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Air Restrictor and Turbocharger Influence for the Formula Student Engine Performance

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Abstract

Paper presents the investigation of Formula Student car engine performance when different air inlet restrictors are applied. AVL BOOST numerical simulation model is created according to real engine parameters. The research includes simulation of restrictor diameters, which varied from 60 mm to 15 mm. The smaller intake manifold pipe diameter influenced engine performance – increased air intake hydraulic resistance and worsened cylinder volumetric efficiency that resulted in lower engine power and higher brake specific fuel consumption. In order to compensate the power loss, turbocharging system was simulated for the selected engine. Simulation results revealed that turbocharger improved engine performance.

Keywords: air intake manifold, air restrictor, numerical simulation, volumetric efficiency, turbocharger

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1. Introduction

Formula Student is widely known among academia members as engineering design competition, which is implemented by undergraduate and graduate students. During design and assembly stage, formula car has to meet

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official *FSAE* rules where a lot of different requirements are pointed. One of these is restriction of air intake manifold pipe (the restriction has to be applied) which has a great influence for engine performance [1].

Air filling into internal combustion engine (ICE) cylinder can be segmented into 3 parts: 1 – preparation, exhaust valve is still open, some exhaust gas are still present in the cylinder, intake valve starts to open; 2 – piston is moving down – combustible mixture is entering the cylinder, intake stroke appears; 3 – additional filling happens – combustible mixture enters the cylinder due to inertia, although the piston moves up towards top dead center (TDC). The last phase is very dependent on engine speed (n, revolutions per minute – rpm) and hydraulic resistance of intake pipes [2].

During the cylinder filling the pressure loss can appear. The combustible mixture temperature increases when it flows through the intake manifold pipes into the cylinder, therefore the fresh air density will always be lower than ambient pressure density. All losses of combustible mixture are evaluated by cylinder volumetric efficiency η_v. The coefficient value depends on intake manifold pipes construction, throttle valve position, combustible chamber shape, intake valve hole shape, diameter and valve timing [3]. The η_v is very dependent on throttle valve position. The volumetric efficiency and pressure in cylinder increases with increased throttle valve opening [4]. The intake manifold pipe length can influence air pressures' wave period. If the pressure wave period is shorter than the time while inlet valve is open, then it is possible to achieve that two crests of the pressure wave can reach open inlet valve [5].

Air and fuel motion in the intake manifold is effected by many factors i.e. pulsating filling into the cylinders, different geometry pipelines, liquid fuel atomization and evaporation, exhaust gas recirculation. The design of air intake manifold has to make lowest air friction, good distribution of air and fuel between cylinders. The manifold pipes must be proper size to be able to give for air a sufficient speed that it could carry fuel drops [2].

Previous experimental research of Formula Student car's air intake manifold with a restrictor (Ø20 mm) showed that engine (engine used from *Suzuki GSXR-600 K3* motorcycle) power decreased from 75.1 kW at 13741 rpm up to 47.8 kW at 10601 rpm (Fig. 1) [6].

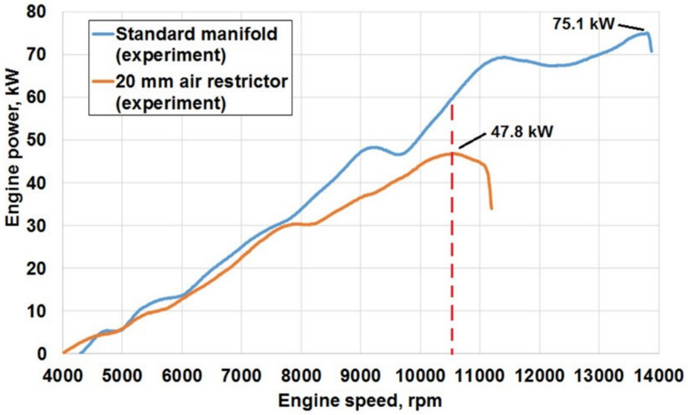

Fig. 1. Engine power dependence on engine speed [6].

