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MODELLING OF THE OVER-EXPANDED CYCLE COMBUSTION ENGINE

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Abstract

The study concerns numerical tests of an internal combustion engine operating according to the over-expanded cycle carried out in the AVL Fire software. The research covered the modelling of a full working cycle of a conventional engine operating in accordance with the classic Otto cycle and an engine operating on the basis of an over-expanded cycle – the Atkinson cycle. As part of the work, three cases of Atkinson's cycle were analysed, by closing the inlet valve before BDC (21° before BDC) and closing the valve after BDC (41° and 75° after BDC). As a result of modelling, space-time distributions of velocity, pressure and temperature in the cylinder of the modelled engine were obtained. Optimizations of the analysed cycles were carried out, finding the best ignition timing, at which it is possible to obtain the highest efficiency and the highest indicated mean effective pressure. The calculations showed that the engine operating according to the over-expanded cycle in order to obtain the best operating parameters requires earlier ignition timing compared to the conventional engine. In addition, in the engine operating according to the Atkinson cycle, there is a drop in the indicated mean effective pressure and an increase in the indicated thermal efficiency compared to the engine operating by the classical cycle.

Keywords: *over-expanded cycle, methane, gas engine, modelling*

1. Introduction

In many research centres around the world, intensive work is being carried out to optimize the combustion process of fuels in internal combustion engines, both stationary and traction. There are many ways to improve the efficiency and performance of an internal combustion engine. These include modifications in the design, power supply as well as the use of modern engine control algorithms. The most difficulties in achieving optimal engine operation are the actions aimed at improving the overall efficiency, reducing the emission of toxic exhaust components and eliminating or reducing the combustion anomalies, including knock combustion [1-3]. Internal combustion engines use a small amount of energy contained in the supplied fuel. Therefore, they are characterized by relatively low efficiency. Engine exhaust after leaving the cylinders is characterized by high temperature and pressure, and the energy contained in them is unproductively dispersed. One of the possibilities to increase the efficiency of the internal combustion engine is to change the circulation of its work, from the traditional Otto cycle to the over-expanded cycle, commonly known in the literature as the Atkinson cycle. A variation of the Atkinson cycle is the Miller cycle, in which, in order to improve the engine's performance, a turbo- or supercharging system was also used [6]. The over-expanded cycle can be characterized as the thermal cycle of the engine, in which the compression ratio is not equal to the expansion ratio: $\varepsilon_k \neq \varepsilon_{ek}$. In terms of energy (maximization of indicated work), it is justified that the degree of engine expansion takes values greater than the degree of compression, contributing theoretically to the total expansion of gaseous combustion products to a better use of energy contained in the exhaust. The over-expanded cycle was first presented by James Atkinson in 1882, who patented the construction of a gas engine using extended expansion in comparison to the compression stroke [4]. The cycle was carried out by making a special crank-piston system. This construction of the gas engine allowed to achieve almost double the difference between the compression stroke and expansion. A characteristic feature of this system was the implementation of four piston strokes that perform a complete four-stroke engine cycle during one revolution of the crankshaft. Thanks to this property, this engine was characterized by higher efficiency compared to the other constructions. Engines carrying out a long-expansion cycle are used in both traction and industrial engines.

Obtaining the over-expanded cycle is possible by adjusting and controlling the valve timing phases. The simplest method is to properly modify the camshaft phases. This modification consists in the proper design of the intake valve cam so that it allows closing the valve during the intake stroke, or during the compression stroke. Proper design of the intake valve cam is a very difficult issue because of the conflicting requirements that it must meet. On the one hand, the sliding part and the runaway cam should be as steep as possible, so as to maximally fill the angle-cross section of the valve allowing the longest time of its opening, on the other hand, such an action can lead to excessive exceeding of the permissible tensions on the cam's working surface, which in effects can lead to serious damage to the timing system and engine.

Another method of changing the valve timing is to use an appropriate mechanism that allows for smooth regulation of the timing during engine operation. The advantage of this method is that it allows you to choose the appropriate timing parameters depending on the speed and load.

