A simulation study into the Atkinson cycle engine utilizing adjustable crank mechanism

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Abstract. Technologies that improve the efficiency of internal combustion engines are attracting ever-growing interest due to increasing demands concerning fuel economy and exhaust emissions. For years, engine evolution was focused on software or control devices development, with acceptance of only small mechanical changes to the well-established engine design. Recently, researchers and engineers put their attention to large mechanical changes to allow achieving high fuel efficiency. In the current study, a set of simulation experiments was performed to investigate the potential of Atkinson cycle realization using a modified Atkinson crank mechanism. The latter was modified by using excenter pin which additionally enabled control of compression ratio as well as the ratio between compression and expansion. Investigated solution was analysed under spark ignition operation and compared to the standard crank mechanism. The simulations were performed using AVL BOOST software. The model was validated using standard spark ignition engine measurement data. Afterwards, the engine was modified to investigate above mentioned strategies to improve thermal efficiency. The research successfully identified strategies, which allow control of engine aspiration and combustion, to hasten real-world application of these advanced combustion systems.

1. Introduction

Great emphasis on ecological aspects, especially those concerning the automotive industry, generates increasing requirements for the emissions of vehicles and their efficiency. This affects the need for continuous development of energy converters. The designs of reciprocating internal combustion engines have been developed for over 150 years. During this period engineers reduced fuel consumption as much as possible and the amounts of emitted toxic compounds while maintaining the best performance. Despite years of work and advanced research, typical engines still require improvement [1]. Diesel engines encounter problems with high NO_X and particulate emissions [2][3][4]. In order to limit the emissions a number of modifications were introduced, such as direct fuel injection, a particulate filter or a selective catalytic reduction [5][6]. The possibility of using biofuels to power engines was also examined [7] to make them more environmentally neutral. Spark ignition engines, although they generate less pollution than diesel engines, are also struggling with certain problems. The lower thermal efficiency compared to the Diesel engine affects the higher fuel consumption. The biggest obstacle for the SI engine in improving thermal efficiency is its tendency to knocking combustion [8]. This unfavorable event prevents engines from obtaining higher compression ratios and thus an optimized working process [9]. In recent years, the concept of homogeneous charge compression ignition (HCCI) combustion has attracted the attention of researchers, allowing for a significant reduction of toxic exhaust compounds emissions while maintaining high engine performance [10][11]. The additional advantage of HCCI combustion technology is fuel flexibility [12][13]. However, the disadvantage of the HCCI system is the inability to active control the ignition timing, which is an obstacle to the commercialization of these engines [14][15]. Engine operation under variable conditions and mixture formation strategies was investigated, but high load still poses a challenge [16][17]. Therefore, to meet future requirements for fuel economy and engine emissions, combustion systems should be constantly developed and new solutions should be sought to achieve higher efficiency of internal combustion engines.

Searching for solutions that increase the efficiency of internal combustion engines attracted interest in engines with unconventional crank and piston systems. The numerous alternative engine mechanical solutions are known however, they have not been introduced into mass production due to high costs involved. There are known solutions in which the axes of the cylinders lie parallel to the axis of the shaft. Such structures, called revolver engines, were developed in the interwar period of the twentieth century. They were characterized by a smaller front surface and mass, compared to conventional constructions. This created the potential for the use this type of engine in the aerospace industry. A detailed review of known revolver engines is presented in [18].

There are also known engines with a standard, perpendicular arrangement of cylinders relative to the shaft. Construction using components known from conventional engines excludes problems related to the production technology of individual engine parts. However, the crank and piston system itself is modified. Noteworthy, here is the engine that implements the Atkinson cycle. In order to implement the Atkinson cycle, the crank and piston system was modified by introducing an additional oscillating member [19]. The Atkinson cycle consists of four strokes as in a conventional engine. The difference between a conventional engine and an engine operating in the Atkinson cycle consists in shortening the intake stroke with respect to the power stroke. Thanks to this, the engine working in the Atkinson cycle can achieve higher thermal efficiency than the Otto cycle engine while maintaining an effective compression ratio at a level that does not cause knocking [20]. Atkinson cycle can be realized using various crank mechanisms e.g. [21]. Similar thermodynamic effects can be realized via variable valvetrain, and reduction of aspirated air by early or late closing of the intake valve [22][23]. Apart from Atkinson cycle, also other solutions to improve piston engines should be mentioned. Dąbrowski et al.[24]demonstrated pneumatic accumulator to increase combustion chamber volume at high engine load to reduce peak pressure and peak temperature of the cycle.

The above mentioned technologies were previously abandoned due to high costs of technology and a large development of control strategies effort. Today, due to high demands concerning toxic emissions and preservation of energy sources, alternative engine designs are considered feasible.

