

Study of Pressure Wave Supercharger Potential using a 1-D and a 0-D Approach

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ABSTRACT

The objective of this paper is to complete a thorough investigation of the pressure wave supercharger (PWS) to explore the potential of this technology in engine applications. The PWS is a non-steady flow device that uses shock waves to pressurize fluids by transferring energy from a high-pressure flow to a low-pressure flow without separation by physical walls. The paper introduces a 1-D model of PWS in GT-SUITE calibrated by experiments on steady flow test rig. The 1-D model respects both exhaust and fresh air in each of the cells, friction and heat transfer in the cells as well as the continual opening and closing of the cells. Moreover, the cell wall temperature is computed and the leakage flow between the cells and housings modeled. The limits of PWS operation regarding pressures, temperatures and mass flows are first mapped on the virtual test rig utilizing the calibrated 1-D code based on the Mazda Comprex device. The device is further tested in GT-SUITE on a Yamaha YZF - R6 SI engine applied by CTU CarTech team as a powertrain in the Formula Student/SAE car. The engine full load, part load and transient response are simulated at different engine speeds and a possible PWS control technique introduced and evaluated by simulation. Further, the PWS control geometry is optimized to find the maximum boost pressure achievable and the optimized device simulated in conjunction with the Yamaha engine. Finally, a 0-D model suitable for prediction of engine response is presented. The 0-D model aims at a simple description of processes inside PWS based on physics and enables a close to real time simulation. The simplified processes are corrected by calibration coefficients determined by the 1-D model and transferred to the 0-D model through regression analysis. Comparison of developed 0-D and 1-D models at the engine transient operation is also provided and discussed.

INTRODUCTION

The idea of direct energy exchange between two media without using mechanical components such as pistons or vaned impellers started in the early 1900s [1]. The first functional device was developed in the 1940s when the Brown Boveri Company (BBC (now ABB)) designed a pressure-exchange wave rotor as an air compressor for the high pressure stage of a gas turbine engine to be used for the propulsion of an experimental locomotive [2]. The wave rotor (WR) is a non-steady flow device that uses pressure or shock waves to pressurize fluids by transferring energy from a high-pressure flow to a low-pressure flow without separation by physical walls. The WR consists of many axial cells in a rotating cylindrical drum, usually driven by an external motor. Probably the most successful realization of the WR technology has been as a pressure wave supercharger (PWS) for internal combustion engines [1] developed by BBC and commercialized under a brand name Comprex. The term COMPREX was coined based on the *compression* and *expansion* non-steady phenomena inside the rotor. Mazda sold about 150 000 cars with a 2.0l diesel engine supercharged by PWS during the late 80's and early 90's [3]. A very interesting application of PWS was also as a supercharger of the F1 Ferrari 126C with 1.5l V6 engine in 1980's. The WR of that racing application had a diameter of 200mm which equaled its length (square design). Moreover, the WR drive was provided from the engine crankshaft and the achievable boost pressure was in the range from 3 to 5 bar absolute. The biggest cause of failure for the Ferrari 126C engine with PWS was the breaking of the drive belt due to the harsh transients. Therefore, as the turbocharger proved to be more reliable, the PWS engine was used only during the practice runs in 1981.

The PWS used as a boosting device in car applications consists of the reverse-flow WR (i.e. exhaust gas enters the

WR on one side and exits on the same side) placed between the air and exhaust housings (Figure 1). Rotation of WR provides control of the boosting process, thus proper opening and closing of the axial cells in the WR. The compression pressure wave created by impact of the exhaust gas on the fresh air in the WR compresses air and after the air outlet is opened it expels air to an intercooler and then to an engine intake manifold. Before the exhaust gas reaches the air outlet, the air outlet is closed. Simultaneously, exhaust pressure is decreased by the expansion wave. This is caused by the appropriate timing of the exhaust outlet opening. That exhaust expansion provides a suction of fresh air through the opened air inlet.