Currently, thanks to modern engine construction solutions and the use of electronic control systems, it is possible to implement an over-expanded cycle through appropriate valve control and engine timing regulation. Many manufacturers of hybrid vehicles use long-expansion cycle engines based on Atkinson's principals. This group includes such concerns as: Ford, Honda, Hyundai, Kia, Lexus, Mazda, Mercedes and Toyota [12, 16].

Engines operating on the principle of over-expansion cycle are characterized by higher efficiency, lower emission of toxic exhaust components, lower mechanical loads as well as thermal loads, which in turn leads to an increase in their durability [18].

Thanks to the use of variable valve timing, it is possible to obtain a cycle of extended expansion in two ways: by closing the inlet valve early during the intake stroke and by closing the intake valve late during the compression stroke [7, 11].

Paper [4] presents the results of the research on the possibility of using the Atkinson cycle to control the amount of air sucked into the engine cylinder in order to reduce the emission of toxic exhaust components of a large industrial self-ignition engine. The concept of Atkinson's circuit was used with earlier closing, where the engine intake valve was closed during the intake stroke. Flue recirculation was also used there. Comparative tests of a conventional engine and an engine operating by Atkinson's cycle, with the same excess air ratio. The influence of the intake valve closing angle on the charge density, combustion pressure and charge temperature in the engine cylinder was analysed. Along with the earlier closure of the engine intake valve, the compression ratio of the engine decreased as the cylinder volume decreased from the closure of the intake valve to the end of the compression stroke. The mass of sucked air and the density of the load in the cylinder of the engine working according to the Atkinson cycle decreased. It has been shown that by changing the closing angle of the intake valve, the heat release rate is significantly influenced, i.e. the course of the combustion process. Early closure of the intake valve caused that the first phase of combustion, i.e. kinetic combustion, began to dominate more. It turned out that with the earlier closing of the intake valve, the engine's efficiency decreased [17]. Early closure of the intake valve caused an increase in emissions, CO and reduction of NOx emissions [20].

One of the research tools, increasingly used in the analysis of processes that make up the working cycle of the combustion engine, is mathematical modelling [9, 14]. The process of mathematical modelling of the working cycle of the piston engine begins with determining the physical model of phenomena occurring during the engine's work cycle, then requires mathematical description of the established physical model, the adoption of appropriate initial and boundary conditions and the numerical solution of equation sets of the adopted mathematical description. In the case of piston engines, modelling is a process of considerable complexity, because it includes thermodynamic and gasodynamic phenomena occurring inside the cylinder with variable volume, including combustion chemistry and charge exchange processes. The complexity of the combustion process itself in the reciprocating engine, associated with its non-stationary character, requires far-reaching simplifying assumptions during modelling [22]. The assumptions made allow to obtain results more or less similar to reality. It is possible to model the combustion of both homogeneous mixtures prepared in the combustion chamber and heterogeneous (non-homogeneous) mixtures created by injecting fuel into the chamber, moreover, the calculations may refer to a spark-ignition engine [8] or a compression-ignition engine [13, 15]. The presented work presents the results of numerical analysis of the thermal cycle of a spark-ignition internal combustion engine that performs the Atkinson cycle. In the engine, to extend the expansion, the method of early closing of the intake valve during the intake stroke and the late closure of the intake valve during the compression stroke was applied. The aim of the work was to examine, by modelling and theoretical analysis in the AVL Fire program, the possibilities of improving the piston efficiency of an internal combustion engine by using a cycle of extended expansion.

2. Research object

The object of numerical analysis was Andoria type S231 (1HC102) internal combustion engine. It is a single-cylinder, water-cooled diesel engine. For the needs of research, the engine has been adapted to work as a spark-ignition engine through appropriate modifications. The modifications consisted in decreasing the compression ratio ε from 16 to 11, by changing the height of the piston crown and mounting the spark plug in the area of the injector [19]. In the inlet manifold a throttle valve for regulating the engine load and fuel injectors were installed, which fed the fuel to the vicinity of the intake valve. The basic data of the test engine are included in Tab. 1.

