CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DOCTORAL THESIS STATEMENT

CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF AUTOMOBILES, INTERNAL COMBUSTION ENGINES AND RAILWAY VEHICLES

DOCTORAL THESIS STATEMENT

A 1-D Unsteady Model of a Twin Scroll Radial Centripetal Turbine for Turbocharging Optimization

Zdeněk Žák

Study Programme: Mechanical Engineering

Field of Study: Machines and Equipment for Transportation

Supervisor: prof. Ing. Jan Macek, DrSc.

Supervisor specialist: doc. Ing. Oldřich Vítek, Ph.D.

Doctoral thesis statement in fulfilment of the requirements for the degree of "Doctor", abbreviated to "Ph.D."

Prague February 2018

Název: 1-D nestacionární model radiální dostředivé turbíny se dvouvstupovou skříní pro optimalizaci přeplňování

The thesis was prepared as a part of the full-time Ph.D. study programme at the Department of Automobiles, Internal Combustion Engines and Railway Vehicles of the Faculty of Mechanical Engineering, CTU in Prague

Candidate: Ing. Zdeněk Žák
Department of Automobiles, Internal Combustion Engines and Railway Vehicles, Faculty of Mechanical Engineering, CTU in Prague
Technická 4, 166 07 Prague 6, Czech Republic

Supervisor: prof. Ing. Jan Macek, DrSc.
Department of Automobiles, Internal Combustion Engines and Railway Vehicles, Faculty of Mechanical Engineering, CTU in Prague
Technická 4, 166 07 Prague 6, Czech Republic

Supervisor specialist: doc. Ing. Oldřich Vítek, Ph.D.
Department of Automobiles, Internal Combustion Engines and Railway Vehicles, Faculty of Mechanical Engineering, CTU in Prague
Technická 4, 166 07 Prague 6, Czech Republic

Opponents:

The doctoral thesis statements were distributed on: ....

The defence of the thesis will be held on ....at .... in the conference room No. 17 (downstair) of the Faculty of Mechanical Engineering, CTU in Prague, Technická 4, Prague 6
in front of the Dissertation Defence Committee in the field of study: Machines and Equipment for Transportation

The dissertation is available at the Department of Science and Research of the Faculty of Mechanical Engineering, CTU in Prague, Technická 4, Prague 6.

doc. Ing. Oldřich Vítek, Ph.D.
Chairman of Branch Board
Machines and Equipment for Transportation
Faculty of Mechanical Engineering, CTU in Prague

1. Introduction

The continual need for the increasing efficiency of all energy conversion processes is very strong not only in the automotive industry. The powertrain of a vehicle has to be efficient as high as possible and ecological during the entire lifecycle on the other hand. To find the optimum compromise is more and more demanding, because many of the requirements are contradictory.

The trends of downsizing, downspeeding and hybridization of vehicle powertrain units are obvious. The focus on prevailing real driving conditions and natural unsteady character of internal combustion engine operation is an actual challenging task. The behaviour of the turbocharged reciprocating internal combustion engine during transients is a crucial factor for vehicle dynamic, formation of emissions and fuel economy. The interactions between internal combustion engine and turbocharger, when the turbine operates under unsteady pulsating flow conditions, significantly influence the overall engine efficiency due to the continually increasing boost pressure level.

During the development of the turbocharged internal combustion engine, it is necessary to develop specific turbocharger concurrently, because only the overall efficiency (i.e. fuel economy) matters. Comprehensive simulation analyses at the early stage of the development are important more than ever. The development of simulation technics, which are able to describe the unsteady phenomena inside the reciprocating internal combustion engine and the turbocharger using the physical background, is the right way how to improve the predictive capability of the models and the overall development process of the powertrain unit. It must be stressed that experimental and simulation research has to be in synergy and the dialog between engineers is fundamental.

The multi entry axial turbines are used for turbocharging of large bore internal combustion engines in stationary and marine applications. Twin entry radial centripetal turbocharger turbines are used in the automotive industry. The twin scroll design is beneficial in conjunction with the engine with firing interval between cylinders around 120 degrees of a crank angle (240 degrees in exhaust manifold branches), i.e. six cylinder engines. The advantages consist in the higher efficiency of a turbine and better engine response during the transients due to better utilization of exhaust gas energy. The twin entry turbines are also used for the four cylinder engines to improve the engine behaviour during transients. The firing interval between cylinders in mentioned case is 180 degrees, thus out of optimum and the high pulsating flow upstream of a turbine cannot be utilized as effective as in the case of six cylinder engine.

The thesis deals with the twin scroll centripetal radial turbine and map-less approach in detail. The experimental research on the steady flow turbocharger test bed is the basis for the development of the turbine model with physical background. The predictive capability of the calibrated twin scroll turbine model is then verified through the simulation of the whole turbocharged compression ignition engine. The simulation results are properly compared with data measured on the experimental six cylinder engine.

2. State of the Art

Standard turbocharger maps are measured on the steady flow hot gas stands with open loop. The main problem of the most frequent experimental method is the narrow range of turbine load, which is represented by the blade speed ratio - BSR. The range of turbocharger speed seems to be relatively wide, but the range of turbine BSR is narrow with operating points close to optimum. The reasons are that the turbine is working with one compressor and the temperature of exhaust gases upstream of the turbine is constant. The standard measurement of turbochargers with twin entry turbine is the same as with the single volute. The inlet volutes upstream of the turbine are connected into one branch downstream of the combustion chamber. The turbocharger test bed remains without any changes.

The most frequent manner how to simulate the turbocharger turbine in engine simulation codes is to utilize the steady flow maps of corrected or reduced mass flow rate and isentropic efficiency of a turbine as a function of the pressure ratio. The steady flow maps are often extrapolated out of the measured range and interpolated to provide the turbine efficiency and instantaneous mass flow rate via machine. The mentioned quasi steady 0-D map based approach is a standard for 1-D/0-D simulation codes.

3. Goals of the Research

The main goal of the thesis is to develop comprehensive methodology, based on the map-less approach, which enables to describe the performance of the radial centripetal turbine with twin scroll under steady and unsteady conditions by the full 1-D model.

The first goal is to develop the specific turbocharger test bed, which is capable to measure the performance of the twin entry turbocharger turbine under steady flow with the different level of the impeller admission. It is also necessary to create the software for evaluation of the directly measured physical quantities.

The second goal is to develop the modular unsteady 1-D model of a radial centripetal turbine with twin scroll in available 1-D simulation software. The model must be able to describe the phenomena inside a turbine, mixing of flows upstream of the impeller, arbitrary level of impeller admission and interactions between the reciprocating internal combustion engine and the turbocharger.

