COMBUSTION PARAMETERS CALIBRATION AND INTAKE MANIFOLD REDESIGN FOR FORMULA STUDENT YAMAHA YZF-R6 ENGINE

Predrag Mrdja[1], Vladimir Petrovic[2], Nenad Miljic[3], Slobodan Popovic [4], Marko Kitanovic[5]

Summary: *In order to improve the performance of previous season 599cc Yamaha YZF-R6 Formula Student air-flow restricted racing engine, an intensive research in developing a trustworthy engine mathematical model, using 1D thermodynamic Ricardo WAVE® simulation environment was carried out. The Internal Combustion Engine Department has provided simulation software and equipment for in-laboratory engine testing. Data acquired during last season control parameter optimization process (ignition and fuelling main maps) on the engine test bench was used to calibrate the combustion model. Research was based on engine effective parameters, because the crank-angle-resolved cylinder pressure measurement was not carried out. Engine work cycle simulation results analysis and combustion parameters decision-making process were processed using MATLAB® in-house developed code. The engine model with recalibrated combustion parameters was used for assessment of characteristic geometrical dimensions for the new intake manifold. Using this approach for intake manifold design we were able to simulate various design concepts in an effective and fast manner.*
Keywords: *Internal combustion engine, Combustion model, Intake manifold, Simulation analysis*

1. INTRODUCTION

Using Ricardo WAVE®, one-dimensional thermodynamic engine work cycle simulation environment, we were able to develop a trustworthy mathematical engine model, based on data acquired from last year's engine testing and control parameter

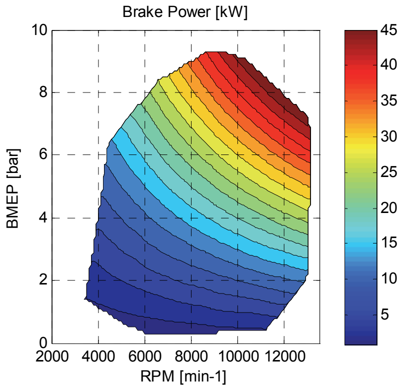
---

[1] M.Sc., Predrag Mrdja, Belgrade, University of Belgrade Faculty of Mechanical Engineering Internal Combustion Engines Department , pmrdja@mas.bg.ac.rs
[2] B.Sc., Vladimir Petrovic, Belgrade, University of Belgrade Faculty of Mechanical Engineering Internal Combustion Engines Department, apoc_or@hotmail.com
[3] Ph.D., Nenad Miljic, Belgrade, University of Belgrade Faculty of Mechanical Engineering Internal Combustion Engines Department, nmiljic@mas.bg.ac.rs
[4] Ph.D., Slobodan Popovic, Belgrade, University of Belgrade Faculty of Mechanical Engineering Internal Combustion Engines Department, spopovic@mas.bg.ac.rs
[5] M.Sc., Marko Kitanovic, Belgrade, University of Belgrade Faculty of Mechanical Engineering Internal Combustion Engines Department, mkitanovic@mas.bg.ac.rs

optimization process, which was carried out on a 599cc Yamaha YZF-R6 Formula Student air-flow restricted racing engine. This paper briefly presents the methodology of determination and functional dependency of in-cylinder combustion model parameters, based on effective engine parameters, with a certain amount of assumptions taken into account which are based on prior experience and familiarity with engine working cycle. The main goal of this project was assessment of geometrical dimensions of a new intake manifold that would provide more intake air into the engine and therefore more power. Simulation initialization is a very important part of the project and it was given substantial attention, because of high complexity and dynamic of processes taking place in engine cylinder and other engine systems. Unlike previous season, when dual plenum [1, 2] concept was applied, plan for this season is designing of the single volume plenum. Last year's dual plenum engine mathematical model coupled with engine test results was used for the Wiebe combustion parameters determination. Obtained parameters were used as simulation input parameters for the new WAVE model with a new intake manifold concept. Simulation analysis was performed for the stationary operational regime of 9000RPM and full open throttle valve.