Previous research [6] revealed that different engine adjustable parameters, like air/fuel ratio (A/F), spark timing, injection duration, has a great influence for the Formula Student engine efficient indicators. Petrol octane number has also an obvious impact for engine power. The literature overview showed that using different type (liquid or gas) and octane number (RON) fuels (91 RON, 93 RON, 95 RON, 97 RON, 98 RON) the lowest brake specific fuel consumption (BSFC) and highest efficiency is achieved with 97 RON and 98 RON fuels [7]. In [8] it was determined that spark timing is essential if ethanol and gasoline fuel mixtures are used. Using gaseous fuels engine torque can decrease due to reduced volumetric efficiency because gas can occupy bigger amount of volume in the intake manifold [9]. Type of fuel injection system also has a remarkable impact for the engine performance. Direct injection can reduce brake specific fuel consumption and in some cases increase engine power if compared with port fuel injection (PFI). Heat loss in cylinder is lower using direct injection, the volumetric efficiency increases because fuel is injected directly into the cylinder [10].

During Formula Student tests the 98 RON petrol fuel was used with PFI system and particular spark timings were adjusted depending on different engine speeds and loads. However, the engine power drop was 35.4% (with Ø20 mm air restrictor) if compared with tested engine, which had an original air intake manifold (Fig. 1).

Engine torque is proportional to combustible mixture amount, which fills the cylinder, when engine is running on homogenous mixture and has $\lambda \leq 1$. In this case, the torque and power can be increased by compressed air before it enters the cylinder, e. g. using turbocharger [11].

The aim of the research – using experimental research and numerical simulation to evaluate the change of power engine parameters when air restriction is being used in the intake manifold system and to apply a turbocharger in order to improve engine performance.

2. Engine performance research methodology

Firstly, engine power and torque were determined using vehicle dyno test bench *CARTEC LPS 2510*, when engine was equiped with original air intake system. Formula Student car has an engine which is used from *Suzuki GSXR-600 K3* motorcycle. Detailed engine technical data is presented in Table 1. Engine has a *MoTec M84* engine control unit which gives ability to adjust spark timing, A/F ratio, fuel injection duration, etc. Secondly, engine power and torque were measured (Fig. 1) when engine had an air restrictor. Air intake manifold with Ø20 mm air restrictor was specially designed and manufactured according to official *FSAE* rules (Fig. 2).

Table 1. Engine *Suzuki GSXR-600 K3* technical parameters.

Parameter	Values	
Engine power at engine speed, kW (rpm)	85.4 (13600)	
Bore, mm	67	
Stroke, mm	42.5	
Compression	12.2	
Cylinder number, pcs.	4	
Engine capacity, dm^3	0.6	
	Intake valve	Exhaust valve
Valve open, ° AV	33 (before TDC)	53 (before BDC)
Valve close, ° AV	68 (after BDC)	30 (after TDC)

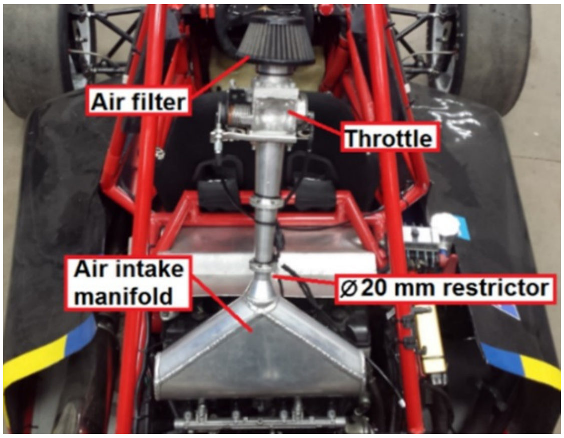

Fig. 2. Formula Student engine air intake manifold with Ø20 mm air restrictor.

In order to evaluate the impact of different air restrictor diameters for the engine power, numerical simulation model of Formula Student engine was created using *AVL BOOST* software (Fig. 3). The simulation of the thermodynamic state of the cylinder is based on the thermodynamics law. The sum of the in-flowing and out-flowing masses let to calculate the variation of the mass in the cylinder [12]:

$$\frac{dm_c}{d\alpha} = \sum \frac{dm_i}{d\alpha} - \sum \frac{dm_e}{d\alpha} - \frac{dm_{BB}}{d\alpha} + \frac{dm_{ev}}{dt}, \qquad (1)$$

here α – crank angle; m_c – mass in the cylinder; dm_i – mass element flowing into the cylinder; m_e – mass element flowing out of the cylinder; m_{BB} – blow-by mass flow, m_{ev} – evaporating fuel.