The third goal is to validate and verify the mentioned methodology by the simulation of the internal combustion engine with the unsteady 1-D model of a twin scroll turbine at steady states and transients. The simulation results have to be compared with experimental data measured on the experimental diesel engine.

4. Experiments - Turbocharger

The first aim of the project was the development of the specific turbocharger test bed, which would allow the measurement of the turbochargers equipped with a twin entry turbine. The standard approach, when the turbine is measured under full equal admission of the impeller like the single scroll turbine, is useless for the description of the interactions between divided sections of the twin entry turbine.

It is necessary to separate the turbine sections on the test bed and to control the flow parameters upstream of the turbine. Then it is possible to study the influence of different conditions upstream of sections and their changes on the turbine performance and overall parameters.

At the beginning of the test bed development, several models of virtual test bed were created and properly tested in the GT-SUITE environment. The virtual open loop turbocharger test bed with a model of the combustion chamber and necessary PID controllers is a very useful tool not only during the development of new testing device but also before any real measurement.

The main dimensions of the test bed were predicted using the mentioned virtual model. The mass flow rates in separated sections are measured and evaluated indirectly through the pressure difference on the orifice with defined diameter. The testing possibilities of the developed test stand are shown in *Figure 1*.

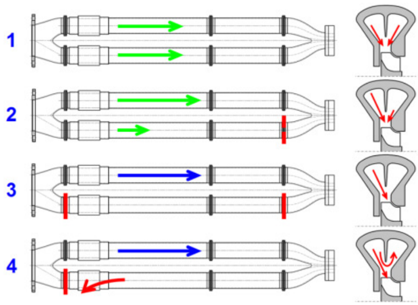

Figure 1 Test bed measurement capability: 1) uniform (full - equal) admission; 2) partial (unequal) admission (throttling in one section); 3) partial admission with closed section; 4) backflow

The twin entry turbine may be measured under full admission of the impeller. It is possible to achieve arbitrary level of partial admission via throttling in sections (*Figure 2*). The extreme level of partial admission is attainable through the enclosure of a section. The measurement of the back flow in section, if occurs, is also feasible.

The map-less approach requires several levels of turbine load (BSR), pressure ratio and impeller admission. It is necessary to measure extreme cases, i.e. full admission and partial admission of an impeller when one turbine section is closed. Three levels of impeller admission were measured in our case - full, partial (throttling in one section) and partial with closed section.

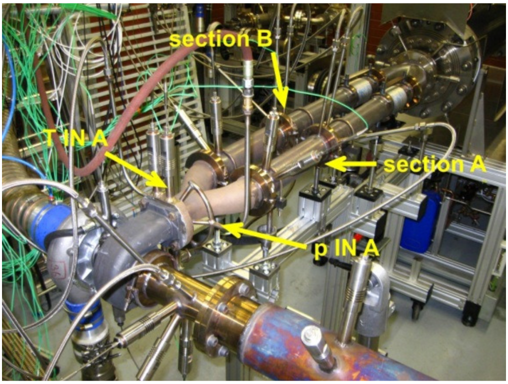

Figure 2 Twin scroll turbocharger test bed overview; separated sections A, B; measuring points of pressure and temperature turbine upstream (analogical for section B)

This is one of great advantage of the map-less approach, because relatively low number of measured operating points under steady flow is sufficient for the description of the twin scroll turbine behaviour. The range of experimental data is also sufficient for the calibration process of the twin scroll turbine 1-D model, which has a physical background. The properly calibrated comprehensive 1-D model also enables reasonable extrapolation, which is so useful at the early stage of the development process.

The map based approach for twin scroll turbine is very different. It is necessary to cover whole range of the turbine working area. The special turbine map has to be measured for each particular level of impeller admission with changing pressure and blade speed ratios. It is essential to measure much more working points in comparison with the map-less approach, what is demanding and very expensive.

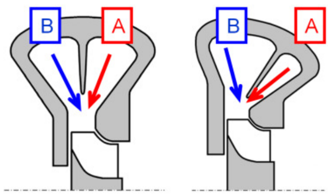

Figure 3 Twin entry turbine housings, symmetric design of sections (left), asymmetric design (right)

The map less approach needs mass flow rates in individual scroll sections and total turbine power at given turbine speed only, nothing else. For comparison and analysis purposes, it is possible to define conventional turbine parameters, as discharge coefficient or isentropic efficiency. The issue is in definition of ideal averaged state for those standard but not necessary parameters. The overall twin entry turbine parameters (*Figure 3*) are weighted in accordance with the isentropic power of each section. The level of partial admission of an impeller is defined as a fraction of the isentropic power in appropriate section to the total isentropic power (1). The admission level of the section B is analogical to relation for section A.

$$level_A = \frac{\dot{m}_A \frac{c_{s\_A}^2}{2}}{\dot{m}_A \frac{c_{s\_A}^2}{2} + \dot{m}_B \frac{c_{s\_B}^2}{2}} \tag{1}$$

The twin scroll turbine pressure ratio (total - static) is calculated via the equation (2).

$$PR_{AB\_t\_s} = \left[1 - \frac{\dot{m}_A \frac{c_{s\_A}^2}{2} + \dot{m}_B \frac{c_{s\_B}^2}{2}}{(\dot{m}_A + \dot{m}_B)\bar{c_p} T_{IN\_AB\_tot}}\right]^{\frac{\bar{\kappa}}{1-\bar{\kappa}}} \tag{2}$$

The overall turbine blade speed ratio is defined as a quotient of wheel tip speed and fictitious isentropic velocity (3).

$$BSR_{AB} = \frac{u_2}{c_{s\_AB}} = \frac{\pi D_{ref} 10^{-3} RPM}{60\ c_{s\_AB}} \tag{3}$$

The overall discharge coefficient of a twin entry turbine is the only exception, because it is defined as a fraction of the mass flow rates sum to the reference mass flow rate via machine (4).

$$\mu_{AB} = \frac{\dot{m}_A + \dot{m}_B}{\dot{m}_{ref}} = \frac{\dot{m}_A + \dot{m}_B}{A_{t\_ref} \frac{p_{IN\_AB\_t}}{\sqrt{r_{IN\_AB\_t}\ T_{IN\_AB\_t}}} \sqrt{\psi_{AB}}} \tag{4}$$

The measurement of a turbine driven by hot gases is influenced by the heat transfer in turbocharger components. A turbine does not work under adiabatic conditions. The correct turbine power is defined in the equation (5). The sum of compressor power and pure power losses in bearings is essential for correct turbine power evaluation in any case. The aim is to identify from experimental results the pure losses in bearings and the compressor power close to adiabatic conditions without the influence of heat transfer from turbine side.