2. ENGINE TESTING AND DATA ACQUISITION

The data acquisition during engine testing was accomplished through high speed CAN communication protocol established between DTA S60 PRO [3] engine control unit (ECU) and dedicated acquisition platform based on the National Instruments PXI system, which enabled the dataflow of all important ECU's information. Serial communication between the ECU and PC was used for real-time adjustment of control parameters and monitoring of stock engine sensor readings within the ECU's calibration software DTASwin. The third set of data was acquired from additional sensors implemented on the test bench devoted for monitoring and logging of effective brake torque, transmission output shaft angular speed, intake air, coolant and oil pressures and temperatures, etc. The application for real-time monitoring and data logging was developed within National Instruments LabVIEW, graphical programming software. Engine testing was carried out at 150 stationary operation regimes represented with different combinations of engine speed and load, and for every one of those regimes spark advance timing and initial value of injection timing was calibrated in terms of getting as much as possible effective torque on the engaged hydraulic dynamometer SCHENCK U1-16H. Beside stationary operating regimes, the focus was devoted to transient regimes, regarding enrichment and enleanment of the intake mixture considering different throttle opening speed, engine speed and load. Used ECU has the ability to control the mixture composition on the basis of lambda control main map and configured gains of lambda PID controller [4]. Some of measured and calculated values are presented in Figure1 such as engine brake power and intake air mass flow as a function of engine speed and brake mean effective pressure (BMEP) are shown in listed order.



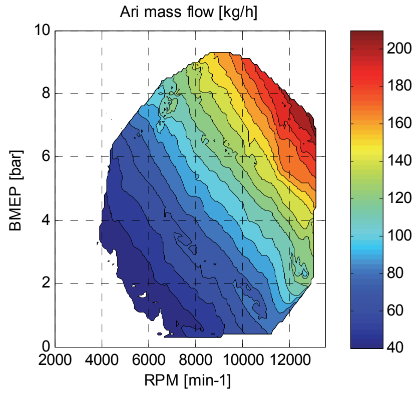


Fig. 1 *Engine Brake Power [kW] and Intake Air Mass Flow [kg/h].*

3. WIEBE COMBUSTION PARAMETERS ANALYSIS

For the purpose of mathematical modeling of heat release process taking place within internal combustion engines, different empirical equations are in use. The most commonly used is the Wiebe equation [5,6], according to which the cumulative mass fraction burned x_b, that is the relative mass of fuel burned as a function of crank angle θ during the work cycle is given by the expression:

$$x_b(\theta) = 1 - \exp\left[-a\left(\frac{\theta - SOC}{BDUR}\right)^{m+1}\right] \tag{1}$$

where the *SOC* is a start of combustion angle, *BDUR* is the total combustion duration angle and parameter *m is called* the combustion mode parameter and defines the shape of the Wiebe combustion profile. This equation is also known as the integral law of combustion. Crank angle derivative of equation (1) represents a differential law of combustion which is given by the expression:

$$\frac{dx_b(\theta)}{d\theta} = \frac{a}{BDUR}(m+1)\left(\frac{\theta - SOC}{BDUR}\right)^m \exp\left[-a\left(\frac{\theta - SOC}{BDUR}\right)^{m+1}\right] \tag{2}$$

where constant a defines level of combustion completeness, and for x_{EOC}=99.9% mass of fuel burned, has the value of:

$$a = -\ln(1 - x_{EOC}) = -\ln(0.001) = 6{,}9 \tag{3}$$

Simulation setup in Ricardo WAVE requires defining of angular combustion duration between 10 and 90% of total combustion duration angle that can be calculated by the following equation:

$$BDUR_{10-90} = BDUR\left(\left(\frac{\ln(1-0{,}9)}{a}\right)^{\frac{1}{m+1}} - \left(\frac{\ln(1-0{,}1)}{a}\right)^{\frac{1}{m+1}}\right) \tag{4}$$

With a known value of *SOC*, *BDUR* and Wiebe parameter *m*, estimation of the angular location of 50% mass fuel burned can be calculated by the equation:

