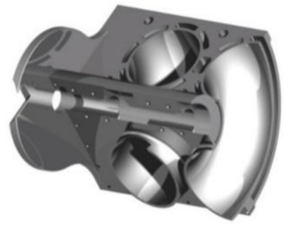
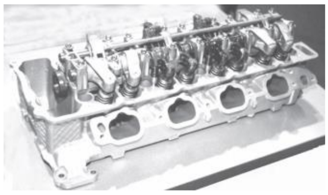
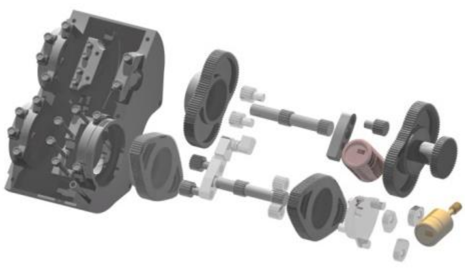
The overall impact of the described piston mechanism kinematics on engine processes is comprehensively presented in this study. For clarity, Table 3 provides a comparison of the characteristics of these two concepts.

Table 3 Comparison of conventional and unconventional engine

Conventional IC engine	Unconventional IC engine
Fixed compression ratio	Varibale compression ratio
Fixed displacement	Variable displacement
Combustion during volume changes	Constant volume combustion
Exhaust valve open before BTC	More complete expansion (exhaust valves open almost at BDC)
Ignition before TDC (negative work)	Ignition near TDC
Gearbox needed (non-constant power engine)	Gearbox not needed (constant power engine)

Table 4 outlines the essential differences and similarities between the basic systems and elements in these two different engine design approaches. It is evident that the proposed concept closely resembles a conventional engine. The primary distinction lies in the motion generator, which consists of non-circular gears that can partially replace the conventional transmission system. Additionally, it can be observed that the cylinders in this concept exhibit a different design due to their angular motion. Table 3 provides a comprehensive overview of the key characteristics of the newly proposed concept. The engine is designed with a variable compression ratio, allowing for operation on multiple fuel types [18, 19] or with different biodiesel fuel [20] ensuring optimal efficiency across various operating conditions. Furthermore, it features an enhanced heat supply mechanism and an improved working fluid distribution system. These advancements collectively contribute to an increase in the thermal efficiency of the IC engine. Last but not least, the engine features a variable displacement, which can be utilized to achieve constant power over a wider range of engine speed.

Table 4 Comparison of basic parts of conventional and unconventional engine

Conventional IC engine	Unconventional IC engine
	
	
	
	
	

Exhaust gas emissions will not be presented in this paper, but they were also analyzed as part of the study on the impact of piston motion, variable displacement, variable compression ratio and heat addition under small volume changes during combustion. Almost constant volume during combustion and variable piston motion contributes to a overall reduction in CO and HC emissions. With slower piston motion around TDC the engine can achieve better performance during cyclic variations, which are quite common in conventional internal combustion engines [21]. Slower piston movement near TDC allows more time for better mixture formation during injection, which benefits the combustion process and engine emissions [22].

5. CONCLUSION

In this paper the analysis of an IC engine with modified piston motion compared to standard piston mechanisms is presented. Differences primarily lie in the implementation of combustion at almost constant volume, variable displacement and variable compression ratio. The study simulated output parameters and engine characteristics across all operating regimes, with some results presented in this article due to the extensive nature of the research. An IC engine represents a heat engine, and its characteristics depend on how the engine interacts with the working fluid inside it. It is well known theoretically that the most efficient cycle for describing the operation of an internal combustion engine is the Otto cycle, provided unconventional cycles such as the Miller and Atkinson are disregarded, which involve different or longer expansion strokes. Increasing compression ratio enhances the efficiency of the Otto cycle, reducing the need for the Atkinson cycle since higher compression ratios increase the expansion ratio of the working fluid, thereby reducing pressure at the end of the expansion stroke. However, achieving extremely high compression ratios with current combustion technology and fuel chemistry is impractical. Hence, the ideal Otto cycle remains the most economical for a constant compression ratio. Therefore, in this paper research focus was on realizing thermodynamic cycles in real engines that approach the ideal Otto cycle model by altering the working fluid. The Otto cycle becomes particularly interesting with increasing compression ratio, aligning with the mechanism described in this concept.

Leonardo da Vinci, one of the greatest Renaissance artists, had ideas far ahead of his time, and many of his inventions were never constructed. His versatility meant that few of his ideas were realized, as he often moved from one idea to another. The brilliant ideas of this polymath mostly remained sketches. In the document "Codex Madrid," Leonardo first presented sketches of non-circular gears. The idea created by Leonardo da Vinci half a millennium ago and the thermodynamic cycle described by Nikolaus Otto are creatively linked and presented in this work. Changing the gear ratio between two gears has enabled achieving heat input at constant volume to the working fluid in the engine cylinder, previously unattainable, thereby increasing the efficiency of converting chemical energy into mechanical work, which was the goal of this research.

This study aimed to bring real cycles closer to ideal ones. Simulations and predictions unequivocally demonstrate that efficiency can be significantly increased under certain conditions. Additionally, this research has enhanced the overall effectiveness of the engine, thereby improving a broader motor-vehicle system. The described research represents a modest scientific contribution to analyzing potential directions for the development of internal combustion engines characterized by increased efficiency and environmental friendliness. These two characteristics are now the primary goals of all human systems as we search for new solutions in hopes of a better future.

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