Tab. 1. Engine S231(1HC102) parameters

Type		4 stroke, water cooled
Clinder number		1-horizontal
Ignition type		Spark ignition
Engine displacment		0.98 dm^3
Engine speed		1270 rpm
Stroke		120 mm
Bore		102 mm
Compression ratio (CR)		11
Intake valve openning		11° after BDC
Intake valve closure	Classic (Otto) engine	28° after BDC
	Atkinson_1	21° before BDC
	Atkinson_2	41° after BDC
	Atkinson_3	75° after BDC
Exhaust valve openning		30° before BDC
Exhaust valve closure		TDC

The over-expanded cycle took place due to the change in the closing angle of the intake valve performed as a result of engine camshaft modification. Three cases of closing the intake valve were analysed: 21º before BDC, 41º and 75º after BDC. The crankshaft angle ranges corresponding to the opening of the intake valve for the three analyzed cases are shown in Fig. 1.

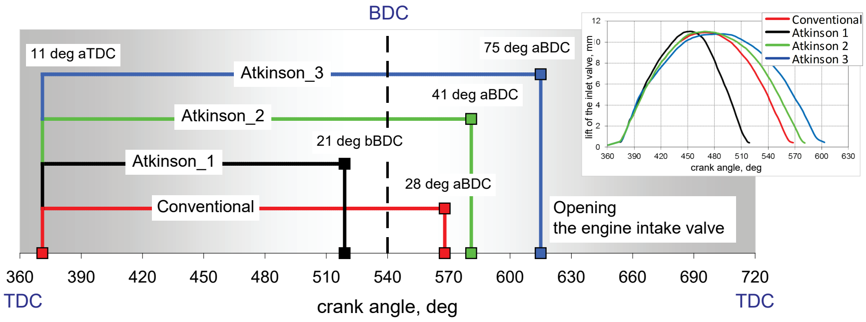

Fig. 1. Intake valve opening phases for classic cycle and Atkinson cycle

3. Modelling

On the basis of the actual dimensions of the experimental engine, a three-dimensional mesh of the engine working spaces has been built (Fig. 2). The calculation grid can be generated by discretizing of the surface or volume. In the AVL Fire program, the finite volume method (FVM) is used to calculate thermal and flow processes.

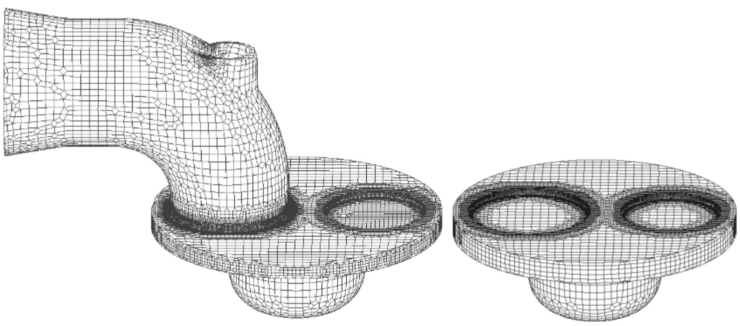

Fig. 2. Computational mesh for engine simulation

Tab. 2. Parameters for modelling

Initial conditions	
Initial pressure	0.9 bar
Initial temperature	340 K
Excess air ratio	1.0
Fuel	methane
Ignition timing	23 ºCA before TDC
AVL Fire sub models used	
Turbulence model	k-zeta-f
Combustion model	ECFM
Ignition model	Spark Ignition
NO creation model	Extended Zeldovich Model

Simulations of the combustion process were performed based on the available ECFM (Extended Coherent Flame Model) combustion model, in which a turbulent flame in the reaction zone having a coherent structure is presented as a set of elementary laminar flames [14]. Speeds and thicknesses of the spreading flame front are determined as an average value. The front of the flame is based on the concept of surface flame density.