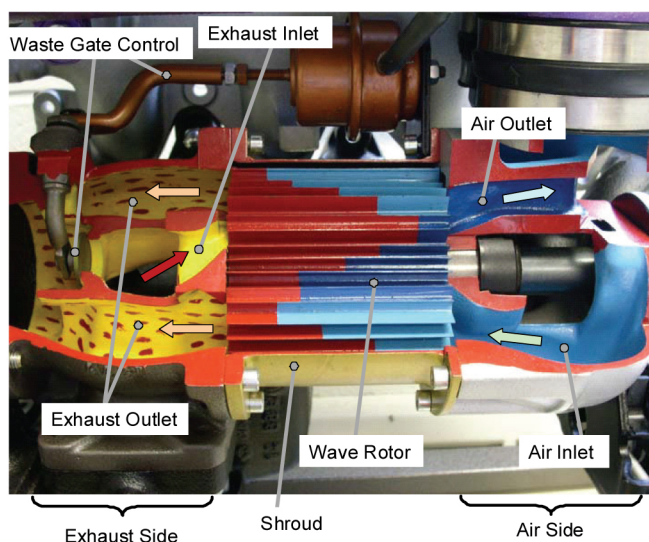


Figure 1. Cross-section of the Mazda Comprex PWS

Recent research activities on PWS have been published mainly by ETH Zurich [4,5], Warsaw University of Technology [6,7], Beijing University of Technology [8] and Michigan State University [1,9].

The PWS engine system considered at ETH Zurich consists of a modern PWS device called Hyprex 95, which offers arbitrary setting of WR speed, gas pocket valve position and angular offset between air and exhaust housings. Moreover, the engine system includes two control throttles and two catalytic converters. To prevent excessive exhaust gas recirculation to compressed air during transients and engine warm up a control system actuating throttles, gas pocket valve and angular offset was designed and experimentally verified on a 1.0l spark ignited IC engine [4,5]. Better insight into the pressure wave process enabled a finite difference 1-D model based on Euler differential equations developed by ETH Zurich together with Warsaw University of Technology [7]. The model uses two-step Lax-Wendroff method and respects such phenomena as leakage, heat transfer and friction. The boundary conditions at both WR sides are determined by method of characteristics. Developed PWS 1-

D model was compared with measured data from a real engine system [4]. Further, a control oriented mean value PWS model was developed on the basis of the one-dimensional linear wave theory using the results of the finite difference model and was used to simulate the transient behavior of the entire engine system in real time [4]. At Beijing University of Technology research on a 2.7l 4-cylinder diesel engine boosted by Comprex 102 device (i.e. by a PWS device with a diameter of 102mm) was undertaken [8]. The analysis results showed that the intake airflow and the exhaust gas temperature had the greatest influence on the power of a PWS boosted engine. Therefore, larger intake manifold volume and higher exhaust temperature were recommended for better engine performance. Moreover, a 3-D non-steady flow model of PWS was completed in commonly available CFD code FLUENT [8]. Michigan State University has a well established WR research program aimed mainly at gas turbine applications [1, 9].

Although the technology is almost a century old, the working principle of direct pressure and enthalpy exchange between exhaust gas and fresh air in a series of WR cells is neither well known nor understood in the broader engineering community. Moreover, with the inevitable move towards downsized turbocharged IC engines, new technical difficulties regarding applied turbomachinery, such as the boost pressure at low end engine speed, transient response, boost pressure control, lubrication and balancing at very high speeds etc., arise. The PWS, also known as Comprex or Hyprex charger, is generally known to respond very quick on load demands, and capable of providing high boost at low engine speeds.

Therefore, the presented work aims to (a) assess the potential and (b) develop tools allowing assessment of the PWS technology for internal combustion engines with regard to today's state of the art in control, actuation, material and technology considering fulfillments of requirements on a modern propulsion system as a serious competitor to current boosting systems. Further, it pursues the development of a technique that allows the PWS to be simulated in detail in a commercially available 1-D simulation tool to enable simple connection of the device to an engine model or any other model available in the commercial code. In this paper, an investigation is presented on example of SI engine for Formula Student/SAE car. The paper also introduces a 0-D model of PWS suitable for prediction of engine response.