$$P_{turb} - P_{wind} = P_{comp\_adi} + P_{bear} \tag{5}$$

The isentropic efficiency of a turbine is calculated as a quotient of turbine power to total-static isentropic power (6). The flow mixing upstream of the impeller is the irreversible process. This fact has to be taken into consideration at valuation of all isentropic values stated at the turbine side.

$$\eta_{turb\_ise} = \frac{P_{turb} - P_{wind}}{P_{ise\_AB\_t\_s}} = \frac{P_{comp\_adi} + P_{bear}}{P_{ise\_AB\_t\_s}} \tag{6}$$

The power losses in bearings cannot be evaluated from the measured oil enthalpy head, because the sensed temperatures are influenced by heat flux from the turbine driven by hot exhaust gases. The built-up regression formula was used for the calculation of power losses in bearings. The pure power losses in bearings compared to the experimental results are shown in *Figure 4*. The method is relatively simple and not absolutely correct. The losses in bearings are not so high compared to compressor power, but the influence on final turbine results is not neglectable.

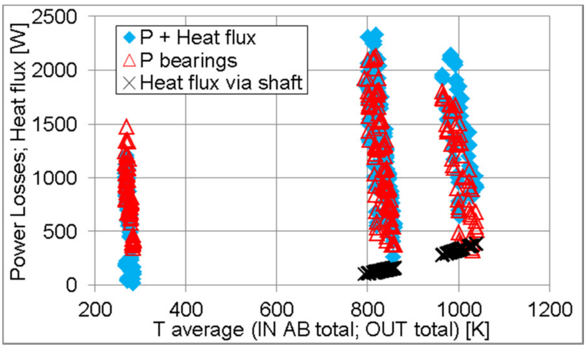

Figure 4 Power losses in bearings (measurement influenced by the heat transfer from turbine side) - blue; pure power losses in bearings - red triangles; heat flux via turbocharger shaft - black; horizontal axis - average of total temperatures at turbine inlet sections A, B and turbine outlet

For the evaluation of turbine power (5), it is essential to know the actual compressor power under any conditions. The specific regression formula based on the Euler theorem for compressors was used for determination of valid compressor power. The compressor power evaluated from measured temperature difference and mass flow rate under cold and hot conditions is compared in *Figure 5*.

Compressor power should not depend on temperature at turbine. At higher temperature at turbine, compressor power is influenced by the heat transfer from the turbine side and the compressor power evaluated from temperatures at compressor inlet/outlet is not correct. The biggest differences are visible at low speeds, where the influence of heat transfer from the turbine on measured values downstream of the compressor is highest. The heat transfer impact from the turbine driven by hot exhaust gases decreases with increasing turbocharger speed.

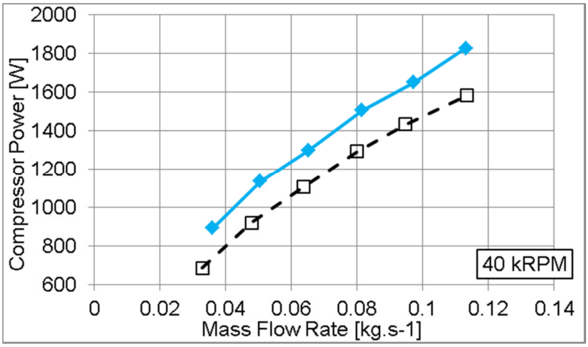

Figure 5 Compressor power evaluated from measured temperature difference; turbine driven by exhaust gases (blue); turbine driven by cold air (black dashed line); turbocharger speed 40 kRPM

The summary experimental results in *Figure 6* show the influence of the tested twin entry turbine design on the isentropic efficiency under different conditions in sections. The impact of different conditions in turbine sections is obvious. The tested twin entry turbine reaches comparable level of optimum isentropic efficiency under partial admission with the level A approximately 0.87 as in the case with the equal admission of the impeller. The turbine under extreme level of admission, with closed section, achieves lower maximum isentropic efficiency compared to previous cases.

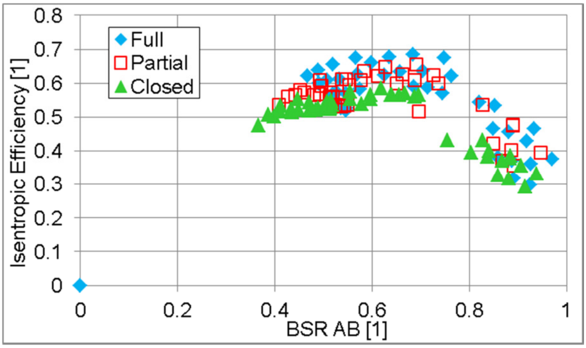

Figure 6 Turbine isentropic efficiency vs. blade speed ratio; full admission (blue); partial admission level A = 0.87 (red squares); one turbine section closed (green triangles)

5. Experiments - Internal Combustion Engine

The goal of the experimental research on the turbocharged internal combustion engine is to describe the synergy between the engine and turbocharger under real conditions. The measured unsteady data are fundamental for evaluation of predictive capability of the developed simulation models, especially the full 1-D twin scroll turbine model. Data from steady state measurements are important for the proper calibration of the internal combustion engine model. Transient load response was measured due to its relevance for vehicle engines, but due to limited feasibility of engine dynamometer control only at constant engine speed. The transients are generally the most demanding operating modes of the simulation models. The stability and capability of the full 1-D twin scroll turbine model to describe rapidly changing values are crucial. The engine with six cylinders in line is suitable for utilization of the twin scroll turbine advantages by virtue of the optimal firing interval between cylinders. The engine layout with pulsation exhaust system and firing interval 240 degrees between cylinders in each exhaust branch was suitable for the research.

The experimental internal combustion engine was equipped with the same type of turbocharger with twin scroll turbine and standard compressor wheel as measured on the steady flow turbocharger test bed. The measurement chain was developed with the focus on the unsteady behaviour of the engine and turbocharger, thus the pressure indication at proper locations was inserted. The engine was equipped with the pressure indication at the intake port inlet, in the cylinder and at the outlet of the exhaust port. The measurement of those three unsteady pressures was required for the three pressure analysis. The pressures at the inlets of turbine sections and at the turbine outlet were indicated too.