The purpose of this work was to examine the parameters of the engine that implements the Atkinson cycle. Using the CAD software, a geometrical model was designed to analyze the kinematics of the tested engine. The crank mechanism geometry was modified by means of an eccentric pin, which allowed us variability of compression ratio. The tests were carried out for different configurations of the designed mechanism. Based on the kinematics of the tested engines and kinematics of the Otto cycle engine, simulations were performed with the use of AVL BOOST software. The test conditions included variable engine load via throttling. The thermal efficiency with consideration of in-cylinder conditions was analyzed and discussed for variable engine configuration.

2. Methods

Numerical calculations were made using the AVL BOOST software. It is an advanced, dedicated tool for zero-dimensional modeling of the engine's working cycle. The engine model contains modules for calculating the gas flow in the inlet and outlet runners, the combustion sub-model based on the assumed course of heat release and the sub-model of heat exchange. In order to carry out the experiment, models of four crank mechanism solutions of the same engine were developed. The engine was operated at three different settings of excenter pin: 0 °, 30 ° and 60 °, as a baseline standard crank mechanism was considered. The models were made on the basis of one engine in which the cylinder diameter was 84 mm and the (baseline) piston stroke was 90 mm. Additional data regarding the geometry of the tested engines is shown in table 1The ε_{exch} parameter means the compression ratio of the Atkinson engine during the load exchange and ε_{power} means the compression ratio during the main compression event.

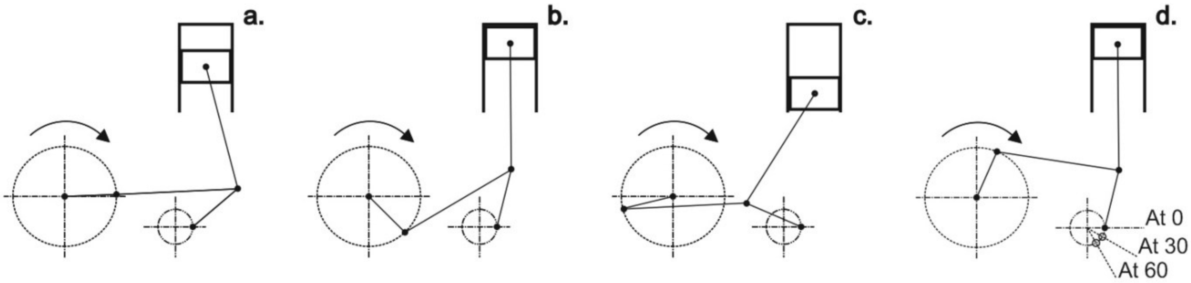

Figure. 1. The Atkinson cycle, a. intake, b. compression, c. work, d. exhaust

Table 1. Data of the engine geometry.

Configuration	$\varepsilon_{exch.}$[-]	ε_{power}[-]	ΔV_{intake}[cm^3]	ΔV_{power}[cm^3]
Standard	12.0	12.0	498.76	498.76
At0	9.9	15.4	319.21	519.41
At30	9.1	12.1	348.68	481.50
At60	6.2	7.7	369.83	461.38

Model calculations were made in the range of indicated mean effective pressure (IMEP) from 0.15 to 0.75 MPa, achieved via variable fuelling and throttling. Air-fuel ratio was set to stoichiometric point. For all investigated conditions the same mass fraction burnt curve, fitted by Wiebe model, was used. Briefly start of combustion was fixed at 0°CA, end of combustion was 50°CA, and Wiebe exponent was set to achieve symmetrical heat release curve. Engine rotational speed was fixed in this experiment to 2500 rev/min. Additional data regarding the combustion conditions and timing angles is shown in table 2.

Table 2. Combustion conditions and timing angles

Combustion conditions	
Start of combustion	0 [°CA]
Combustion duration	50 [°CA]
Shape parameter	3.5 [-]
Vibe parameter	6.9 [-]
Timing angles	
Intake valve opening	341 [°CA]
Intake valve closing	592 [°CA]
Exhaust valve opening	133 [°CA]
Exhaust valve closing	375 [°CA]

3. Results and discussion

Figure 2 shows volume above the piston for standard crank mechanism and Atkinson mechanism for variable position of the excenter pin. The straight forward effects of the different engine geometries are manifested by pressure-volume diagrams shown in figure 3. Variable compression ratios result with different end of compression temperatures. Additionally, the volume at piston top dead center varies, which further affect peak pressures. If standard engine configuration is considered as reference condition, positioning of the excenter pin between 0°(At0) and 30° (At30) increases peak pressure from 1.4 MPa to 2.2-2.4 MPa, accordingly. It can be also noted, that besides changes in the main event, realization of modified Atkinson cycle affect gas exchange event to a high extent.