$$CA50 = SOC + BDUR\left(\frac{\ln(1-0{,}5)}{a}\right)^{\frac{1}{m+1}} \tag{5}$$

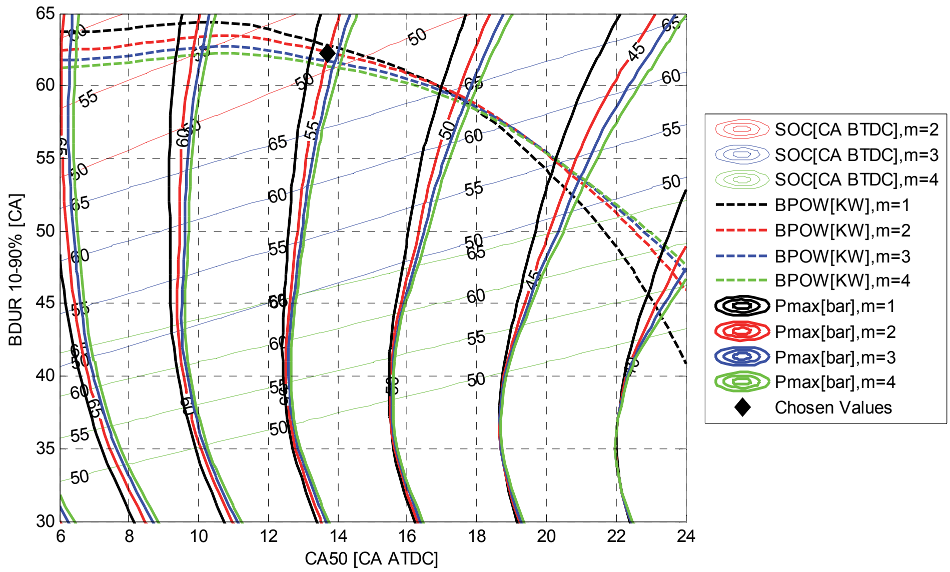


Fig. 2 *Correlations between combustion parameters for measured engine effective power, start of combustion and in-cylinder maximum pressure as function of $BDUR_{10\text{-}90}$, CA50 and m.*

In Figure 2 are shown some of simulation results for combinations of *BDUR* and *CA50* for different *m* values that meet the condition of engine brake effective power measured during engine testing, which is 43.7[kW]. At this particular regime model was air mass flow calibrated for measured value of 163.7[kg/h]. Assuming that maximal in-cylinder pressure value for this class of engines is between 50-60[bar], as well as taking in consideration previously listed conditions, it is concluded that for given operating regime, combustion parameters lay within the following limits: *BDUR*=58-64, *CA50*=10-18 and *m*=1-4. Taking into account angular position of SOC corresponding combustion parameters combinations are shortlisted. During engine testing advance timing was 50 degrees [BTDC], and this information was used for the final determination of combustion parameters, which will be used as input for simulations related to intake manifold design.

The Figure 3 shows changes in parameters $BDUR_{10\text{-}90}$, *SOC* and in-cylinder pressure as the function of combustion parameters *CA50* and *m* for the given operating regime, and which meet the condition of measured brake effective power of 43.7 [kW]. It can be observed that there are two distinctive areas in the Figure 3. For greater values of *CA50* parameter, $BDUR_{10\text{-}90}$ does not change significantly with the change of the parameter *m*, but the peak of in-cylinder pressures are lower than expected. For smaller values of *CA50* parameter, with the change of the *m* parameter $BDUR_{10\text{-}90}$ tends to decrease with increase of *m* and vice versa. For an assumed value of in-cylinder pressure during work cycle of 55 [bar], as well as *SOC* assumed at 50 [CA BTDC], it could be read from the figure which combustion parameters need to be used for initialization of simulation models for designing new intake manifold. It is assumed that the combustion parameters do not depend on engine volumetric efficiency on this working regime.

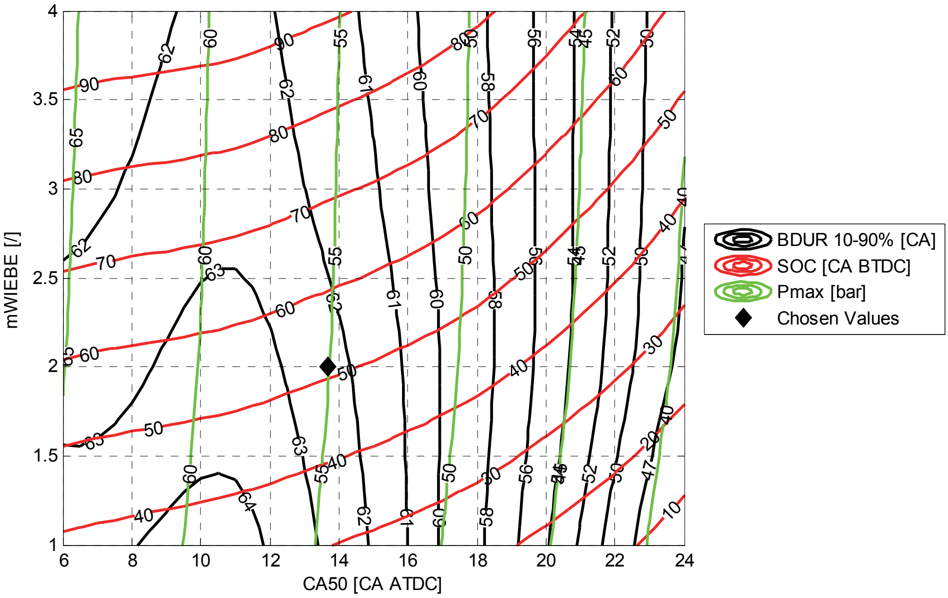


Fig. 3 *Correlations between combustion parameters for measured engine effective power, combustion duration, start of combustion and in-cylinder maximum pressure as function of CA50 and m.*