6. Simulation - Twin Entry Turbine

The model completely developed in the GT-SUITE simulation environment is fully modular, relatively easy to rebuild and ready for recalibration. It enables to adapt the current model to required specific design of a turbine. The model includes the twin volute with symmetrical and asymmetrical design, the scrolls are thus generally asymmetrical in the model. When one section of a scroll is closed, the model behaves like a single scroll turbine automatically. The operating mode with closed section, as an extreme level of the impeller admission, was also measured on the turbocharger test bed. It is possible to simulate vaneless or bladed nozzle ring. The radial turbine presented in the thesis is equipped with a parallel symmetrical twin scroll and vaneless nozzle ring. The current model is adiabatic but ready for very specific purposes of non-adiabatic conditions in relation to turbocharger energy balance with required heat fluxes. The 1-D model is fully unsteady, so it enables to describe fast changing values inside the whole turbine. Every physical quantities and turbine parameters are computed online directly in the model. The model predicts backflows in sections.

The turbine basic geometry is required for the 1-D model. Inlet diameter of scroll section (circular cross section) has equivalent area as inlet port of a real turbine with non-circular shape. The length of each section scroll is required. Only half of the length is used in the model, then one section begins to interact with the other. The turbine wheel is described by main dimensions such as inlet diameter and width, outlet large and small diameter and impeller centre-line length of flow inside a channel. The impeller in radial direction is modelled as single rotating channel with appropriate equivalent diameter (circular cross section). The last are dimensions of the turbine outlet pipe. The reference area of a turbine is also needful for computation of the proper discharge coefficient.

The full 1-D map-less approach is based on the physical description of phenomena inside the turbine scroll, mixing of flows from separated sections, impeller and turbine outlet. The simplified scheme of the turbine model developed in GT-SUITE is drawn in *Figure 7*. Parallel sections A and B are connected in the zone of flow mixing modelled using the flowsplit template in function of flow joint. The calibration of the flow joint is prerequisite. The diameters of inlet and outlet ports are controlled via actual dimension of vaneless nozzle ring in accordance of calibrated values. The mixing of flows occurs at the right place and correct pressures impeller upstream. The calibrated discharge coefficients also take place in the orifices between section outlets and flow joint. The flow after mixing continues via the vaneless nozzle ring. The nozzle outlet diameter, upstream of first transformation from stator to rotor, is given by the actual angle alpha 2, thus one of fundamental calibration coefficient. The portion of overall mass flow rate is separated in the zone of nozzle ring and flows through the parallel circuit of leakages. The leakages are divided into static and rotating. The rotating leakage is exposed to the same acceleration as the rotating channel representing the radial part of the turbine wheel is. The portion of mass flow rate via the static and rotating leakages is the subject of calibration. After the flow left the nozzle ring, the total state transformation from static coordinates to rotating coordinate system between the nozzle and rotating channel takes place.

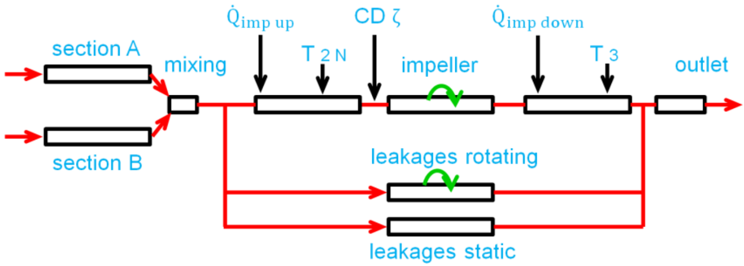

Figure 7 Simplified scheme of a 1-D radial centripetal turbine with twin scroll

The impeller is simulated by two pipes. The first one, in radial direction, is the rotating channel exposed to acceleration. The second is the outlet part of the impeller in axial direction. The pipe that simulates the rotating channel is exposed to the acceleration, which depends on actual turbine wheel speed. The pipe of rotating leakage is thus exposed to the same acceleration at the inlet and outlet as the rotating channel. The transformation from rotating coordinate system to static coordinates of stator begins at impeller outlet. After the finalization of second transformation, the mass flow rate from the parallel circuit of leakages joins the main turbine mass flow rate. The model is terminated by the outlet pipe. The basic torque is calculated using the Euler turbine theorem (7).

$$Tq_{Euler} = \tag{7}$$

$$= \dot{m}_{2\_N} 0.5 D_{imp\_IN} 10^{-3} c_{2\_t} - \dot{m}_3 0.5 D_{imp\_OUT\_ave} 10^{-3} c_{3\_t}$$

The physical robustness of the Euler turbine theorem consists in the dependence of torque on the tangential components of absolute velocities at the impeller inlet c 2_t and outlet c 3_t and appropriate mass flow rates. The relevant turbine power (8) results from the basic power, based on the Euler turbine theorem, reduced by windage losses - P wind. The windage losses are calibrated under steady flow via the calibration coefficient K wind.

$$P_{Euler} - P_{wind} = P_{comp\_adi} + P_{bear} \tag{8}$$

The isentropic efficiency of a turbine is valid only under steady flow conditions. At unsteady turbine operation, the isentropic turbine efficiency is not relevant due to the mass accumulation inside the different part of the model. The accumulation of mass during unsteady operation is natural behaviour of the model and also of the real turbine, so the efficiency calculated from isentropic enthalpy head cannot be used, because the isentropic enthalpy differences cannot be simply integrated. The efficiency is biased and unusable for the evaluation of unsteady results. From the general point of view, the relevant physical quantities that describe the performance of the turbocharged internal combustion engine are brake values such as brake torque and brake specific fuel consumption, so only the brake efficiency of the whole engine is important and decisive. The partial efficiency of the turbine or turbocharger is irrelevant.

The real twin scroll radial turbine, in compliance with map-less philosophy, is represented by several experimental results. The parameters were measured at different pressure ratio, relatively broad range of blade speed ratio and under different levels of the impeller admission. No classical steady flow map is required during the entire process. The steady flow calibration procedure of the 1-D model covers all measured working points of the tested turbine. The definition of isentropic states, in the case of a turbine with twin scroll where the mixing of flows takes place, is problematic, because the mixing of flows is an irreversible process. The crucial physical values describing the turbine performance are mass flow rate and corresponding turbine power.

The goal of the calibration procedure of the 1-D turbine model was to find the best model setup under steady flow via the combination of calibration coefficients, where the differences between simulation and experimental results are lowest. A simple virtual steady flow turbine test bed, with features of the ideal turbine dynamometer, was used for the purposes of the steady flow calibration procedure. The forced mass flow rates and temperatures from experiments were specified for each turbine section in the model. The turbine speed was also at the same value as at the correspondent measurement. The simulation results were compared with the experimental data at the same conditions at the turbine inlet and outlet.