Figure 2. FS.02 car of CTU CarTech team during Formula Student Germany competition in 2010

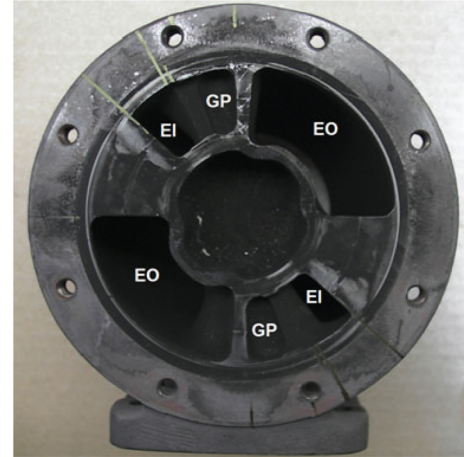


Figure 4. Control geometry on exhaust side of Mazda Comprex-93 where EI...exhaust inlet, EO...exhaust outlet, GP...gas pocket

PWS 1-D MODEL

The 1-D model in this paper relates to the modeling technique introduced in [11] while enhancing the model by new features (such as leakage modeling and cell wall temperature computation) and calibrating it using measurement on a steady flow test rig with combustor. The 1-D model was developed based on the control geometry of the Mazda PWS Comprex-93 (Figure 1, Figure 3 and Figure 4).

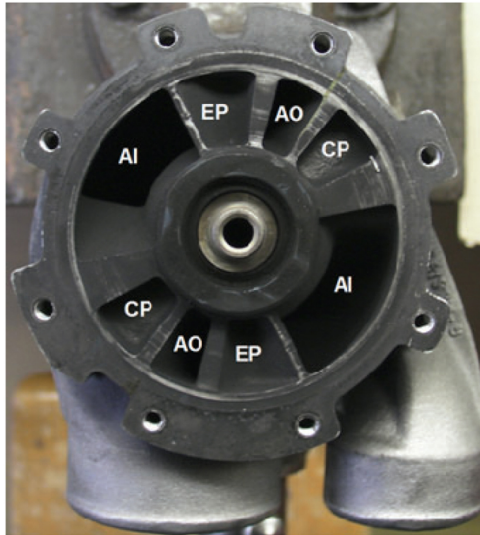


Figure 3. Control geometry on the air side of Mazda Comprex-93 where AI...air inlet, AO...air outlet, EP...expansion pocket, CP...compression pocket

LAYOUT OF PWS

The inlet and outlet ports are distributed on the circumference of the housings (Figure 3 and Figure 4), the angular offset between the EI port opening edge and AO opening edge (also between the exhaust and air housing) is 19 deg. As there are two cycles per WR revolution, there are always two inlets and two outlets on the face. The WR contains 34 cells in each of the two rows opened and closed by rotation of the WR. The WR (Figure 1) is bedded in the air housing and its roller bearings are cooled by the fresh airflow ingested by the WR through the AI port. A schematic layout of PWS device is presented in Figure 5. The standard design solution to improve operation away from the design point uses auxiliary connections in the housings, thus bypassing gas between the cells and the control ports. These connections in the form of so called pockets are manufactured in the inner face of the housing surface. The Mazda Comprex-93 supercharger includes six pockets, i.e. two compression and two expansion pockets in the air housing and two gas pockets in the exhaust housing.

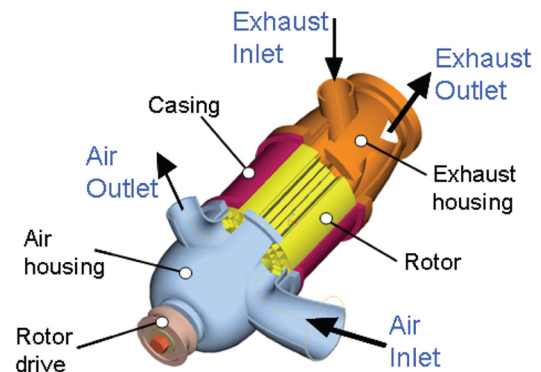


Figure 5. Layout of PWS

CONSTRUCTION OF THE MODEL USING GT-SUITE ELEMENTS

All 68 WR cells in the two rows of the PWS were modeled and associated with the control geometry of the Mazda Comprex (as shown in [Figure 3](#) and [Figure 4](#)), and the continual opening of the cells was simulated. A 1-D model in GT-POWER has already been presented in [11].