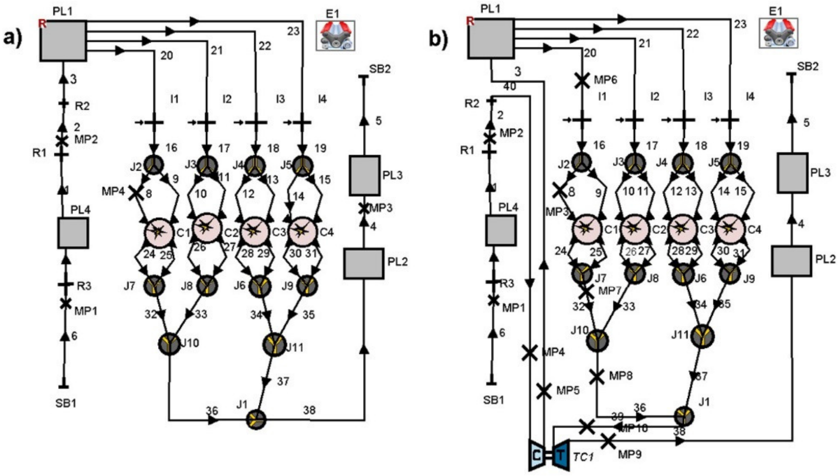

Fig. 3. *AVL BOOST* numerical simulation model of Formula Student engine: a) engine without turbocharger; b) engine with turbocharger.

Numerical simulation process was done with *AVL BOOST* software where Vibe Two Zone function was used [12]. Cylinder is divided into two zones where burned charge and unburned charge is present. Flame front, which has no mass, is simulated as very thin layer between two zones [13].

Fig. 3a) presents engine numerical model, which was used for engine simulation with standard manifold and simulations with air restrictors (from 60 mm to 15 mm diameter). Fig. 3b presents numerical model for engine simulation, which has a turbocharger system. The numerical model was created according to real engine after the engine maximum power with standard intake manifold was determined on dyno test bench. Designed and manufactured new intake manifold system with Ø20 mm air restriction for the engine was tested also on dyno test bench. The influence of different diameter restrictors for engine performance were investigated using *AVL BOOST* software. In order to evaluate the turbocharger influence for the engine performance, new numerical model with turbocharging was created.

3. Numerical simulation results

Numerical simulation results of engine with standard intake manifold showed that engine power is 58.45 kW. The air intake pipe had a diameter of 60 mm (Fig. 4). The achievable engine power is similar to real engine tests (difference 0.76% from 58.9 kW). Such small difference showed that numerical model is adequate to real engine. The reference point for simulation was taken at 10500 rpm engine speed where it achieved 58.9 kW during the dyno tests (Fig. 1).

Such engine speed was taken because the maximum power (46.76 kW) with Ø20 mm restrictor was achieved at the same engine speed (Fig. 1). The simulation and tests were performed when A/F ratio was 12:1 and wide open throttle (WOT). The simulation showed 314.6 g/kWh of BSFC for standard air intake manifold case.

Overall engine power reduced up to 30.57 kW when diameter of air intake manifold restrictor reduced from Ø60 mm to Ø15 mm (engine speed 10500 rpm, WOT, A/F ratio = 12:1). Engine power with Ø20 mm restrictor, which is necessary according to *FSAE* rules, was 46.37 kW. That was 0.83% (46.76 kW) difference from real tested engine with Ø20 mm air restrictor. The simulated BSFC increased up to 339.76 g/kWh. Engine power reduced and BSFC increased due to increased intake hydraulic resistance, lower air filling into the cylinder (worse volumetric efficiency) (Fig. 5).

