NUMERICAL ANALYSIS OF IN-CYLINDER PRESSURE AND TEMPERATURE CHANGE FOR NATURALLY ASPIRATED AND UPGRADED GASOLINE ENGINE

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Abstract: *The paper presents numerical analysis of in-cylinder pressure and temperature change for naturally aspirated gasoline engine and two of its upgrades - upgrade with turbocharger only and upgrade with turbocharger along with air cooler. Numerical analysis was performed with 0D (zero-dimensional) numerical model. In-cylinder temperatures, for each engine rotational speed, are the highest for engine upgraded only with the turbocharger. The highest observed in-cylinder temperature of turbocharged engine was obtained at 5000 rpm and amounts 2542.4 °C. In-cylinder pressures are the highest for engine upgraded with turbocharger and air cooler for all rotational speeds except the highest one. The highest observed in-cylinder pressure of a turbocharged engine with air cooler was obtained at 5000 rpm and amounts 129.7 bars. Presented analysis showed that the selected air cooler can be improved at highest engine rotational speed.*

KEYWORDS: NUMERICAL SIMULATION, IN-CYLINDER PROCESS, GASOLINE ENGINE, ENGINE UPGRADE

1. Introduction

Gasoline engines with spark ignition are one of the known types of internal combustion engines [1]. Its characteristics and specifications are dependable on many parameters.

Researchers are currently investigating various elements related to gasoline engines. Kilicarslan and Qatu [2] performed an exhaust gas analysis of gasoline engine based on engine speed. Elsemary et al. [3] investigated spark timing influence on the performance of a gasoline engine fueled with a mixture of hydrogen-gasoline.

Control and regulation systems are essential elements of any gasoline engine, which ensures engine proper operation. Yar et al. [4] developed and presented first principle based control oriented model of a gasoline engine which includes multi-cylinder dynamics. Nonlinear constrained torque control system for a gasoline engine developed Kang et al. [5].

Alternative fuels for gasoline engines are investigated by many authors. Elfasakhany [6] performed gasoline engines performance evaluation and pollutant emissions analysis by using ternary bio-ethanol-iso-butanol-gasoline blends. Effect of addition of hydrogen and exhaust gas recirculation on characteristics of hydrogen gasoline engine investigated Du et al. [7].

Turbocharging process which uses the energy of engine exhaust gases is one of the best methods for improving naturally aspirated engine operating parameters and characteristics. Modeling and control of the air system for a turbocharged gasoline engine investigated Moulin and Chauvin [8]. An upgrade of turbocharging process involves air cooler after charger, in order to perform proper cooling of air which enters into the engine cylinders [9]. Air cooling allows an increase of engine volumetric efficiency and decrease of maximum in-cylinder temperature when compared to the engine which has only the turbocharger.

In this paper is presented numerical analysis of in-cylinder pressure and temperature change for naturally aspirated gasoline engine and two of its upgrades - upgrade only with turbocharger and upgrade with turbocharger along with air cooler. Numerical analysis was performed with 0D (zero-dimensional) numerical model. It was obtained that in-cylinder temperatures, for each engine rotational speed, are the highest for engine upgraded only with the turbocharger. In-cylinder pressures are the highest for engine upgraded with turbocharger and air cooler for all rotational speeds except the highest one. Presented analysis showed that air cooler, selected in this analysis, can and should be improved at highest engine rotational speed.

2. Numerical model equations for in-cylinder temperature and pressure change calculation

Numerical model used for simulations is 0D (zero-dimensional) model presented by Medica [10]. 0D model is basically developed for simulation of diesel engines and after a while is upgraded on QD (quasi-dimensional) model [11] which results are presented in [12] and [13] for high-speed four-stroke diesel engine and in [14] for slow-speed two-stroke diesel engine.

To be able to simulate the operating parameters of a gasoline engine with the mentioned 0D model, the numerical model is modified in necessary elements which present differences in operating characteristics between gasoline and diesel engines. The modified 0D model is tested on several gasoline engines. For all analyzed gasoline engines and for its operating parameters were obtained deviations between producer specifications and numerical model results in the range of ± 3 %.