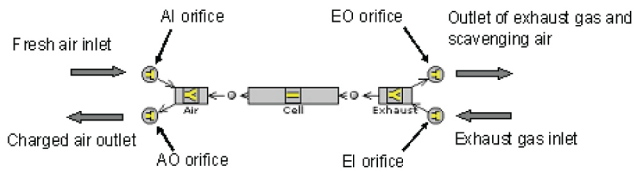


Figure 6. Basic gas dynamic model of a cell in GT-POWER

The cells are opened and closed with a certain time delay dependent on the angle between the cells and the rotor speed. In the case of 34 cells in one row the angular distance between cells is of 10.6° . It is introduced by the delay elements connected to the orifice actuator. The model accounts for both exhaust gas and air in each cell. The cells of one cycle (34 cells in two rows on 180deg of rotor revolution) are connected to particular flow split element representing the inlet/outlet port. There are two flow paths (volumes) leading to each of the ports from the PWS inlet/outlet in the air/exhaust housing. (See for instance Exhaust Outlet port and path in [Figure 1](#).) The pockets are modeled using the flow split elements and their volume is kept same as for the Mazda PWS ([Figure 3](#), [Figure 4](#)); their opening is controlled by the same type of time-adjustable orifices like in the case of rotor cells. The flow split element with opening control orifices was also employed for modeling of the gas passage allowing flow of the exhaust gas from the EI port to the gas pocket - GP ([Figure 7](#)). In case of the Mazda Comprex that gas passage flow path was constant and did not enable boost pressure control by its adjusting as at modern PWS devices [12].

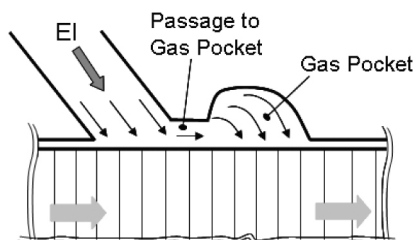


Figure 7. Supply of exhaust gas to the gas pocket via the gas passage

Each cell can communicate with its four neighbors ([Figure 8](#)). Accordingly, this leakage flow was modeled by connecting the cell pipe model at both ends with the particular

neighboring cells. The WR cells arrangement is similar to the honeycomb structure of a catalytic convertor. Thus, during the rotor cell wall temperature calculation it is assumed that there is no heat transfer from cell to cell, and the cell outside wall is regarded as insulated or adiabatic.

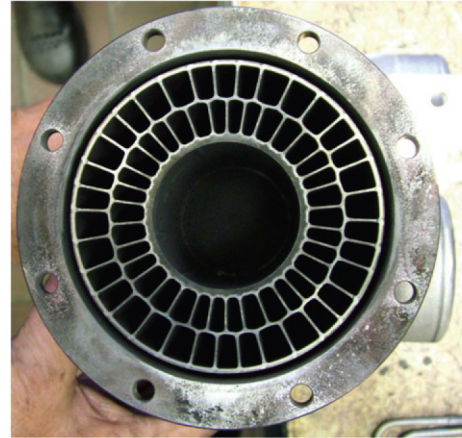


Figure 8. Wave rotor of Mazda Comprex-93

Even though the simulation of the PWS on the steady flow test rig is fast enough (one operation point computed on a 3.0GHz machine takes from 3 to 10 mins, depending on the PWS speed) the computation time gets longer when the PWS is to be connected to the engine model (the steady state computation of one operation point can also take up to 4 hrs). Therefore, to enable faster computation of the PWS model in conjunction with an engine model, the number of cells was decreased to a quarter of the original number of cells while retaining all modeling features described above.

1-D MODEL CALIBRATION

Both models, 68 cell and 17 cell, were calibrated by measurement of PWS Mazda Comprex-93 (WR length = WR diameter of 93mm) on the steady flow test rig. The PWS test rig was built using the existing turbocharger test rig (which was equipped with the combustor and the external source of constant compressed air pressure of 350 kPa absolute at mass flow rates up to 1000 kg/h) and is adopted for PWS tests at CZ a.s. Company, Turbo division, a partner of Josef Bozek Research Center (JBRC) - [13].