4. RUNNER LENGTH AND PLENUM VOLUME ANALYSIS

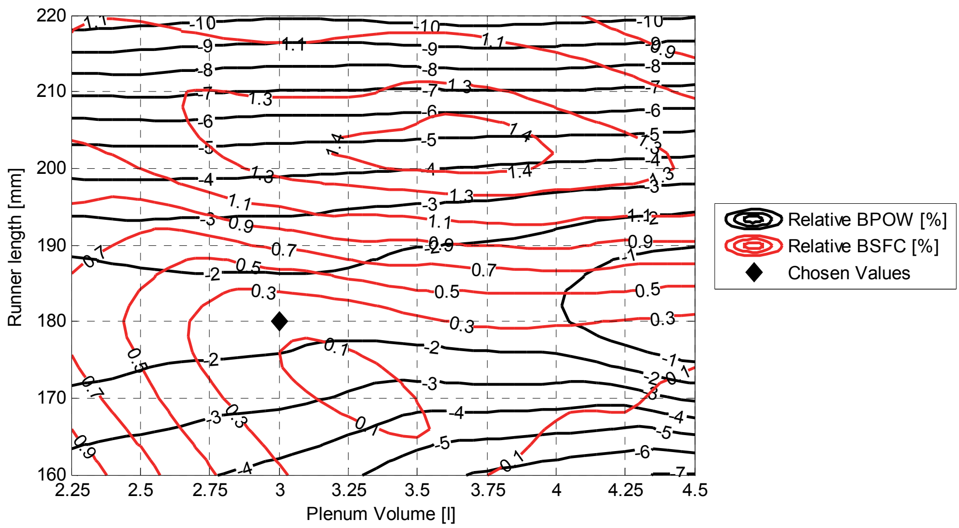


Fig. 4 *Relative engine brake power and brake specific fuel consumption as a function of plenum volume and runner section length.*

During engine model simulation initialization, the length of the intake runners and the plenum volume were set to vary. The plenum volume was divided in 15 sub volumes and air distribution to each engine cylinder was taken into account. Figure 4 shows the relative change in brake effective power and the relative brake specific fuel consumption due to varying runner lengths, l=160-220 [mm], and total intake plenum volume, V=2.25-4.5 [l]. It also shows the effect of intake plenum dimensions on brake specific fuel consumption. Taking into account the dynamic response [7] of the engine it was decided that the volume of the intake plenum should not be greater than 3 liters. Intake runner length was set at 180 [mm] as a baseline, but the possibility is left to correct the length in the range of -30 - +90 [mm] from the baseline on the physically-made intake manifold, in order to validate the mathematical model on the engine test bench during this season's engine retesting.

5. CONCLUSION

Designing an intake manifold for a racing engine using contemporary simulation methods provides a number of benefits, like cost-efficient and time-preserving examination of various concepts, and a possibility of reliable optimization of specific geometrical dimensions. The quality of simulation results greatly depends on reliable and accurate definition of the initial parameters. This paper in shortly describes an approach to solving this problem in only one engine operating regime based on engine brake effective parameters. For further research it is planned to conduct a crank-angular-resolved cylinder pressure measurement, and detailed in-cylinder pressure trace analysis as well as the subsequent recalibration of the engine mathematical model.

REFERENCES

[1] Badih A. Jawad, Jeffrey P. Hoste and Brian E. Johnson (2002) Formula SAE Dual Plenum Induction System Design. *SAE International – SAE Technical Paper Series*, no. 2002-01-0457.

[2] Mark Claywell, Donald Horkheimer, Garrett Stockburger (2006) Investigation of Intake Concepts for a Formula SAE Four-Cylinder Engine Using 1D/3D (Ricardo WAVE-VECTIS) Coupled Modeling Techniques. *SAE International – SAE Technical Paper Series*, no. 2006-01-3652.

[3] S Series User Manual (2012) DTA Competition Engine Management Systems, from www.dtafast.co.uk accessed on 2013-04-20

[4] Sigurd Skogestad (2001) Probably the best simple PID tuning rules in the world. *AIChE Annual Meeting*

[5] Ricardo WAVE 2012.12 (2012) User Manual Ricardo

[6] Dan Cordon, Charles Dean, Judith Steciak and Steven Beyerlein (2007) One-dimensional engine modeling and validation using Ricardo WAVE – Final Report

[7] Leonard J. Hamilton, Jim S. Cowart, Jasen E. Lee, Ryan E. Amorosso (2011) The Effects of Intake Plenum Volume on the Performance of a Small Naturally Aspirated Restricted Engine. *Journal of Engineering for Gas Turbines and Power,* Vol. 133, no. 012801