Engine cylinder is presented as a separate control volume with periodical change of the volume. The shape is determined by the volume walls (cylinder, head and piston face). The differential equation for the temperature change related to the crank angle is:

$$\frac{\mathrm{d}T_\mathrm{c}}{\mathrm{d}\varphi}=\frac{1}{m_\mathrm{c}\left(\frac{\partial u}{\partial T}\right)_\mathrm{c}}\left[\begin{array}{l}\sum\limits_\mathrm{i}\frac{\mathrm{d}Q_\mathrm{c,i}}{\mathrm{d}\varphi}-p_\mathrm{c}\frac{\mathrm{d}V_\mathrm{c}}{\mathrm{d}\varphi}+\sum\limits_\mathrm{j}\left(h\frac{\mathrm{d}m}{\mathrm{d}\varphi}\right)_\mathrm{c,j}-\\-u_\mathrm{c}\frac{\mathrm{d}m_\mathrm{c}}{\mathrm{d}\varphi}-m_\mathrm{c}\left(\frac{\partial u}{\partial\lambda}\right)_\mathrm{c}\frac{\mathrm{d}\lambda_\mathrm{c}}{\mathrm{d}\varphi}\end{array}\right] \quad (1)$$

All indicated members of the equation (1) are related to the state in the cylinder. The work transmitted to the piston, as pressure forces to the moving boundary is:

$$\frac{\mathrm{d}W_\mathrm{c}}{\mathrm{d}\varphi}=p_\mathrm{c}\frac{\mathrm{d}V_\mathrm{c}}{\mathrm{d}\varphi} \quad (2)$$

The heat exchange over cylinder boundaries (except the sensitive heat admitted by mass exchange) has the members in the heat of fuel combustion Q_f and heat transferred to cylinder walls $Q_\mathrm{c,w}$ [15]:

$$\sum_\mathrm{i}\frac{\mathrm{d}Q_\mathrm{c,i}}{\mathrm{d}\varphi}=\frac{\mathrm{d}Q_\mathrm{f}}{\mathrm{d}\varphi}+\frac{\mathrm{d}Q_\mathrm{c,w}}{\mathrm{d}\varphi} \quad (3)$$

The cylinder pressure is determined from the gas state equation:

$$p_\mathrm{c}=\frac{m_\mathrm{c}\,R_\mathrm{c}\,T_\mathrm{c}}{V_\mathrm{c}} \quad (4)$$

The heat exchange between the working fluid and the cylinder walls was calculated by using an equation:

$$\frac{\mathrm{d}Q_\mathrm{c,w}}{\mathrm{d}\varphi}=\sum_\mathrm{i}\alpha_\mathrm{c}A_\mathrm{w,c,i}\left(T_\mathrm{w,i}-T_\mathrm{c}\right)\frac{\mathrm{d}t}{\mathrm{d}\varphi} \quad (5)$$

where the mean heat transfer coefficient α_c is calculated by an empirical equation presented by Woschni [16].

The combustion process is described by the heat release rate:

$$\frac{\mathrm{d}Q_\mathrm{f}}{\mathrm{d}\varphi}=\frac{\mathrm{d}x_\mathrm{f}}{\mathrm{d}\varphi}\cdot m_\mathrm{f,1pr}\cdot H_\mathrm{d}\cdot\eta_\mathrm{comb} \quad (6)$$

where the relative amount of combusted fuel increment $\mathrm{d}x_\mathrm{f}/\mathrm{d}\varphi$ is calculated by equation presented by Vibe [17].

In the above equations, used symbols are: T = temperature, φ = engine crankshaft angle, m = operating medium mass, u = operating medium specific internal energy, Q = heat amount, V = operating area volume, p = operating medium pressure, h = operating medium specific enthalpy, λ = excess air ratio, W = work, R = operating medium gas constant, A = control volume surface, t = time, x = relative amount of combusted fuel, H_d = fuel lower heating value, η_{comb} = efficiency of the combustion process, 1pr = per one engine process, f = index for fuel, w = index for cylinder walls, c = index for engine cylinder. Calorific gas properties (u, h, $\partial u/\partial\lambda$, $\partial u/\partial T$) are modeled from the analytical expressions relating the temperature and gas composition [18], [19]. To make the simulation as fast as possible, it is assumed that in each engine cylinder happens the same change of pressure and temperature (phase-shifted).