4. Simulation results

The amount of fresh charge delivered to the engine cylinder depends mainly on the time of opening the intake valve. Fig. 3a presents a summary of the mass streams of the charge supplied to the cylinder for a conventional engine and for the engine operating according to three analyzed cases of the Atkinson cycle. It can be seen that in each case, in the first phase of the filling stroke, there is a sudden increase in the stream of incoming charge due to the opening of the intake valve. In the next phase, there is a change in the direction of the stream and there is a return flow to the intake manifold, caused by the flow of the rest of the exhaust gases from the previous cycle of the engine's operation. The next stage is the increase and decrease of the charge mass stream in accordance with the intake valve lift. For the first Atkinson cycle, in which the intake valve is closed 21 deg before BDC, no flow is visible after closing this valve. In the case of other circuits in which the intake valve closing takes place after BDC already in the compression stroke, there are visible backflows caused by the pushing of the load by the piston moving up to the TDC position. The biggest return flows are characterized by an engine operating according to the Atkinson 3 cycle, in which the closing of the intake valve takes place at the latest, 75 deg after BDC. In this causes a large part of the charge already filling the cylinder to be pushed through the piston back into the intake port. Indeed, the so-called the effective compression ratio of the engine and the amount of charge remaining in the cylinder will decrease (Fig. 3b). Less load in the cylinder will of course translate into lower engine performance [21]. Fig. 3 also shows that closing the intake valve before the piston reaches BDC the charge is prevented from pushing it back through the intake valve, i.e. return flows. However, it should be remembered that at this time there is a so-called overlap period in the engine, the phenomenon of co-opening the intake and exhaust valves, and in the engines the subsequent closing of the intake valve takes place due to other desired phenomena, such as rinsing the cylinder.

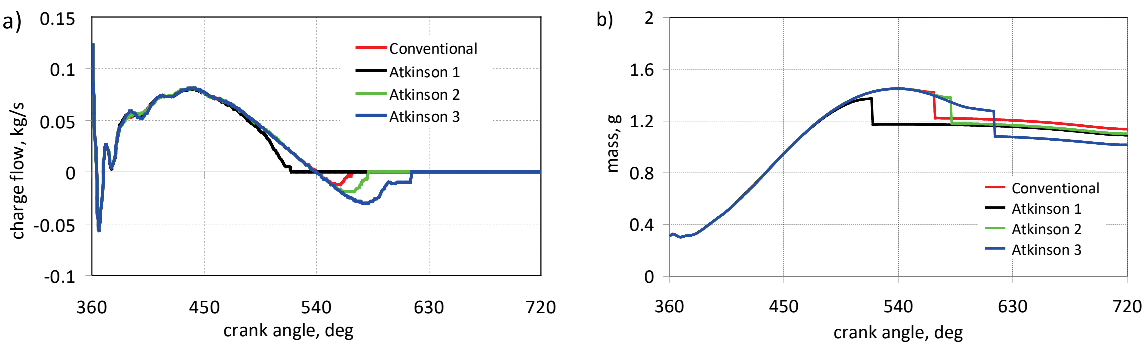

Fig. 3. Flowrate of fresh charge (a) and total mass of charge (b) for conventional and Atkinson cycles

Figure 4 presents flow velocity fields for four modelled engine work cases. The flow velocity fields indicate the level of fresh vortex turbulence in the cylinder of the engine, which contributes to the homogeneity of the mixture in the cylinder, increase the speed of the flame front after initiation of ignition and intensifies the combustion process itself.

Figure 5a shows the pressure waveforms in the initial compression stroke phase for a conventional engine and for the engine operating according to the Atkinson 1 circuit. It shows that as a result of earlier closing of the intake valve in an over-expanded cycle, the pressure decreases resulting in a reduction of the maximum compression pressure (Fig. 5b). The lower compression pressure, in turn, reduces the maximum pressure and temperature of the combustion process.

As a result of modelling, there were obtained, among others, the courses of changes in the combustion pressure (Fig. 6a) and the heat release rate (Fig. 6b) in the engine cylinder operating according to the over-expanded cycle, which were compared with the conventional engine cycle. The highest value of pressure and heat release rate was recorded for a conventional cycle in which the inlet valve closed in 28 deg after BDC. The lower mass of the charge burned in the engine cylinder corresponding to the over-expanded cycles compared to the classical engine causes the combustion process to be slower and the maximum combustion pressures reach lower values.