To provide more detailed information on efficiency penalty for gas exchange process, figure 4 shows gas exchange IMEP, calculated for the exhaust and intake strokes versus net IMEP, calculated for the whole cycle. At0 engine design provides the highest loss of indicated work for the gas exchange. The positioning of excenter pin at 60°CA provides the smallest work losses. Interestingly, standard engine configuration provides relatively high gas exchange IMEP (low losses), comparable with At60 configuration. It results from differences in swept volumes for intake stroke and power stroke. The work of exhaust stroke was calculated for volume swept starting from end of power stroke, thus it was increased in comparison with related intake stroke length.

Nevertheless, at At0 configuration the lowest specific fuel consumption was achieved for whole investigated load range. In comparison with standard engine, configuration indicated specific fuel consumption (ISFC) was reduced by 20% for low load, and by 5% for high load. This advantage results mainly from high main event compression ratio achieved for Atkinson configuration. Positioning of the eccentric pin at 30° provides compression ratio close to standard configuration, i.e. 12:1. Even at this configuration, Atkinson cycle reduces fuel consumption by approximately 15% at net IMEP = 0.25 MPa. It should be also noted that At30 engine configuration enables achieving higher maximum IMEP (obtained at ambient pressure aspiration) than for At0. To provide more insight into throttling losses and the range of engine load control via intake pressure figure 6 shows intake pressures applied at all investigated conditions.

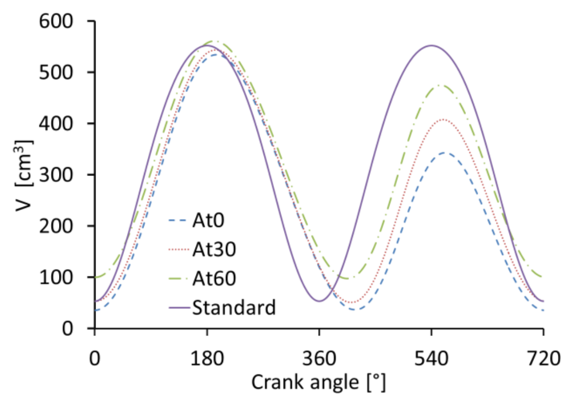

Figure 2. Volume above the piston for all investigated engine configurations.

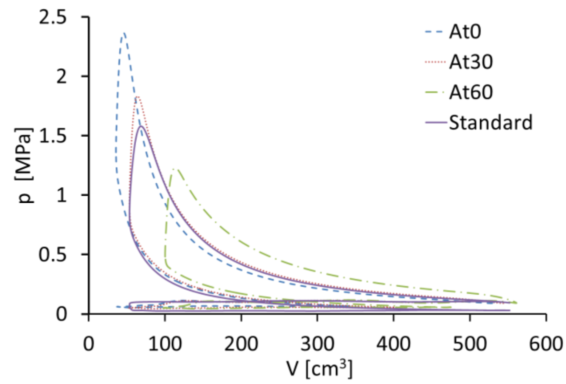

Figure 3. Pressure-volume diagrams for all investigated engine configurations, IMEP≈0.25 MPa.

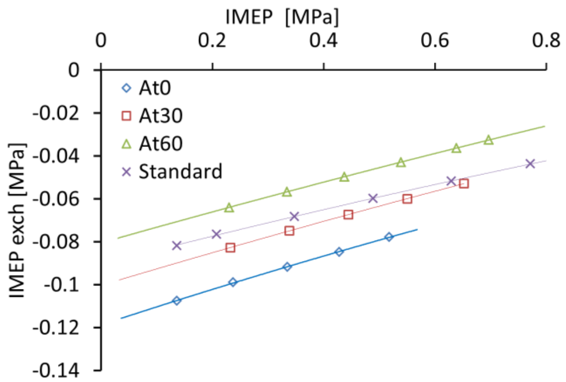

Figure 4. Indicated mean effective pressure (IMEP) calculated for the charge exchange with respect to net IMEP calculated for the whole cycle.

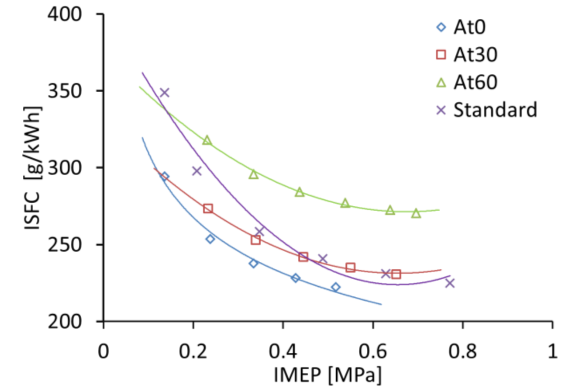

Figure 5. Indicated specific fuel consumption (ISFC) with respect to net indicated mean effective pressure.

