INFLUENCE OF INCREASED PRESSURE FOR OVER-EXPANDED ENGINE PERFORMANCE

Karol Grab-Rogalinski
Czestochowa University of Technology
Institute of Thermal Machinery
Tel+48 34 3250503
fax+48 34 3250555
e-mail grab@imc.pcz.pl

Abstract: *The article presents a study of modelling a combustion cycle of spark-ignition gas engine. During the simulation the influence of turbocharging for engine performance and exhaust gas emissions was tested. The fuel which was use during the simulation was methane, which is the most common fuel used in power generation systems. The studies were performed with use of AVL BOOST software which is 1-D tool and allow to perform very fast calculation of engine combustion cycle. The results show that the use of turbocharging in over-expanded cycle allow to increase in power output for the gas engine.*

Keywords: *gas engine, over-expanded cycle, emissions, simulation*.

1 INTRODUCTION

The over-expanded cycle was introduced by British engineer James Atkinson in 1885 [2]. The principals of Atkinson cycle were based on an assumption that expansion stroke will be longer than compression stroke. The original concept of such engine was based on special design of the crank mechanism. The purpose of such cycle was to use better the energy stored in exhaust gases. Shiga et al. observed the increase in thermal efficiency of the engine with Atkinson cycle [3].

This concept of the engine in this days is very popular in engines for passenger cars especially in hybrids and in industrial engines for CHP purpose. Modern engine design with over-expanded cycle is realized by proper camshaft phases. There are to methods where intake valve closure relative to the bottom dead center (BDC) is earlier or later. Such solution was presented by R. H. Miller in 40's of XX century [4]. Over-expanded cycle causes decrease in engine performances what is mainly cause by decrease in volumetric efficiency [10, 11, 12]. Decrease in volumetric efficiency cause a decrease in in-cylinder pressure and temperature. Lower pressure and temperature allows to decrease possibility of knock combustion occurrence [5, 6, 7] and decrease in NOx emission [6, 7, 8, 9, 10]. To reduce the drawback related to the engine performance the turbocharging or supercharging can be applied. This not only not only will increase the engine performance but also it will increase thermal efficiency.

Knock combustion is a negative phenomenon which can lead to engine damage [1]. One of the methods to prevent knock combustion is over-expanded cycle engine.

This paper presents research done with 1-D simulation software AVL Boost. This software is a fully integrated IC engine simulation software which delivers advanced models enabling accurate prediction of engine performance, exhaust gas emissions and acoustics.

2 SIMULATION SETUP

Simulation was done in AVL BOOST software for three cases of engine setup. First case was for originally cam phases, the same as in test engine. In second case the phase for intake cam was shortened in that manner that the intake valve closure was before bottom dead center (BDC). The second case was for over-expanded cycle engine. Third case was for over-expanded cycle engine with turbocharger. The turbocharger was used in simulation for obtaining the same indicated parameters for over-expanded cycle engine as for Otto cycle engine in first case. The simulated cases in this research are presented in table 1.

Tab. 1. Simulation tests

Simulated case	M	S I	S II	SIII
λ [-]	1	1	1	1
IVC [deg aBDC]	60	60	-10	-10
TC [-]	No	No	No	Yes
No. of calculated cycles	-	100	100	100
RPM	1260	1260	1260	1260
IT [deg bTDC]	27	27	27	27
Fuel	Methane	Methane	Methane	Methane

In first stage of simulation the parameters for combustion model had to be chosen. The geometrical parameters were the same as for test engine. The engine chosen for simulation was 1-cylinder spark ignited gas engine. The geometrical data for the engine are presented in table 2.

Tab. 2. Enginel data (1HC102 engine)

Parameter	
Displacement [dm^3]	1
CR [-]	11
IVO [deg bTDC]	20
IVC [deg aBDC]	60
EVO [deg bBDC]	60
EVC [deg aTDC]	20

The combustion model which was chosen for calculation among others available was VIBE 2-zone. This model was chosen because of exhaust gas emission calculations. The parameters for VIBE function were set to optimize simulated pressure trace with one which was measured on the test engine. The comparison of simulated pressure trace and recorded from test engine is presented in figure 1.