3. *Characteristics and specifications of base engine and both engine upgrades*

The base engine is a four stroke, high speed, naturally aspirated gasoline engine with direct fuel injection. The engine is designed for the usage in automotive applications. Base engine does not have any upgrades. Main operating characteristics and parameters of the base, naturally aspirated engine are presented in Table 1.

In Table 1 are also presented used cylinder materials and fuel basic specifications. Those data were the baseline for the correct heat exchange calculations in the engine cylinder.

Table 1. *Analyzed naturally aspirated engine main operating characteristics*

Fuel	Gasoline
Fuel lower calorific value	43 MJ/kg
Fuel density	0.75 kg/l
Number of cylinders	4
Ignition order	1-3-4-2
Compression ratio	11
Cylinder bore	84 mm
Stroke	86 mm
Cylinder clearance volume	0.0477 l
Engine cooling	Water
Materials:	
Cylinder head	Aluminum
Piston	Aluminum
Cylinder liner	Cast Iron

Numerical simulation was firstly performed for the base, naturally aspirated engine. For base engine, along with other operating parameters, was obtained curves of change in cylinder temperature and pressure.

After simulation of base engine, it is performed the first base engine upgrade - inclusion of the turbocharger. Turbine and charger operating maps were described by polynomials and included in numerical simulation as a new subroutine along with equations for operating parameters calculation. During the engine upgrade with turbocharger engine base operating and geometrical characteristics remain unchanged, because one of the intentions was to investigate the possibility of engine proper operation with selected turbocharger without any base engine modifications. The main geometrical characteristics of selected turbocharger KKK 30.60/13.21 are presented in Table 2. Turbine and charger operating maps are obtained from the turbocharger producer.

Table 2. *Geometry parameters of selected turbocharger KKK 30.60/13.21 [20]*

Charger inlet diameter	0.0457 m
Charger outlet diameter	0.0762 m
Intake turbine flowing surface	0.0013 m^2

Numerical simulation of engine with included turbocharger was performed and again, along with other operating parameters, was obtained curves of change in cylinder temperature and pressure.

Second and final base engine upgrade was including air cooler after charger into engine simulation. Air cooler is air-air heat exchanger. In such heat exchanger numerical description, it is necessary to define heat exchanger cooling medium (air) mass flow, pressure loss and overall efficiency. For selected, standard charging air cooler, according to producer specifications [21], air pressure loss and cooler overall efficiency were presented in relation to cooling air mass flow, Fig. 1.

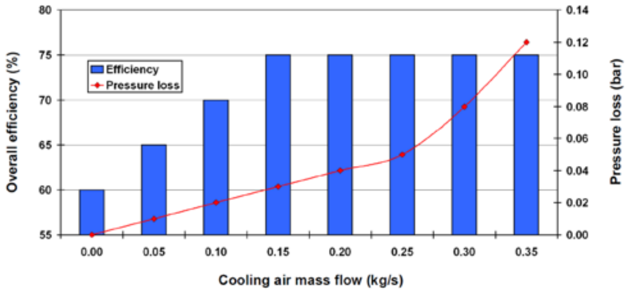

Fig. 1. *Air cooler pressure loss and overall efficiency in relation to cooling air mass flow*

Final, third simulation was performed and along with other operating parameters, was obtained curves of change in cylinder temperature and pressure for the engine with both upgrades (turbocharger + air cooler).

4. *Results of in-cylinder pressure and temperature change with discussion*

Numerical model results of in-cylinder pressure and temperature change for all three simulated gasoline engine variants (base engine and two upgrades) are presented. Differences of analyzed engine variants are the most notable in high pressure and high temperature parts of in-cylinder process. In all the figures (from Fig. 2 to Fig. 7) it is presented the high temperature and high pressure part of in-cylinder process in relation to engine crank angle.