The model was calibrated via coefficients: nozzle exit angle, deviation of nozzle exit angle, impeller exit angle, flow separation coefficient, correction of impeller incidence loss, coefficient of windage losses, discharge coefficient of static leakages, discharge coefficient of rotating leakages, pressure loss coefficient in impeller pipe, discharge coefficient at section A outlet (upstream of flow mixing), discharge coefficient at section B outlet (upstream of flow mixing), pressure loss coefficient in section A and pressure loss coefficient in section B.

The aim of steady flow calibration was to find the proper combination of all calibration coefficients with lowest overall error (9) between simulation results and experiments. Three parameters were taken into account during the results evaluation. The simulated and measured pressure ratio of section A, pressure ratio of section B and turbine power under steady flow were compared. After the steady flow calibration, the fully calibrated model of a twin entry turbine was ready for the on-engine simulation.

$$\Delta = \frac{1}{3}\left[abs\left(\frac{PR_{A\_sim}}{PR_{A\_exp}} - 1\right) + abs\left(\frac{PR_{B\_sim}}{PR_{B\_exp}} - 1\right) + \right.$$
$$\left. + abs\left(\frac{\{P_{Euler} - P_{wind}\}_{sim}}{\{P_{turb} - P_{wind}\}_{exp}} - 1\right)\right] \tag{9}$$

The comparison of the experimental and simulated pressure ratios of turbine sections is presented in *Figure 8*. The turbine power and isentropic efficiency are stated in *Figure 9*. The isentropic efficiency of a turbine is relevant in the case of full admission of the impeller.

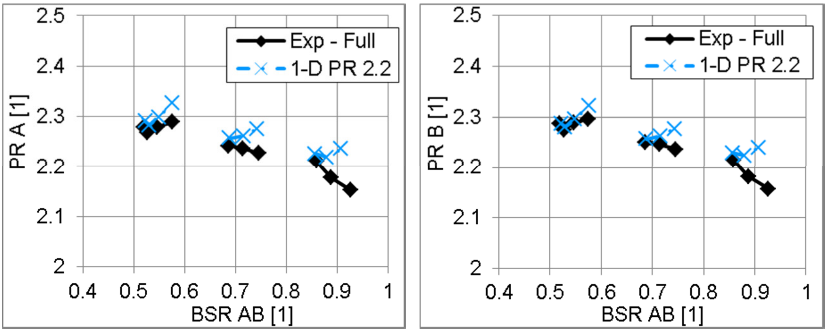

Figure 8 Pressure ratio A (left) and B (right) vs. BSR (approximate pressure ratio level PR AB = 2.2), full admission of an impeller; experiments (black); simulation 1-D turbine (blue crosses)

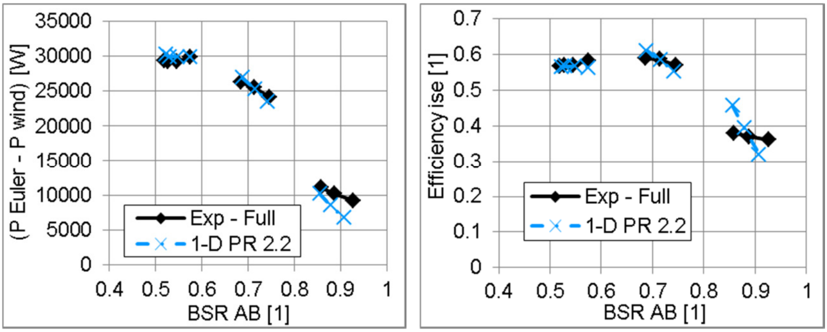

Figure 9 Turbine power (left) and isentropic efficiency (right) vs. BSR (approximate pressure ratio level PR AB = 2.2), full admission of an impeller; experiments (black); simulation 1-D turbine (blue crosses)

Simulated turbine power at high blade speed ratios is lower than power evaluated from experiments and concurrently the pressure ratios are higher than measured. It is not possible to achieve required turbine power and pressure ratios A, B under cold conditions using any combination of calibration coefficients in the turbine model. The problem consists in the level of accuracy of the experiments under cold conditions, when the turbine was driven by the cold air only. The important fact is that the power of a turbine under cold conditions at high blade speed ratios is relatively low and not so important for the simulation in conjunction with the internal combustion engine, which is the main goal of the work.

7. Simulation - Internal Combustion Engine

The goal of the on-engine simulations was the verification of the turbine model behaviour under real conditions of the highly pulsating flow. The six cylinder diesel engine model was connected with the unsteady full 1-D model of the twin entry radial centripetal turbine. The unsteady 1-D model of the twin entry turbine was fully calibrated under steady flow conditions and utilized for the engine simulation without any modification or recalibration. It has to be stressed that the internal combustion engine was equipped with the same type of the turbocharger, which was tested on the turbocharger test bed, but two pieces of the turbocharger were used during the work.

The model of the experimental internal combustion engine was properly calibrated using the available data (geometry, material properties, moments of inertia etc.) and measured physical quantities. Engine steady states and transients were investigated. For the internal combustion engine valuation as a whole machine, the important parameters are the brake mean effective pressure (*Figure 10*) and brake specific fuel consumption (*Figure 11*). The experimental and simulated values are fully comparable.

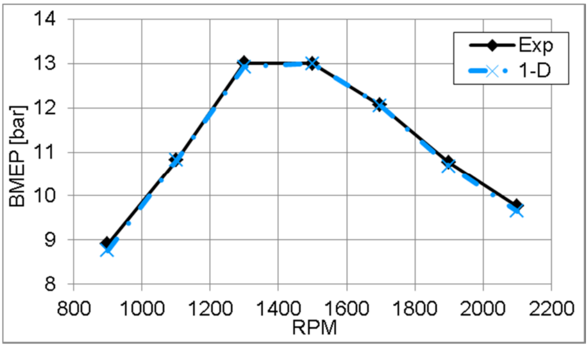

Figure 10 Brake mean effective pressure, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line)

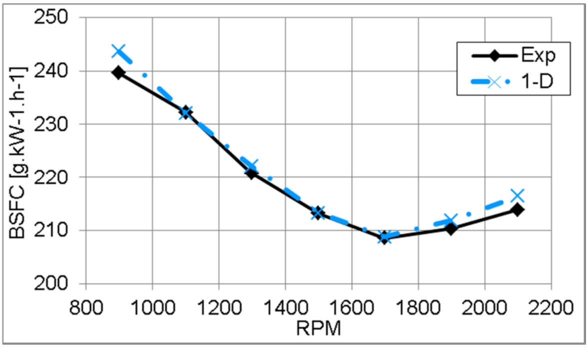

Figure 11 Brake specific fuel consumption, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line)

The comparison of measured and simulated turbocharger speed is in *Figure 12*.