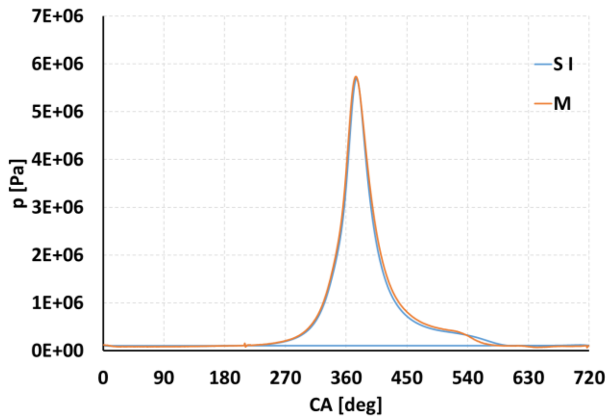

Fig. 1. Pressure trace comparison between test engine and simulated model

For the purpose of the simulation two models were build, one without turbocharger and one with turbocharger. Models of the tested engine are presented in figure 2.

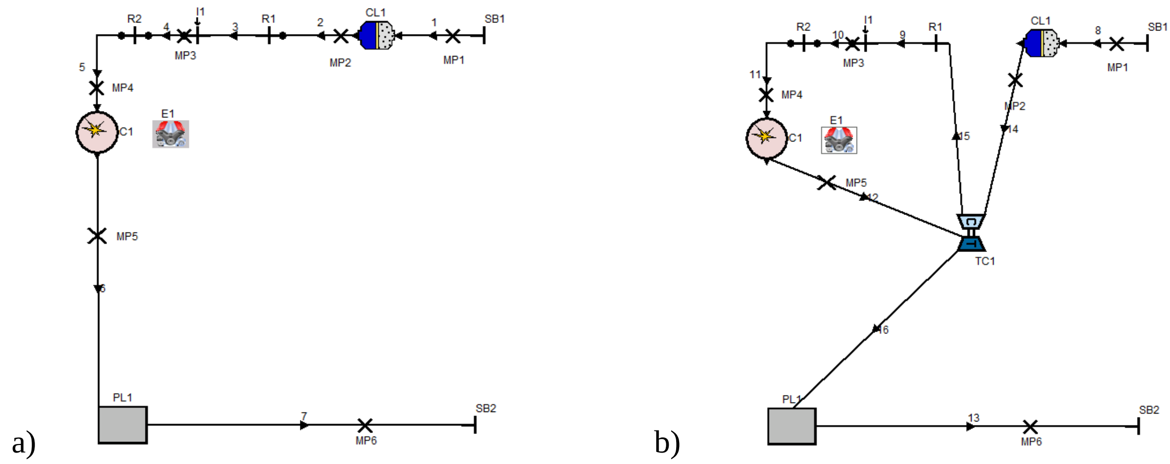

Fig. 2. Models used in simulation, a) NA, b) TC

In case of turbocharged engine calculation some simplifies were conducted. First it was set that engine is working at steady state operation point. Such assumption allowed to calculate a simple model of turbocharger in AVL Boost. The calculation of the simple model doesn't need complete map for turbine and compressor but only some basic parameters as overall efficiency of turbocharger, pressure ratio for turbine, mechanical efficiency etc.

3 RESULTS AND DISCUSSION

Figure 3 presents comparison of pressure trace for simulation case S I and S II. As can be seen the maximum value of combustion pressure is caused by decrease in volumetric efficiency related with intake valve closure before BDC (Bottom Dead Center).

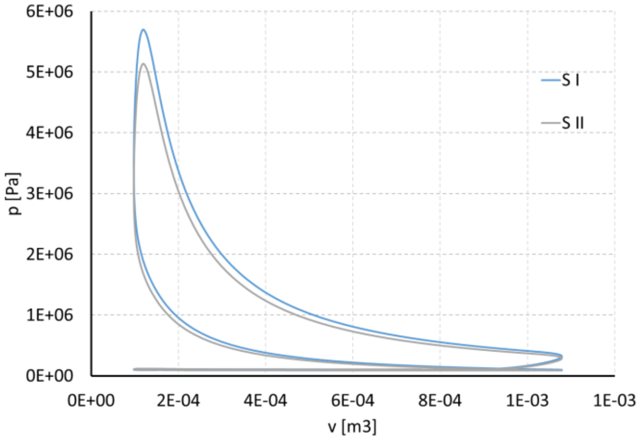

Fig. 3. Comparison of pressure trace for engine with configuration S I and S II

Characteristic for earlier intake valve closure is the shape of exchange process loop. The trace of comparison for charge exchange loop is presented in figure 4.