The reduction of air inlet pipe reduced cylinder filling with air, which resulted in lower pressure in the cylinder. Simulation showed that with standard intake manifold the pressure was 105.96 bar (Fig. 6). Pressure reduction up to 97.73 bar was observed with Ø20 mm restrictor.

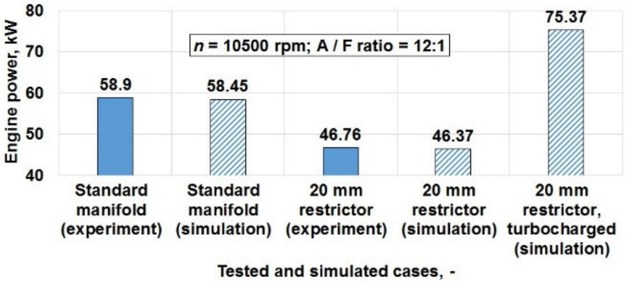

Fig. 4. Engine power dependence on tested and simulated cases.

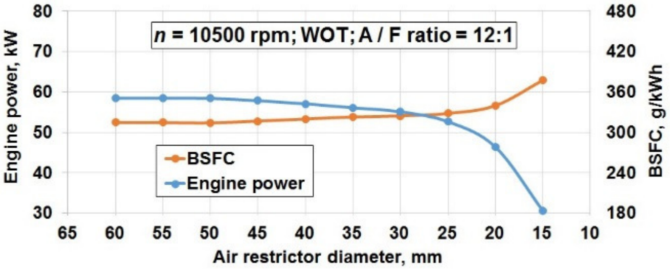

Fig. 5. Engine power and brake specific fuel consumption dependence on different air restrictor diameters.

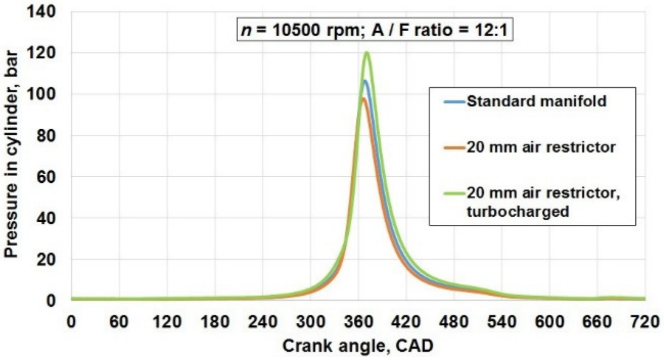

Fig. 6. Pressure in cylinder dependence on different air intake systems.

In order to compensate the power loss due to reduced cylinder volumetric efficiency, the turbocharger system was applied in new *AVL BOOST* engine model (Fig. 3b). Simulation results showed that with turbocharger, which has 1.2 bar pressure, the cylinder pressure increased up to 120.31 bar (18.76% higher if compared with simulated

Ø20 mm restrictor). Such pressure increase could give a higher power for the engine and it would be possible to achieve 75.37 kW (38.47% higher if compared with Ø20 mm restrictor case). The application of turbocharger could also reduce BSFC up to 288.29 g/kWh (9.12% lower if compared with standard intake manifold and 15.15% lower if compared with Ø20 mm restrictor).

4. Conclusions

Simulation results showed that *AVL BOOST* numerical model of Formula Student engine is adequate to real engine reference points, which were taken at 10500 rpm engine speed, wide open throttle and A/F ratio = 12:1. The numerical model could be used for further engine performance analysis and development.

Engine maximum power decreased from 58.45 kW (with standard manifold) up to 46.37 kW (with Ø20 mm restrictor) because of increased air intake hydraulic resistance and worse cylinder volumetric efficiency. Simulation revealed that air restriction also increased brake specific fuel consumption.

Turbocharging could be one of the solutions in order to compensate engine power loss. With 1.2 bar turbocharger pressure it is possible to achieve ~38% higher engine power if compared with simulated Ø20 mm restrictor cases.

Developed and applied numerical simulation model could be used for further Formula Student engine performance improvement. Different lengths of air intake manifold pipes or variable geometry air intake system, which have a noticeable influence for the engine power and torque, ignition timing and air/fuel ratio optimization could be investigated in the future works.

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