4.1. Cylinder temperature change for all simulated engine variants at different engine rotational speeds

At engine rotational speed of 3000 rpm, gasoline engine upgraded only with a turbocharger (without air cooler) gives the highest in-cylinder temperatures, with a peak value of 2491.2 °C. Engine upgraded with a turbocharger and air cooler at 3000 rpm gives lower in-cylinder temperatures than engine upgraded only with a turbocharger, but cylinder temperatures for engine with both upgrades are higher in comparison with a naturally aspirated engine. Peak in-cylinder temperature at 3000 rpm for the gasoline engine upgraded with a turbocharger and air cooler amounts 2471.8 °C. It can be concluded that air cooler causes notable decrease in cylinder temperature when compared to engine upgraded only with a turbocharger, Fig. 2. The lowest in-cylinder temperatures at 3000 rpm are achieved, as expected, for naturally aspirated engine. Peak in-cylinder temperature for naturally aspirated engine amounts 2443.8 °C at 3000 rpm.

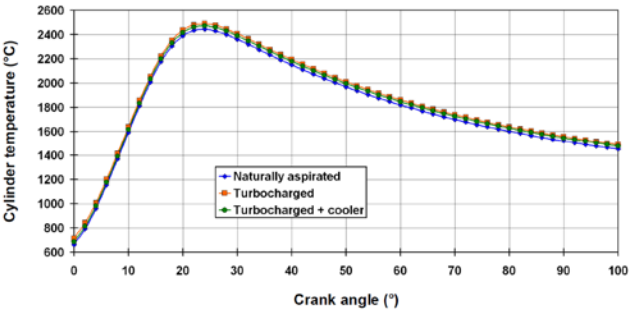

Fig. 2. *Cylinder temperature change for the analyzed engine at rotational speed of 3000 rpm*

At engine rotational speed of 5000 rpm can be noticed significant differences in change of engine cylinder temperature for three simulated engine variants, Fig. 3. As before at 3000 rpm, at 5000 rpm the highest in-cylinder temperatures are obtained for the gasoline engine upgraded only with a turbocharger. Peak temperature value for engine upgraded with a turbocharger (without air cooler) at 5000 rpm amounts 2542.4 °C. Engine upgraded with a turbocharger and air cooler at 5000 rpm gives lower in-cylinder temperatures than engine upgraded only with a turbocharger, while at the same time in-cylinder temperatures for engine with both upgrades are higher in comparison with a naturally aspirated engine. Peak in-cylinder temperature at 5000 rpm for the engine upgraded with a turbocharger and air cooler amounts 2461.4 °C. Air cooler significantly decreases in-cylinder temperatures at 5000 rpm, because maximum in-cylinder temperature for the engine with two upgrades is lower at 5000 rpm than at 3000 rpm, Fig. 3.

Again, as before, at 5000 rpm the lowest in-cylinder temperatures were achieved for naturally aspirated engine while temperature peak amounts 2431.1 °C, lower than at 3000 rpm.

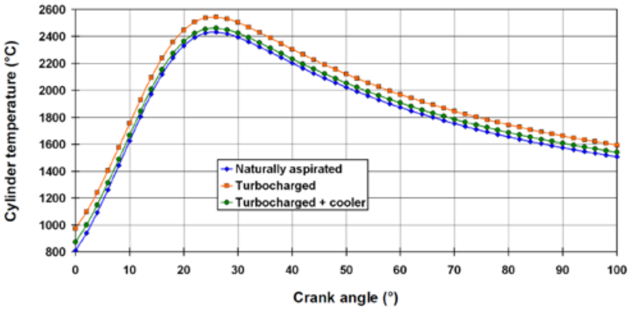

Fig. 3. *Cylinder temperature change for the analyzed engine at rotational speed of 5000 rpm*

At the highest engine rotational speed (6000 rpm), some conclusions about engine in-cylinder temperature change for three simulated engine variants differ in comparison with the lower engine rotational speeds. The same conclusion as before can be seen for engine upgraded only with a turbocharger, which at 6000 rpm again gives the highest in-cylinder temperatures and the peak temperature amounts 2505.6 °C, Fig. 4.

For the lower engine rotational speeds were valid a conclusion that engine with turbocharger and air cooler gives in-cylinder temperatures higher than naturally aspirated engine. At the highest engine rotational speed of 6000 rpm, in some parts on in-cylinder process, temperatures for engine with two upgrades are lower in comparison with a naturally aspirated engine. This conclusion leads to the fact that on the highest engine rotational speed, air cooler has the highest cooling medium mass flow and efficiency, so the temperature of air which enters into engine cylinders is much lower than on the lower rotational speeds.