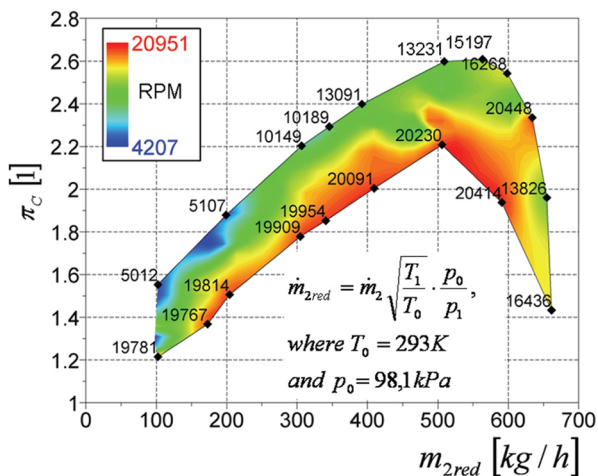


Figure 9. Measured performance map (Mazda CX-93) of PWS speed (values in rpm) for exhaust inlet temperature of 900K on steady flow test rig, where π_c represents static pressure ratio at air side and m_{2red} is reduced mass flow of compressed air

During the measurement of Mazda CX-93 on the steady flow test rig in open loop and further while simulating the virtual steady flow test rig in GT-SUITE the mass flow and exhaust gas temperature were forced at PWS exhaust inlet (EI), and the mass flow of compressed air at air outlet (AO) was balanced to match the EI. The diagram in Figure 9 presents measured flow characteristics of Mazda CX-93 device at EI temperature of 900K. The mass flow was adjusted from 100kg/h to 650kg/h. Moreover, the PWS was driven by an electric motor and its speed controlled from 0 to 20 000rpm using a motor controller. For instance at 100kg/h the PWS achieved the highest pressure ratio of approx. 1.6 at speed of 5000rpm and the pressure ratio of 1.2 at approx. 20 000rpm. Further, at 300kg/h the PWS achieved the highest pressure ratio of 2.2 at the speed of approx. 10 000rpm, and the pressure ratio of 1.8 at the highest speed of approx. 20 000rpm. The operation envelope is constrained by the maximum achievable pressure ratio and the maximum PWS speed. From Figure 9 follows that the pressure ratio of compressed air rises almost linearly with the mass flow rate up to its maximal value of 2.6 at 560 kg/h. Beyond this mass flow, the PWS device losses its capability to transfer the pressure from exhaust to air side and the air pressure ratio falls abruptly.

To calibrate the 1-D model the discharge coefficients at orifices representing air inlet (AI), air outlet (AO), exhaust outlet (EO), Gas Pocket and Gas Passage were varied depending on the PWS speed to obtain a 1-D model that could predict the PWS behavior reasonably well. The results of that calibration are presented in Figure 10, Figure 11, Figure 12, Figure 13. The diagrams shown are results for an AO (compressed air) mass flow rate of 300kg/h and exhaust inlet temperature of 900K.

From the AI and EO mass flow patterns comparison in Figure 10, it appears that the largest discrepancy between the simulation and measurement is 5% error and occurs at a PWS speed of 5000rpm. At all other speeds it is below 5% for both models. The predicted boost pressure (Figure 11) is within the 5% margin from 12000 to 18000rpm; at 10000rpm and 20000 the predicted boost pressure deviates to a maximum of 10%. The largest boost pressure deviation of 26% is for 17 cells model at the lowest PWS speed of 5000rpm. The EI pressure (Figure 11) is predicted within 5% from 10000 to 20000rpm for both models, with the largest discrepancy of 7% at 5000rpm.

The temperature prediction at AO (Figure 12) is within 5% margin from 10000 to 20000rpm. At the lowest PWS speed of 5000rpm the model underpredicts by 20%. Both 1-D models predict approx. 30K higher EO temperatures than measured ones. Nevertheless, the trend for the predicted temperature is correct.

The internal exhaust gas recirculation of PWS at AO is well predicted from 10000rpm to 20000rpm of PWS speed with almost zero recirculation; at the lowest PWS speed of 5000rpm the models predict 20% lower internal EGR than the measurement.

During the calibration it was discovered that the angular phasing between the housings and the modeling of the gas passage to the gas pocket had the greatest influence on the output. The results are very sensitive to the angular phasing of the housing. This phase is the angle between the starting edge of the EI port and starting edge of AO port. As it can take into account the manufacturing and assembling tolerances, this angular shift parameter was also used to calibrate the model. Therefore, the calibrated 1-D models had 20deg of the angular shift between the housings in place of 19deg measured on the Mazda Complex-93. The gas passage to the gas pocket (Figure 7) is another input which has to be modeled with care as it has significant impact on the PWS behavior.