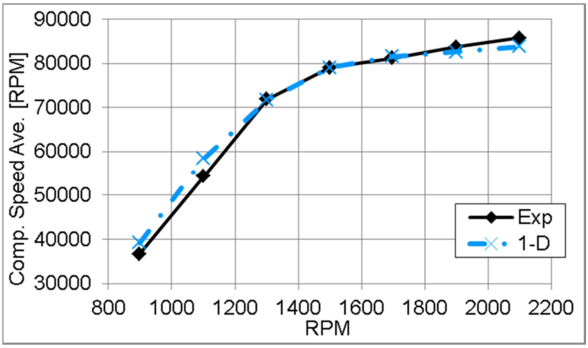

Figure 12 Compressor speed, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line)

The pressure indicated at inlet of the turbine section A is compared with the simulated pressure in *Figure 13*. The accordance with the indicated values is relatively good.

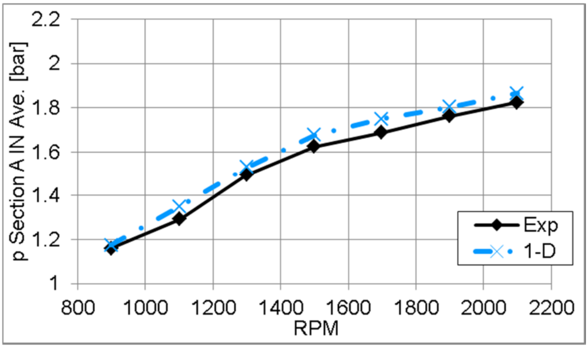

Figure 13 Pressure at inlet of turbine section A, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line)

The engine was used as a source of highly pulsating flow of exhaust gases. The unsteady conditions upstream and downstream of the turbine are important from the turbine model point of view. The pressures at the inlet of the turbine section A (*Figure 14*), indicated and predicted by the 1-D turbine model, are almost similar.

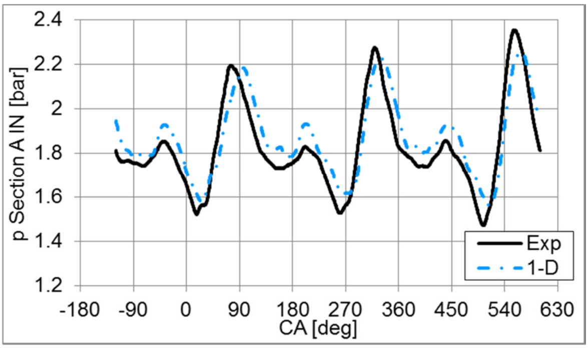

Figure 14 Pressure at inlet of turbine section A, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line); 2100 RPM, BMEP = 9.8 bar

The integral data from simulations of the turbocharged internal combustion engine with the unsteady full 1-D model of the twin scroll turbine confirmed the predictive capability of the turbine model under real conditions of highly pulsating flow. The level of results compared with experiments is relatively high at all working points. The performance of the turbine 1-D model under highly unsteady conditions is very important for the model utilization in practice.

The goal of the transient simulation was to verify the stability, robustness and predictive capability of the full 1-D turbine model with the twin scroll. Rapidly changing conditions upstream of a turbine are the most demanding conditions for the developed turbine model. The transients, at given constant engine speed, were defined by the fuel mass flow rate in time.

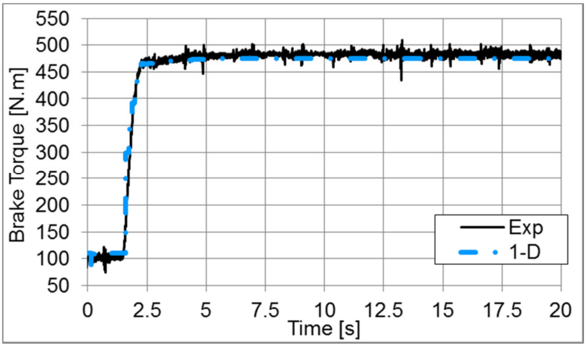

Figure 15 Brake torque, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line); 900 RPM

The maximum amount of fuel corresponds with the steady state point at full engine load. The information about the injected fuel mass from the injector is not available. The comparison of measured engine brake torque and simulation with full 1-D turbine model is in *Figure 15*. The turbocharger speed (*Figure 16*) and pressure at inlet of the turbine section A (*Figure 17*) predicted by the full 1-D turbine model are comparable with experiments. When we compare experimental values with simulation results at engine steady states, it is clear that the 1-D turbine model is consistent in prediction at transient. The turbocharger speed at the end of the transient (*Figure 16*) corresponds with the predicted value from steady state, but the speed measured during transient is slightly lower than from experiment at steady state.

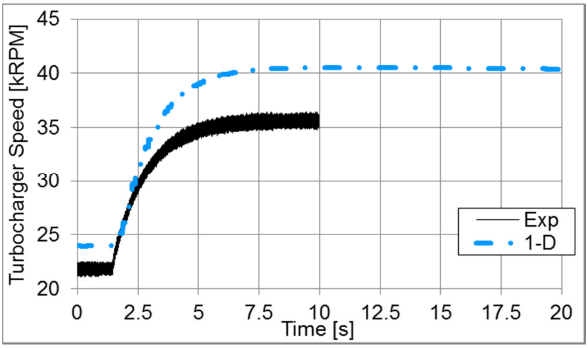

Figure 16 Turbocharger speed, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line); 900 RPM

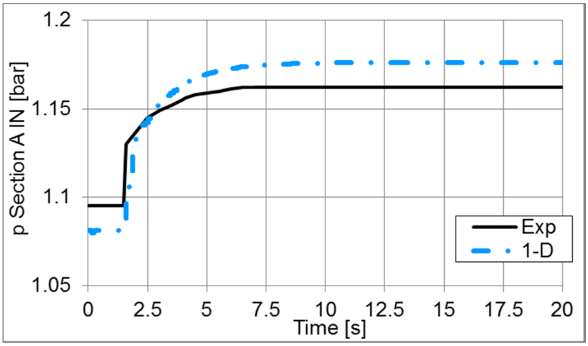

Figure 17 Pressure at inlet of turbine section A, experiment (black solid line), simulation with full 1-D unsteady turbine (blue dashed and dotted line); 900 RPM

8. Generalization of Results and Discussion

The developed unsteady 1-D model of a radial centripetal turbine with the twin scroll is modular. It is possible to adapt current version to specific design and dimensions of the required turbine and recalibrate the new model under steady flow conditions in compliance with experiments. The number of required measurements is relatively low, compared to classical map based approach, by virtue of the physical background of the model. The design of each section is independent, thus the scrolls are generally asymmetrical. The number of turbine sections and their layout are practically unlimited. The model implicitly enables the single scroll turbine simulation. It is easy to close one section and the model then behaves like a single entry turbine. If required, the dimensions of the inlet volute and vaneless or bladed nozzle ring have to be tailored. The model is able to operate under adiabatic or diabatic conditions. The heat transfer in each part of the turbine model can be simulated, but it was not performed yet. The 1-D turbine model is able to simulate the backflow in each section. The current model was not calibrated for those conditions.