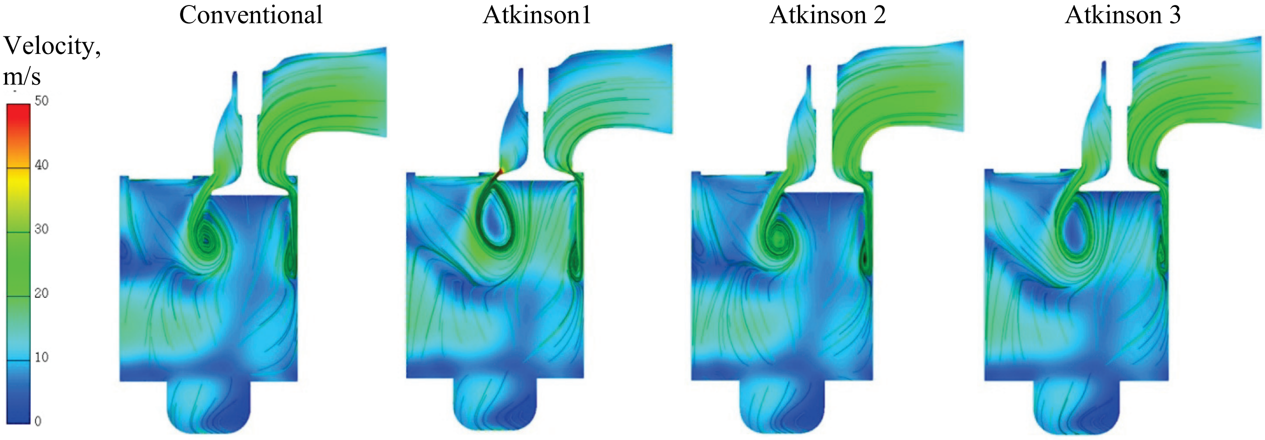

Fig. 4. Velocity fields of fresh charge for analysed cases for 40° CA before BDC during the intake stroke

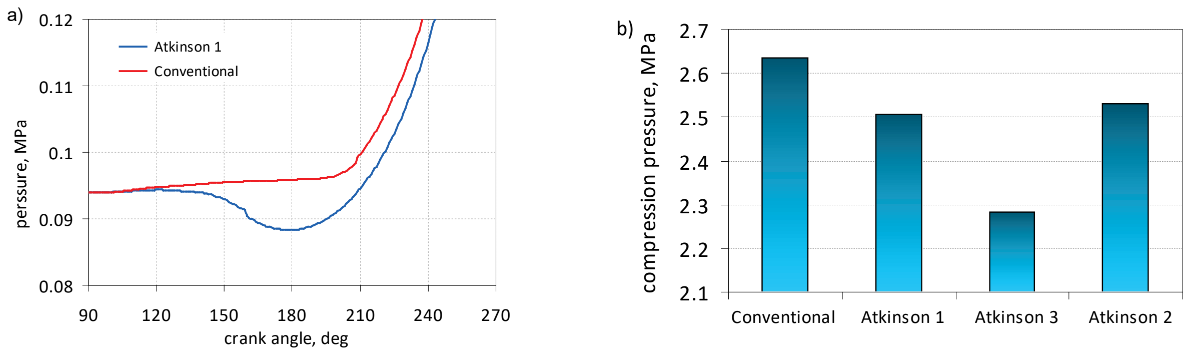

Fig. 5. Compression pressure (a) and peak compression pressure (b) for conventional and Atkinson cycles

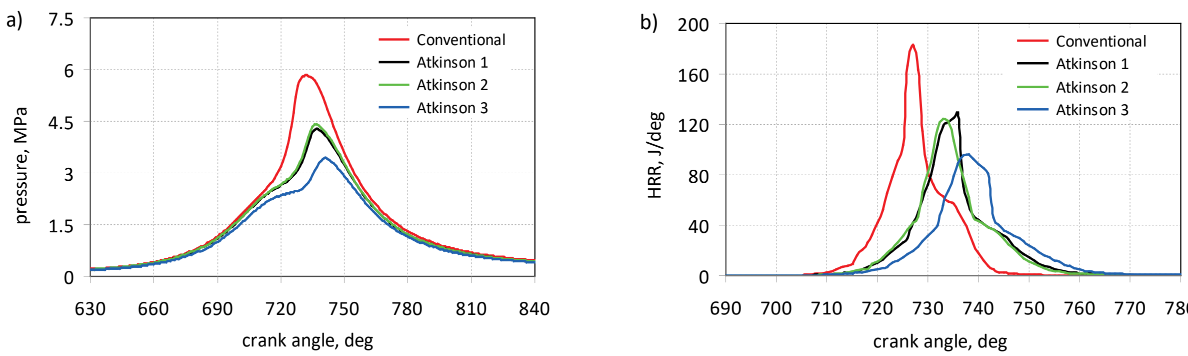

Fig. 6. Combustion pressure (a) and HRR (b) for conventional cycle and three analysed cases of Atkinson cycle