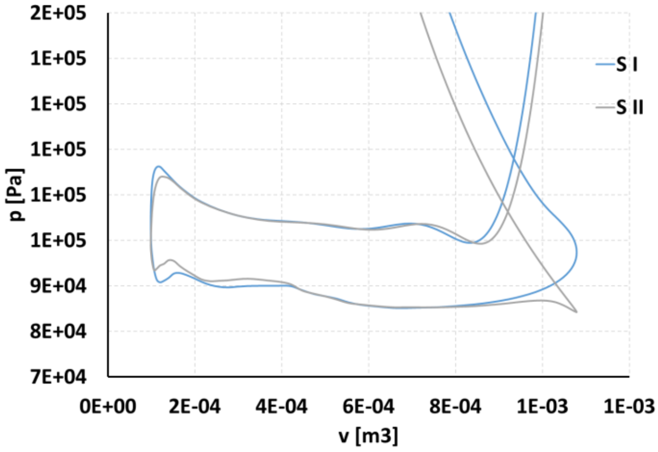

Fig. 4. Comparison of charge exchange loop pressure trace for engine with configuration S I and S II

As can be seen for case S II where intake valve is closed bBDC there is a pressure drop, what cause lower pressure during the end of compression stroke. In such case there can be observed decrease in maximum combustion temperature and decrease in engine performance. Performance of the both simulated cases are presented in table 3.

Tab. 3. Performance for the engine in configuration S I and S II

	S I	S II
T_{max} [K]	2540,62	2517,89
N [kW]	9,8	8,89

To increase engine performance in an over-expanded cycle engine the turbocharging was used. Turbocharging not only allow to increase engine performance but also increase engine indicated efficiency by use of energy stored in hot exhaust gases.

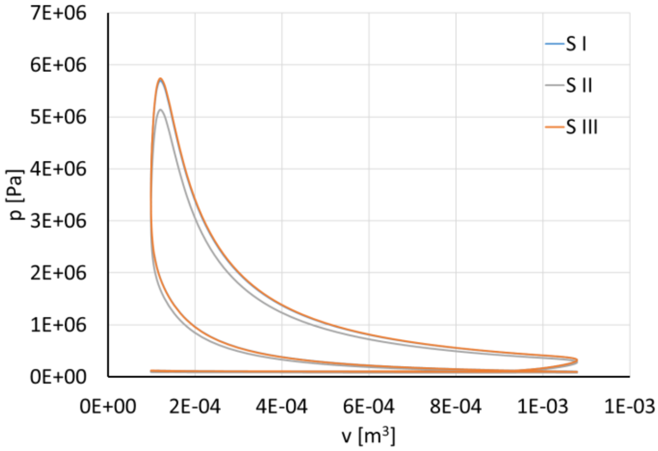

Fig. 4. Comparison of pressure trace for simulation cases S I, S II and S III

As can be observed for case S I and S III the pressure trace is the same at high pressure loop. The difference can be observed in charge exchange loop, what is presented in figure 5. In charge exchange loop can be observed that for use of turbocharging the intake pressure was almost the same as pressure of exhaust gases and much higher than for naturally aspirated (NA) engine model.

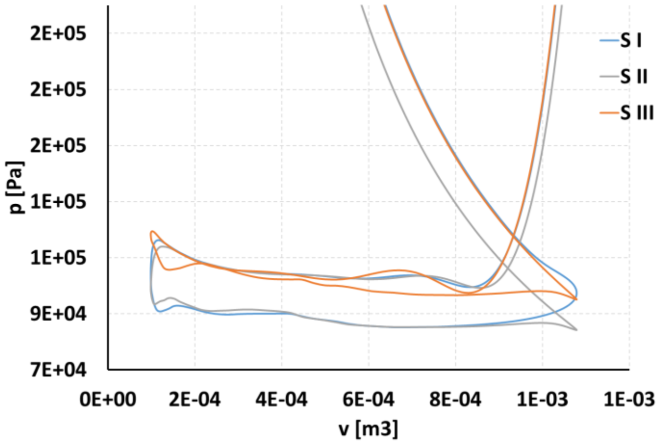

Fig. 5. Comparison of charge exchange loop for three simulated cases

In case of this studies the increase in charge overpressure was only 0,15 bar. This overpressure allowed to obtain the same engine performance as for S I case with naturally aspirated engine (NA). The comparison of engine performance for case S I, S II and S III are presented in table 4.