The 1-D turbine model, fully calibrated at steady flow conditions, is then prepared for the unsteady and transient simulation connected with the model of the internal combustion engine. The calibrated twin scroll turbine 1-D model enables to derive similar smaller and bigger size machines. The main dimensions would be tailored to a smaller and bigger turbine and steady flow calibration coefficients of the original measured and calibrated turbine would be utilized for the simulation purposes of virtual prototypes. The full 1-D twin scroll turbine model is suitable for sensitivity analyses of main turbine features on overall parameters, because the phenomena inside the turbine are described by the model. The turbine model results may help at the beginning of the development process of a turbocharged internal combustion engine. The main features and parameters of the calibrated model are transferable to a similar turbine. The turbine model presented in the thesis is completely prepared in GT-SUITE environment, but the model with the same features is possible to develop in any simulation software with similarly capable 1-D flow solver. The developed 1-D model of a twin scroll turbine proved its capability at steady and unsteady flow conditions.

The specific turbocharger open-loop test bed for a twin scroll turbine is completely prepared and verified. It enables to measure a twin scroll turbine under equal full admission and arbitrary unequal partial admission of an impeller. The test bed is fully prepared for the measurement of backflow in turbine sections. The methodology of the measured steady flow data evaluation, including specific regression formulas for the compressor and turbine, and their utilization in the calibration process of the 1-D turbine model is also verified and ready to use for any turbocharger.

The map-less approach described in the thesis as a comprehensive methodology enables to create the physical based model of any turbocharger turbine. Relatively low number of measurements, compared with the map based approach, is required for the steady flow calibration process. The main dimensions of a turbine are also required. The map-less approach in relation to the 1-D turbine model provides useful information about the turbine as a machine, which is not known in case of the 0-D map based approach.

Advantages of map-less approach:
The steady flow turbine maps are not required during the entire development process, but may be generated with advantage of the 1-D approach. It is not required to measure huge set of the steady flow maps for each level of the impeller admission. The number of measured operating points for the turbine description at different level of admission is relatively low in the case of map-less approach. The map-less approach utilizes the entire turbine model, which involves the volumes inside a turbine and their natural accumulation of mass at unsteady operating conditions like a real machine. This feature is important at unsteady and transient conditions. The model is thus fully unsteady with mixing of flows at nozzle ring and proper conditions. It enables to achieve extreme partial admission including the backflow in sections. The full 1-D turbine model also enables the sensitivity analyses of main dimensions on the overall parameters, which are important for the development of a similar virtual turbine. The virtual turbine may be beneficial at the beginning of the new internal combustion engine development. The physical background of the turbine model enables extrapolation of the parameters outside the calibrated range. The physical approach should be generally more capable for the development of virtual prototypes, based on a calibrated similar turbine. In case of the 0-D map based approach, the turbine is not modelled but only described by the steady flow maps, which are fitted by the simulation software.

Disadvantages of map-less approach:
The turbine 1-D model requires the knowledge of the geometric dimensions of main turbine parts such as scrolls, impeller and outlet part. The current calibration process with many calibration coefficients is generally demanding and time-consuming. The computational time requirement of the full 1-D turbine model at unsteady operation is notably higher, compared with the 0-D approach. The usage of the steady flow turbine map in combination of the 0-D turbine model is simple, fast and operative.

9. Conclusions

The main goal of the thesis was to develop, validate and verify the comprehensive methodology, which utilizes the map-less approach for radial centripetal turbines equipped with the twin scroll. The map-less approach does not utilize the classical steady flow maps of a turbine during entire process of the full 1-D turbine model development.

The specific steady flow turbocharger test bed with separated turbine sections for measurement of the twin entry turbines was developed. The open loop hot gas stand is suitable for achievement of the arbitrary level of turbine impeller admission. The unequal partial level of admission is reached via the throttling in a turbine section and extreme partial admission by closure of one section. The turbine was tested under different level of impeller admission and load. All experimental data, measured on the steady flow turbocharger test bed, were evaluated by the in-house software developed for the purposes. The software includes the evaluation of the compressor power under adiabatic conditions, power losses in bearings and all relevant physical quantities, which describe the twin scroll turbine behaviour under steady flow conditions. The data are necessary for the calibration process of the full 1-D twin scroll turbine model.

The same type of the turbocharger was tested under real conditions in conjunction with the six cylinder diesel engine. The measurement chain of the internal combustion engine focused on the turbine behaviour. The important pressures at the engine and upstream/downstream of the turbine were indicated. The steady states and also transients at constant engine speeds were measured. The aim of the experiments was to obtain relevant data, which are essential for the verification of the twin scroll turbine model predictive capability under highly pulsating flow of exhaust gases, thus the real operating conditions of a turbocharger turbine.

For the verification of the full 1-D twin scroll turbine model performance in engine simulation, a detailed model of the experimental internal combustion engine was created in GT-SUITE environment. The model of the six cylinder diesel engine equipped with a twin entry turbine was properly calibrated using the experimental data. A single cylinder engine model was derived for the evaluation of the experimental data, especially for the three pressure analyses.

The developed modular unsteady full 1-D model of a radial centripetal turbine with twin scroll is a suitable tool for the description of the interactions between the internal combustion engine and a turbocharger. The model also describes the phenomena inside a turbine with mixing of flows upstream of the impeller at proper location under valid conditions in sections. The physical approach respects conditions for mixing of flows inside the scroll, asymmetry of flow admission, turbine scroll design, dimensions of the impeller and interactions among the parts inside a radial turbine. The turbine model was properly calibrated at steady flow conditions using the experimental data measured on the turbocharger test bed. The best accordance of simulation and experimental results was achieved by proper combination of calibration coefficients.

The 1-D model of a twin scroll turbine, after steady flow calibration process, is ready for highly unsteady simulation under pulsating flow conditions. The robustness of the developed twin scroll turbine model was proven under unsteady conditions of highly pulsating flow of exhaust gases on the engine. The results of unsteady engine simulation with the 1-D turbine model are satisfactory at engine steady states and also during transient operation at constant engine speed. The comprehensive methodology utilizing the map-less approach was validated and verified on the tested radial turbine with the twin scroll.