In the next stage of numerical tests, which was the optimization of the engine operating according to the classical cycle and the over-expanded cycle was performed, in which the inlet valve closed 21 deg before BDC. The optimization parameter was the ignition timing, which was changed in the range from 48 to 23 deg before TDC for the classical engine and from 57 to 23 deg before TDC for the engine operating according to the Atkinson cycle. The changes in indicated pressure and indicated efficiency were analysed, which were calculated on the basis of the pressure trace in the cylinder of the engine model. Fig. 7 shows the pressure trace in the cylinder of a conventional engine and the engine operating according to an over-expanded cycle for the analysed ignition timing range.

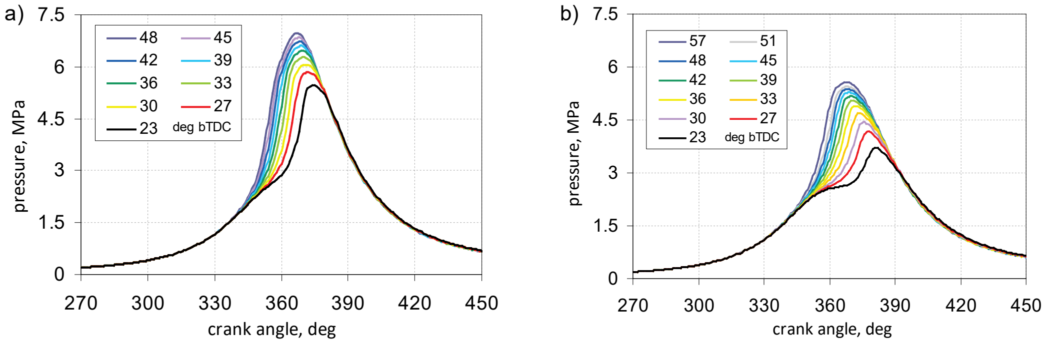

Fig. 7. Combustion pressure for conventional (a) and Atkinson cycle (I case)

The values of indicated pressure and indicated efficiency were calculated on the basis of pressure curves for each ignition timing angle [10].

Indicated mean effective pressure according to equation (1):

$$IMEP = \frac{1}{V_d}\int_0^{720} pdV, \tag{1}$$

where:
p – the cylinder pressure,
V – the cylinder volume,
V_d – the stroke volume.

Indicated thermal efficiency according to equation 2 [10]:

$$ITE = \frac{IMEP \cdot V_d}{Q_e} 100\%, \tag{2}$$

where:
Q_e – the amount of heat delivered to the engine in the fuel.

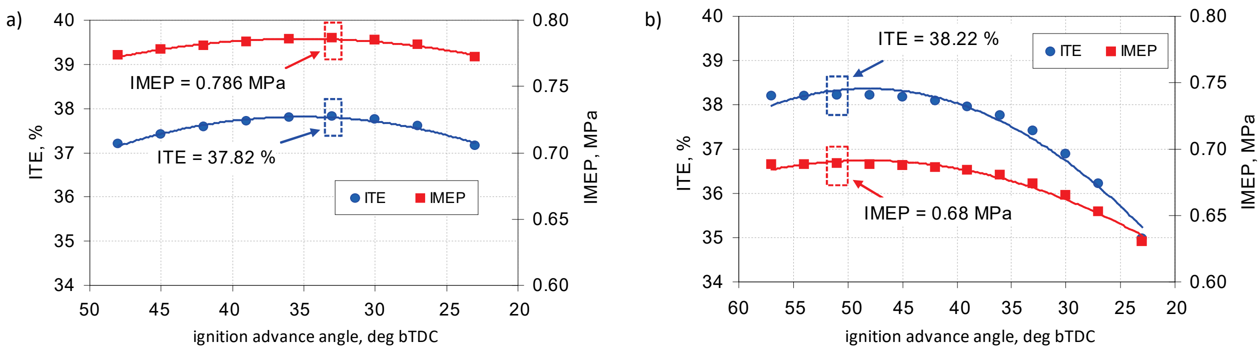

Fig. 8. Indicated mean effective pressure and indicated thermal efficiency vs. ignition timing for conventional cycle engine (a) and Atkinson cycle engine (Atkinson 1 case) (b)