Tab. 4. Comparison of engine performance for case S I, S II and S III

	S I	S II	S III
IMEP [bar]	9,59	8,70	10,18
N_i [kW]	9,8	8,89	10,4
T_{max} [K]	2540,62	2517,89	2537,98
η_v [-]	0,74	0,67	0,75
η [-]	0,3105	0,3114	0,3148
ISFC [g/kWh]	231,88	231,24	228,75
Parameters at the start of combustion			
p [bar]	12,19	10,82	12,15
T [K]	704,24	686,59	696,28

The modification of engine cycle has influence for emission of exhaust toxic components. The results of calculation for exhaust toxic components are presented in table 5.

Tab. 5. Exhaust gas emission for simulated engines

	S I	S II	S III
NO_x [g/kWh]	0,224	0,173	0,212
CO [g/kWh]	240,27	242,21	236,16
HC [g/kWh]	1,76	1,76	1,71

Decrease of NO_x emission was observed for both over-expanded cycle cases. Much lower emission on NO_x was for S II case where only over-expanded cycle without turbocharging was used. That trend is related with maximum combustion temperature which was lower for over-expanded cycle engine models.

4 CONCLUSION

The results of simulation studies for over-expanded cycle gas engine shows that the over-expanded cycle engine is more efficient than Otto cycle engine. On the basis of conducted researches the following conclusion can be made:

1) Early intake closure is an effective method for decrease in maximum temperature of combustion.
2) Early intake closure causes a decrease in engine performance.
3) Over-expanded cycle has higher indicated efficiency compared to classic Otto cycle.
4) Addition of charging system to over-expanded cycle engine allow to increase both engine performance and indicated efficiency.
5) Application of over-expanded cycle cause decrease in exhaust gas emission compared to Otto cycle engine.

ACKNOWLEDGEMENTS

The numerical investigation was done with use of AVL Boost which was used under the university partnership program between AVL List GmbH and Czestochowa University of Technology.

The research was partially done under the project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691232 — Knocky — H2020-MSCA-RISE-2015/H2020-MSCA-RISE-2015 and the research was additionally co-financed by Polish Ministry of Science within the frame of science support funds for international co-funded projects in 2016-2019.

REFERENCES

[1] Atkinson J. Gas Engine pat. US367496 (A) — 1887-08-02.

[2] Shiga S, Hirooka Y, Miyashita Y, Yagi S, Machacon HTC, Karasawa T, Nakamura H. Effect of over-expanded cycle in a spark-ignition engine using late-closing of intake valve and its thermodynamic consideration of the mechanism. International Journal of Automotive Technology 2001;2(1):1-7.

[3] Miller RH. Supercharging and internal cooling for high output. ASME Transactions 1947;69:453-464.

[4] Grab-Rogaliński K, Szwaja S. Influence of intake valve closure angle on IC engine indicated parameters. Journal fo KONES 2015; 22(3):29-36.

[5] Mikalsen R, Wang YD, Roskilly AP. A comparison of Miller and Otto cycle natural gas engine for small scale CHP application. Applied Energy 2009;86:922-927.

[6] Grab-Rogaliński K, Szwaja S. Miller cycle application to gaseous supercharged SI engine. Combustion engines 2015;3:881-885.

[7] Lake T, Stokes J, Murphy R, Osborne R. Turbocharging Concepts for Downsized DI Gasoline Engines. SAE paper 2004-01-0036.

[8] Kapus PE, Poetscher P. ULEV and fuel economy – a contradiction. SAE paper 2000-01-1209.

[9] Kapus PE, Denger D, Holladn T. Intelligent simplification – ways towards improved fuel economy. SAE paper 2002-01-0235.

[10] Wu Ch, Puzinauskas PV, Tsai JS. Performance analysis and optimization of a supercharged Miller and Otto engine. Applied Thermal Engineering 2003;23:511-521.

[11] Wik Ch, Hallback B. Reducing emission using 2-stage turbocharging. WARTSILLA Technical Journal, 01.2008.

[12] Heywood JB. Internal combustion engine fundamentals, New York, McGraw-Hill, 1988.