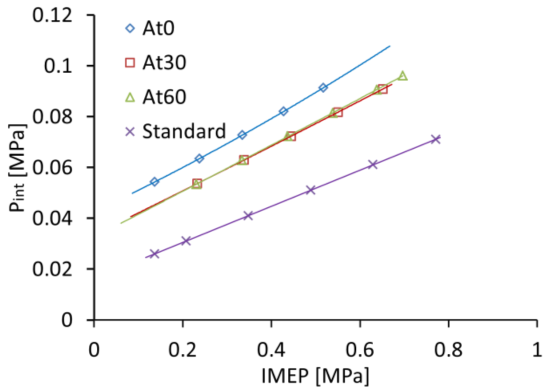

Figure 6. Average intake pressure with respect to net indicated mean effective pressure.

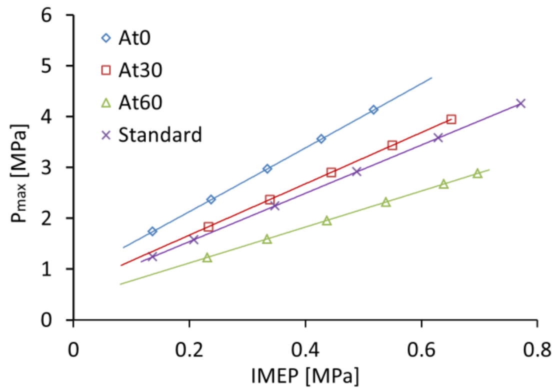

Figure 7. Maximum in-cylinder pressure with respect to net indicated mean effective pressure.

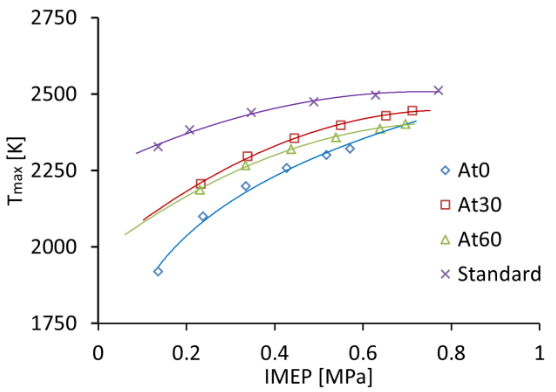

Figure 8. Maximum in-cylinder temperature with respect to net indicated mean effective pressure.

Configuration At0 enables reduction of engine throttling by approximately 50% in comparison to standard configuration. Intake pressures for two remaining cases, i.e. At30 and At60 are almost the same, between two latter cases. Nevertheless, figure 5 shows that At30 provides much better fuel efficiency than At60. This is a result of very low compression ratio of 7.7 for the latter case.

Although, ISFC for At60 configuration is higher than for standard engine design, this configuration has some important advantages. Low peak pressures and low peak temperatures, shown in figure 7 and figure 8 respectively, enable reduction of nitrogen oxides production at elevated engine load. Reduced compression ratio enables application of boost to improve engine performance, without shortcomings resulting from excessive emissions and combustion harshness. Moreover, such engine configuration would enable application of optimal combustion timing even at high load. Thus achieving high thermal efficiency throughout whole spectrum of engine loads would be attainable.

4. Conclusions

A spark ignition engine with variable crank mechanism geometry was analyzed in the study. The investigations were carried out for standard in-line crank mechanism and Atkinson mechanism. However, the original Atkinson design was modified using excenter pin which enabled variability of a compression ratio as well as the ratio between compression and expansion lengths. The simulation study was aimed at fuel efficiency analysis with consideration of acceptable pressure and temperature conditions in the cylinder. The findings of the study can be summarized as follows:

1. Atkinson engine configuration enables increase of thermal efficiency at low load regime by approximately 20% in comparison to standard crank mechanism, mainly because of increased compression ratio and reduced pumping losses.

2. However, the Atkinson engine operation is manifested by high peak pressures which precludes achieving of high loads.
3. High loads are attainable when Atkinson engine is modified by using proposed excenter pin. The modification allowed us variation of compression ratio to achieve high efficiency and low loads and limit peak pressures and peak temperatures at high loads.

The presented initial results proven that modified crank mechanism based on Atkinson design can provide additional flexibility, which enables optimal engine operation both under low and high loads. To fully understand and quantitatively evaluate the proposed engine design we should perform more simulations including boosted engine operation and optimized combustion.

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