The PWS behavior can also be qualified using the same diagrams (Figure 10, Figure 11, Figure 12, Figure 13). The PWS device ingests much more air than it delivers to the engine as compressed air; for instance at 15000 rpm the AI mass flow is 1.8 time higher than the compressed air (see Figure 10). The scavenged air dilutes the exhaust gas in EO port while decreasing its temperature (Figure 12 and Figure 13). The boost (AO) pressure is higher than the back (EI) pressure in the PWS speed range from 15000 to 17000rpm. The boost pressure behavior deteriorates below the PWS speed of 10000rpm and above of 20000rpm. There is no internal exhaust gas recirculation from 10000 to 20000rpm (Figure 13).

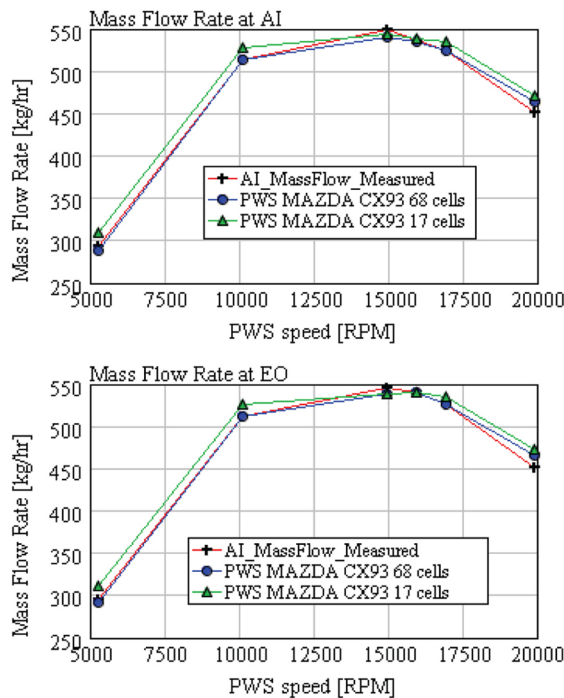


Figure 10. Calibration results of air inlet (AI) -above- and exhaust outlet (EO) mass flows for 68 cell and 17 cell models at 300kg/hour of air outlet (AO) mass flow and exhaust inlet (EI) temperature of 900K

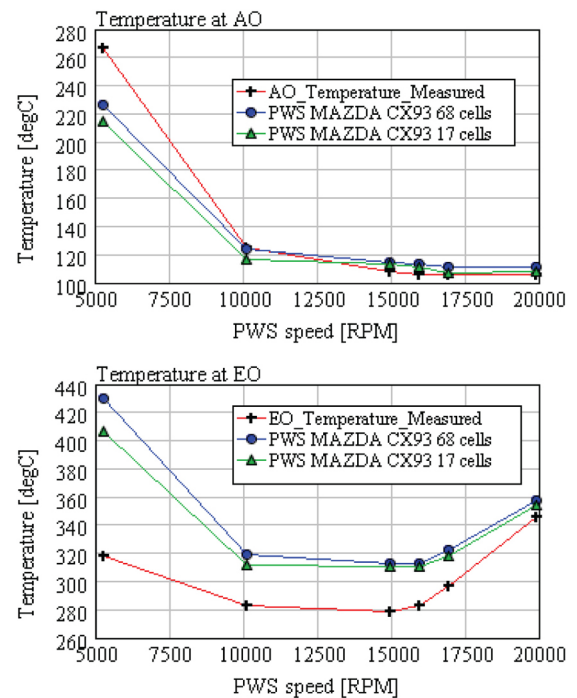


Figure 12. Calibration results of air outlet (AO) -above- and exhaust outlet (EO) temperatures for 68 cell and 17 cell models at 300kg/hour of air outlet (AO) mass flow and exhaust inlet (EI) temperature of 900K