Figure 8 presents the results of calculating the indicated mean effective pressure and indicated thermal efficiency for the classical engine and the engine that performs the Atkinson cycle as a function of the ignition timing. For the classic engine, an angle of 33 deg before the TDC was the optimal ignition timing, while for the engine operating according to the over-expanded cycle, was earlier and occurred at an ignition timing equal to 51 deg before TDC. The maximum indicated pressure obtained at the optimum ignition timing for a conventional engine was 0.786 MPa and was higher compared to the Atkinson cycle engine for which the IMEP = 0.68 MPa. The reason for this was that the pressure values associated with the combustion process in the engine cylinder were lower. The maximum efficiency of the classical engine, however, turned out to be lower compared to the engine operating in the over-expanded cycle. In the first case, it was 37.82%, while in the second case it was 38.22%.

5. Conclusions

As part of numerical research, modelling of the full working cycle of a conventional engine was performed, working according to the classic Otto cycle and the engine operating on the basis of an over-expanded cycle - the Atkinson cycle. The implementation of the Atkinson cycle in the internal combustion engine is one of the possibilities to increase the efficiency of the engine by modifying its design. Based on the simulations carried out, the following conclusions can be made:

- implementation of an over-expanded cycle by closing the inlet valve after BDC, during the compression stroke causes the so-called reverse flows, characterized by the pushing of fresh charge into the intake port by the engine piston and reducing the mass of the charge in the cylinder in the next cycle of the engine operation,
- implementation of an over-expanded cycle by closing the intake valve before reaching the BDC by piston prevents the process of pushing the load through the inlet valve, i.e. return flows,
- lower mass of the charge burned in the engine cylinder corresponding to the over-expanded cycle compared to the classic engine causes the combustion process to be slower and the maximum combustion pressures reach lower values,
- in the over-expanded cycle the pressure decreases in the initial stage of the compression stroke, resulting in the reduction of the maximum compression pressure, which in turn causes the reduction of the maximum pressure and temperature of the combustion process,
- an engine operating in an over expanded cycle in order to obtain the maximum indicated mean effective pressure and maximum indicated thermal efficiency requires earlier ignition timing in comparison to a conventional engine,
- in the engine operating according to the over-expanded cycle, there is a drop in the indicated mean effective pressure compared to the engine operating by the classical cycle, which may result in a reduction of the power and torque of the engine,
- the implementation of the Atkinson cycle in the combustion engine contributes to the increase in indicated efficiency, which can lead to a reduction in the brake specific fuel consumption of the engine operating according to this circuit.

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References

[1] Kociszewski, A., Jamrozik, A., Tutak, W., Sosnowski, M., *Computational analysis and experimental research into lean mixture combustion in multi-spark plug SI engine*, Journal of KONES Powertrain and Transport, Vol. 13, No. 3, pp. 123-130, 2006.

[2] Tutak, W., *Possibility to reduce knock combustion by EGR in the SI test engine*, Journal of KONES Powertrain and Transport, Vol. 18, No. 3, pp. 485-492, 2011.

[3] Szwaja, S., *Knock and combustion rate interaction in a hydrogen fuelled combustion engine*, Journal of Kones Powertrain and Transport, Vol. 18, No. 3, pp. 431-438, 2011.

[4] Atkinson, J., *Gas Engine pat. US367496 (A)* – 1887-08-02.