At the 6000 rpm peak in-cylinder temperature for the engine with turbocharger and air cooler amounts 2401.6 °C, while for naturally aspirated engine peak in-cylinder temperature amounts 2415.1 °C.

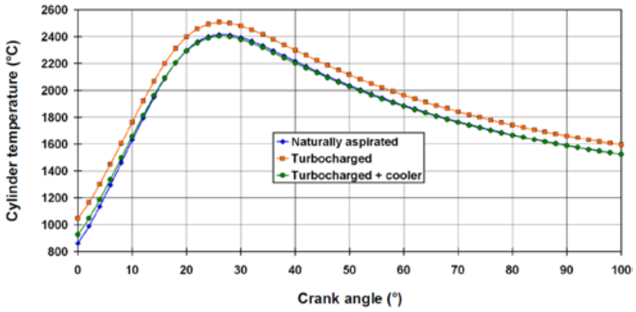

Fig. 4. *Cylinder temperature change for the analyzed engine at rotational speed of 6000 rpm*

4.2. Cylinder pressure change for all simulated engine variants at different engine rotational speeds

Naturally aspirated engine at 3000 rpm has significantly lower in-cylinder pressures when compared to engine with turbocharger or to an engine with turbocharger and air cooler, Fig. 5. Peak in-cylinder pressure for a naturally aspirated engine, at 3000 rpm, amounts 63.2 bars. Again, the highest values of in-cylinder pressures at 3000 rpm has an engine with both upgrades and peak value of in-cylinder pressure for this engine variant amount 81.7 bars. An engine which is upgraded only with a turbocharger at 3000 rpm has in-cylinder pressure values slightly lower when compared to engine with both upgrades, while when this engine is compared with naturally aspirated one in-cylinder pressures are significantly higher. At the engine rotational speed of 3000 rpm, engine upgraded only with a turbocharger has peak in-cylinder pressure value equal to 77.4 bars.

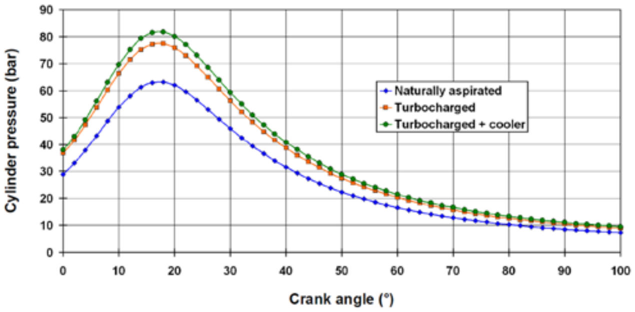

Fig. 5. *Cylinder pressure change for the analyzed engine at rotational speed of 3000 rpm*

In general, the same conclusions for in-cylinder pressure change for all three simulated engine variants, which are valid for engine rotational speeds of 3000 rpm, are also valid for engine rotational speed of 5000 rpm. The only difference can be seen in Fig. 6 - engine with turbocharger or an engine with turbocharger and air cooler has much higher in-cylinder pressures in comparison to naturally aspirated engine at 5000 rpm.

So, it can be concluded that turbocharging process causes a significant increase in engine in-cylinder pressure values especially at high engine rotational speeds. At the same high engine rotational speeds, with turbocharger and air cooler will be obtained the highest in-cylinder pressure values.

At 5000 rpm, peak value of in-cylinder pressure for engine upgraded with turbocharger and air cooler amounts 129.7 bars, for engine upgraded only with a turbocharger it amounts 122.1 bars and for naturally aspirated engine amounts 72.3 bars.