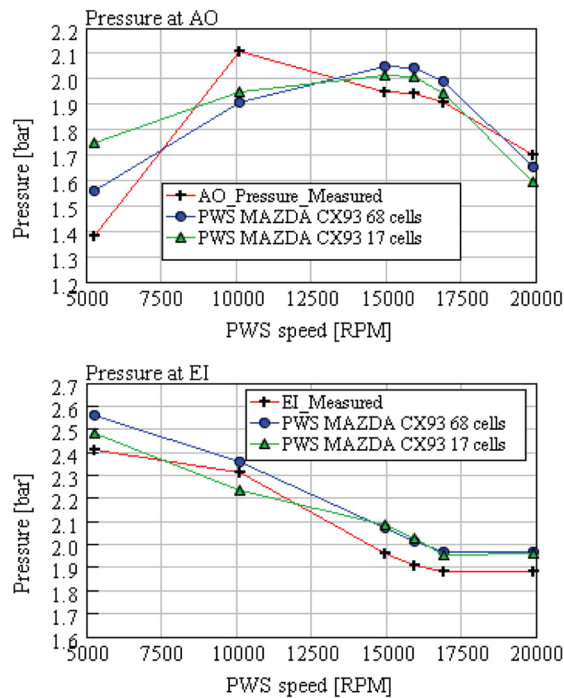


Figure 11. Calibration results of air outlet (AO)-above- and exhaust inlet (EI) static pressures for 68 cell and 17 cell models at 300kg/hour of air outlet (AO) mass flow and exhaust inlet (EI) temperature of 900K

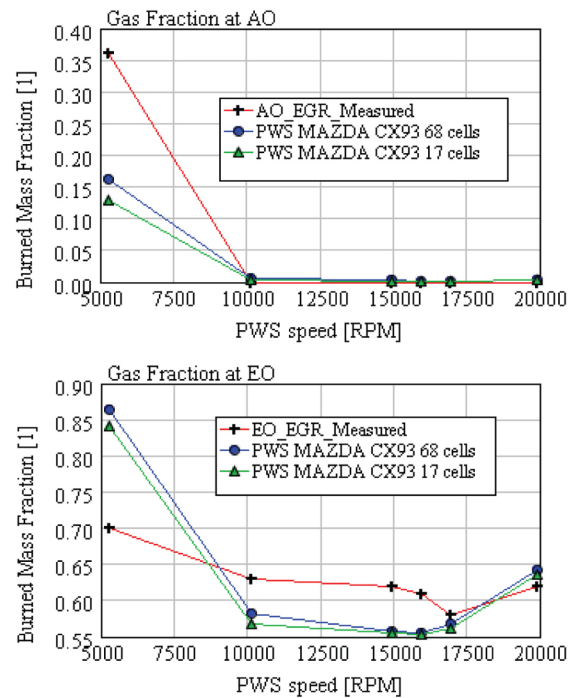


Figure 13. Calibration results of internal exhaust gas recirculation in AO-above- and scavenging in EO for 68 cell and 17 cell models at 300kg/hour of air outlet (AO) mass flow and exhaust inlet (EI) temperature of 900K

PWS 1-D MAPPING ON VIRTUAL TEST RIG

To find operational limits and investigate the influence of exhaust temperature and mass flow on PWS operation in areas not included in the experimental matrix, the CX-93 was simulated on the virtual steady flow test rig (Figure 14) in GT-SUITE using the full 68 cell model.

The exhaust temperature was varied from 500K to 1300K and the PWS speed from 10000rpm to 20000rpm. Further, the EI pressure was set to 1.0bar, 2.0bar and 3.0bar absolute (i.e. to be able to define the mass flow at EI). The mass flow at AO was balanced to the same value as EI. Following diagrams (Figure 15-Figure 16) present the PWS behavior in coordinates of EI temperature (x-axis) and PWS speed (y-axis).

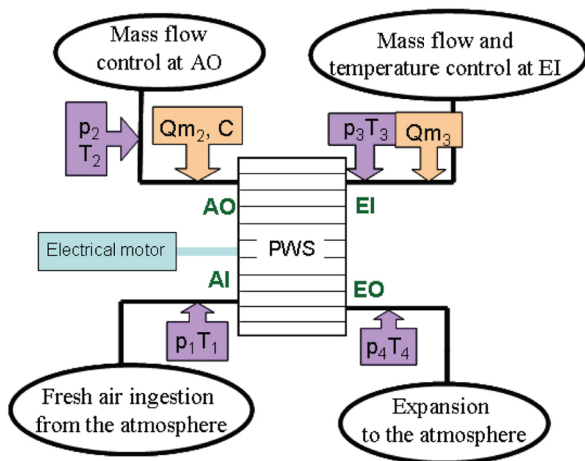


Figure 14. Scheme of the test rig, where p is pressure, T temperature, Qm mass flow and C is concentration of exhaust gas in AO