[5] Benajes, J., Serrano, J. R., Molina, S., Novella, R., *Potential of Atkinson cycle combined with EGR for pollutant control in a HD diesel engine*, Energy Conversion and Management, Vol. 50, pp. 174-183, 2009.
[6] Grab-Rogaliński, K., Szwaja, S., *Miller cycle application to the gaseous supercharged SI engine*, Combustion Engines, Vol. 162 (3), pp. 881-885, 2015.
[7] Grab-Rogaliński, K., Szwaja, S., Tutak, W., *The Miller cycle based IC engine fuelled with a CNG/hydrogen*, Journal of KONES Powertrain and Transport, Vol. 21, No. 4, pp. 137-144, 2014.
[8] Jamrozik, A., *Modelowanie obiegu cieplnego czterosuwowego silnika tłokowego o zapłonie iskrowym*, Modelowanie Inżynierskie, Nr 51, T. 20, pp. 28-34, 2014.
[9] Jamrozik, A., Tutak, W., Kociszewski, A., Sosnowski, M., *Numerical simulation of two-stage combustion in SI engine with prechamber*, Applied Mathematical Modelling, Vol. 37 (5), pp. 2961-2982, 2013.
[10] Jamrozik, A., Tutak, W., Pyrc, M., Gruca, M., Kočiško, M., *Study on co-combustion of diesel fuel with oxygenated alcohols in a compression ignition dual-fuel engine*, Fuel, Vol. 221, pp. 329-345, 2018.
[11] Pielecha, I., Czajka, J., Borowski, P., Wisłocki, K., *Thermodynamic indexes of Atkinson cycle combustion engine operation under transient conditions*, Combustion Engines, Vol. 154 (3), pp. 517-524, 2013.
[12] Sendyka, B., Sochan, A., *Increase of the total efficiency using the Atkinson cycle in the spark ignition engine*, Journal of KONES Powertrain and Transport, Vol. 16, No. 2, pp. 407-411, 2009.
[13] Tutak, W., *Modelowanie obiegu cieplnego tłokowego silnika spalinowego o zapłonie samoczynnym*, Modelowanie inżynierskie, Nr 49, pp. 73-78, 2013.
[14] Tutak, W., Jamrozik, A., *Validation and optimization of the thermal cycle for a engine by computational fluid dynamics modeling*, Applied Mathematical Modelling, No. 40 (13-14), pp. 6293-6309, 2016.
[15] Tutak, W., Jamrozik, A., Gruca, M., *CFD modeling of thermal cycle of supercharged compression ignition engine*, Journal of KONES Powertrain and Transport, Vol. 19, No. 1, pp. 465-472, 2012.
[16] Prajwowski, K., Osipowicz, T., *Hybrid vehicle diagnostics*, Journal of KONES Powertrain and Transport, Vol. 24, No. 1, pp. 309-315, 2017.
[17] Jankowski, A., *Chosen problems of combustion processes of advanced combustion engine,* Journal of KONES, Vol. 20, No. 3, pp. 203-208, Warsaw 2013.
[18] Jankowski, A., Kowalski, M., *Creating Mechanisms of Toxic Substances Emission of Combustion Engines,* Journal of KONBiN, 4(36), DOI 10.1515/jok-2015-0054, pp. 33-42, Warsaw 2015.
[19] Jankowski, A., Kowalski, M., *Environmental Pollution Caused by a Direct Injection Engine,* Journal of KONES, Vol. 22, No. 4, DOI: 10.5604/12314005.1168461, pp. 133-138, Warsaw 2015.
[20] Jankowski, A., Sandel, A., Sęczyk, J., Siemińska-Jankowska, B., *Some Problems of Improvement of Fuel Efficiency and Emissions in Internal Combustion Engines,* Journal of KONES, Vol. 9, No. 1-2, pp. 333-356, Warsaw 2002.
[21] Kowalski, M., Jankowski, A., *Research Performance of Novel Design of Diesel Engine*, Journal of KONES, Vol. 24, Issue 4, DOI: 10.5604/01.3001.0010.3157, pp. 99-108, Warsaw 2017.
[22] Zurek, J., Kowalski, M., Jankowski, A., *Modelling of Combustion Process of Liquid Fuels under Turbulent Conditions,* Journal of KONES, Vol. 22, Issue 4, DOI: 10.5604/12314005.1168562, pp. 355-364, Warsaw 2015.

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