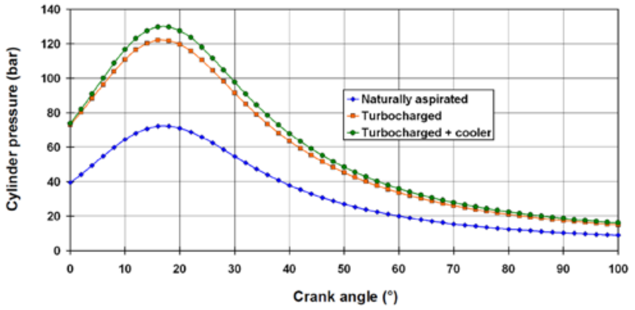

Fig. 6. *Cylinder pressure change for the analyzed engine at rotational speed of 5000 rpm*

At the highest engine rotational speed (6000 rpm) engine with turbocharger or an engine with turbocharger and air cooler also has significant higher in-cylinder pressures in comparison with a naturally aspirated engine, Fig. 7. The only difference which occurs at the highest engine rotational speed (in comparison to lower rotational speeds) is that the highest in-cylinder pressures are obtained for the engine only with a turbocharger, not as before for the engine with a turbocharger and air cooler. The reason of this occurrence can be found in Fig. 4. Decrease in in-cylinder temperature at 6000 rpm caused by air cooler after the turbocharger is significant, therefore simultaneously with an in-cylinder temperature decrease occurs decrease of in-cylinder pressure. So, only at 6000 rpm, the highest values of in-cylinder pressure will be obtained with engine upgraded only with a turbocharger.

This fact leads to conclusion that selected air cooler is not the best option for a simulated engine at the highest engine rotational speed. One of the future research directions of this engine and its upgrades will surely be to find or design a new air cooler, which will operate at 6000 rpm as at lower rotational speeds. The limit during an air cooler exchange will surely be not to exceed usual values of cylinder maximal pressures (usual values are from 150 bars to 170 bars).

Peak values of in-cylinder pressure at 6000 rpm are: for naturally aspirated engine - 69.1 bars, for engine upgraded with turbocharger - 118.2 bars, and for engine upgraded with turbocharger and air cooler - 109.8 bars.

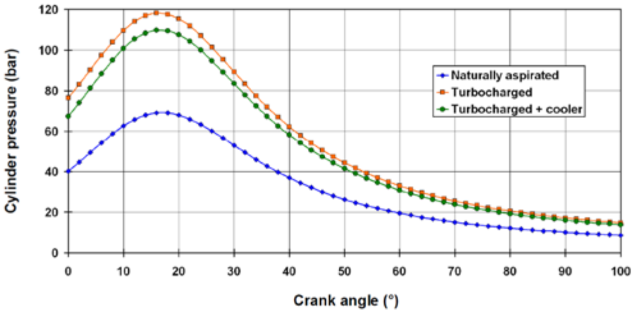

Fig. 7. *Cylinder pressure change for the analyzed engine at rotational speed of 6000 rpm*

5. Conclusions

This paper presents numerical analysis of in-cylinder pressure and temperature change for naturally aspirated gasoline engine and its upgrades - upgrade with turbocharger only and upgrade with turbocharger along with air cooler. It was analyzed by numerical 0D (zero-dimensional) model how engine upgrades influenced in-cylinder pressure and temperature change for the variety of engine rotational speeds.

In-cylinder temperatures, for each engine rotational speed, are the highest for engine upgraded only with the turbocharger. Engine upgraded with turbocharger and air cooler has lower in-cylinder temperatures than engine upgraded only with a turbocharger, what is expected because of air cooling before its entrance into engine cylinders. At the highest engine rotational speed (6000 rpm) air cooler significantly reduces in-cylinder temperature, so at the highest rotational speed, in-cylinder temperatures for an engine with turbocharger and air cooler are lower in comparison with naturally aspirated engine. As expected, the lowest in-cylinder temperatures are obtained for a naturally aspirated engine, for all engine rotational speeds except the highest one.

In-cylinder pressures are the highest for engine with two upgrades for all rotational speeds except the highest one. At 6000 rpm, air cooler after charger significantly reduces temperature of air which enters into engine cylinders and consequentially reduces the values of in-cylinder pressure.

Engine upgraded only with a turbocharger has values of in-cylinder pressure slightly lower in comparison with an engine which has both upgrades, for each engine rotational speed except the highest one. When compared turbocharged engine with naturally aspirated - turbocharged engine has significantly higher values of in-cylinder pressure at each engine rotational speed.

Presented analysis showed that selected air cooler (engine with both upgrades) can be improved at the highest engine rotational speed (6000 rpm) what will be the guideline for future research.

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