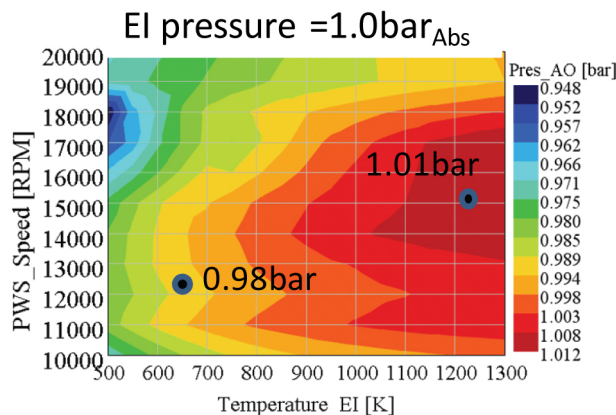


Figure 15. Boost pressure behavior for different EI pressure, $p_{AO}=0$ bar means that PWS is outside the operation region

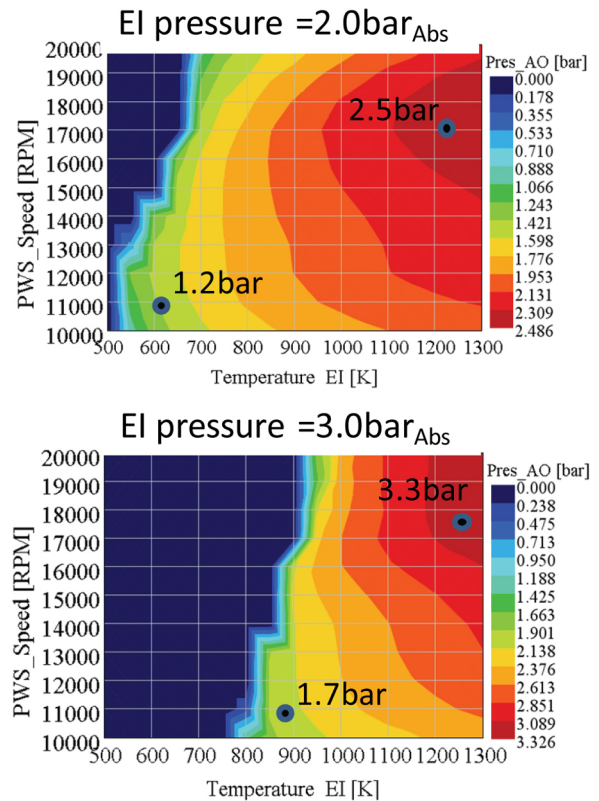


Figure 15 (cont'd). Boost pressure behavior for different EI pressure, $p_{AO}=0$ bar means that PWS is outside the operation region

The PWS operation region is shown in diagrams in Figure 15. For the lowest EI pressure of 1.0bar, the PWS device works at all investigated temperatures and rotor speeds. At higher EI pressures (2.0 and 3.0bar absolute) a blue area appears where the PWS does not work, i.e. the boost pressure drops significantly. The PWS loses the capability of pressure transformation from exhaust to air side at the border of working area where the EI temperature is the lowest and the mass flow the highest. Authors plan to investigate that area closer with regard to the possibility of the WR choking at those specific operation conditions.

The higher the EI pressure, the smaller the operation region. Therefore, the higher EI pressure the higher EI temperature has to be achieved to sustain the boosting process. At certain operating conditions (represented by EI pressure and temperature and PWS speed) there are abrupt changes in PWS behavior at which the boosting process breaks down suddenly. The highest boost pressures are achieved at the highest exhaust temperatures and for PWS speeds between 13000 and 20000rpm (Figure 15). At the lowest exhaust temperatures the pressure exchange process does not run efficiently and the boost pressure is considerably lower than the EI pressure. For the steady flow test rig simulation there is no internal exhaust gas recirculation (EGR) over the WR