The developed, validated and verified methodology with the map-less approach is fully prepared for the employment in practice. The differences between the physical map-less approach and map based approach increase with the level of pulsating flow and under extreme conditions during the engine transient operation. The simulation support of experiments, higher simulation and design, based on the full 1-D turbine models, may contribute to the acceleration of turbocharger and internal combustion engine development process. The longtime goal is the extensive library of turbocharger models, as a part of appropriate knowledge database, based on the map-less approach, which can be also utilized for purposes of virtual prototypes.

References

[1] DIXON S. L.: Fluid Mechanics, Thermodynamics of Turbomachinery. Pergamon Press London 1975

[2] ZINNER, K., "Supercharging of Internal Combustion Engines". Springer Heidelberg 1978

[3] HEYWOOD, J. B.: Internal Combustion Engine Fundamentals. McGraw- Hill series in mechanical engineering, printed in USA. McGraw-Hill, 1988. ISBN 0-07- 028637-X.

[4] GT-SUITE Application Manuals, version 7.3, Gamma Technologies Inc., Westmont, IL, 2012.

[5] Romagnoli A, Martinez-Botas R, Performance prediction of a nozzled and nozzleless mixed-flow turbine in steady conditions, INTERNATIONAL JOURNAL OF MECHANICAL SCIENCES, Vol: 53, Pages: 557-574, ISSN: 0020-7403, 2011

[6] Romagnoli A, Martinez-Botas RF, Rajoo S., Steady state performance evaluation of variable geometry twin-entry turbine, INTERNATIONAL JOURNAL OF HEAT AND FLUID FLOW, Vol: 32, Pages: 477-489, ISSN: 0142-727X, 2011

[7] Serrano, J.R., Arnau F.J., Dolz V., Tiseira A., Cervelló C., A model of turbocharger radial turbines appropriate to be used in zero- and one-dimensional gas dynamics codes for internal combustion engines modelling, Energy Conversion and Management, Vol: 49, Pages: 3729– 3745, ISSN: 0196-8904, 2008

[8] Payri F., Serrano J.R., Fajardo P., Reyes-Belmonte M.A., Gozalbo-Belles R., A physically based methodology to extrapolate performance maps of radial turbines, Energy Conversion and Management, Vol: 55, Pages: 149–163, ISSN: 0196-8904, 2012

[9] Chiong MS, Rajoo S, Martinez-Botas RF, Costall AWet al., Engine turbocharger performance prediction: One-dimensional modeling of a twin entry turbine, ENERGY CONVERSION AND MANAGEMENT, Vol: 57, Pages: 68-78, ISSN: 0196-8904, 2012

[10] Chiong MS, Rajoo S, Romagnoli A, Costall AW, Martinez-Botas RFet al., Integration of meanline and one-dimensional methods for prediction of pulsating performance of a turbocharger turbine, ENERGY CONVERSION AND MANAGEMENT, Vol: 81, Pages: 270-281, ISSN: 0196-8904, 2014

[11] Galindo J., Tiseira A., Fajardo P., García-Cuevas L.M., Development and validation of a radial variable geometry turbine model for transient pulsating flow applications, ENERGY CONVERSION AND MANAGEMENT, Vol: 85, Pages: 190-203, ISSN: 0196-8904, 2014

[12] Chiong MS, Rajoo S, Romagnoli A, Costall AW, Martinez-Botas RFet al., Non-adiabatic pressure loss boundary condition for modelling turbocharger turbine pulsating flow, ENERGY CONVERSION AND MANAGEMENT, Vol: 93, Pages: 267-281, ISSN: 0196-8904, 2015

[13] De Bellis V., Marelli S., Bozza F., Capobianco M., 1D simulation and experimental analysis of a turbocharger turbine for automotive engines under steady and unsteady flow conditions, 68th Conference of the Italian Thermal Machines Engineering Association, ATI2013, Energy Procedia, Vol: 45, Pages: 909-918, ISSN: 1876-6102, 2014

[14] Hu, X. and Lawless, P., "Predictions of On-Engine Efficiency for the Radial Turbine of a Pulse Turbocharged Engine," SAE Technical Paper 2001-01-1238, 2001, doi:10.4271/2001-01-1238.

[15] Westin, F. and Ångström, H., "Calculation Accuracy of Pulsating Flow through the Turbine of SI-Engine Turbochargers - Part 1 Calculations for Choice of Turbines with Different Flow Characteristics," SAE Technical Paper 2005-01-0222, 2005, doi:10.4271/2005-01-0222.

[16] Westin, F. and Ångström, H., "Calculation Accuracy of Pulsating Flow through the Turbine of SI-engine Turbochargers - Part 2 Measurements, Simulation Correlations and Conclusions," SAE Technical Paper 2005-01-3812, 2005, doi:10.4271/2005-01-3812.

[17] Winkler, N., Ångström, H., and Olofsson, U., "Instantaneous On-Engine Twin-Entry Turbine Efficiency Calculations on a Diesel Engine," SAE Technical Paper 2005-01-3887, 2005, doi:10.4271/2005-01-3887.

[18] Winkler, N. and Ångström, H., "Study of Measured and Model Based Generated Turbine Performance Maps within a 1D Model of a Heavy-Duty Diesel Engine Operated During Transient Conditions," SAE Technical Paper 2007-01-0491, 2007, doi:10.4271/2007-01-0491.

[19] Hellstrom, F., Renberg, U., Westin, F., and Fuchs, L., "Predictions of the Performance of a Radial Turbine with Different Modeling Approaches: Comparison of the Results from 1-D and 3-D CFD," SAE Technical Paper 2010-01-1223, 2010, doi:10.4271/2010-01-1223.

[20] Serrano, J., Pla, B., Gozalbo, R., and Ospina, D., "Estimation of the Extended Turbine Maps for a Radial Inflow Turbine," SAE Technical Paper 2010-01-1234, 2010, doi:10.4271/2010-01-1234.

[21] Sakellaridis, N. and Hountalas, D., "Meanline Modeling of Radial Turbine Performance for Turbocharger Simulation and Diagnostic Applications," SAE Technical Paper 2013-01-0924, 2013, doi:10.4271/2013-01-0924.

[22] De Bellis, V., Bozza, F., Schernus, C., and Uhlmann, T., "Advanced Numerical and Experimental Techniques for the Extension of a Turbine Mapping," SAE Int. J. Engines 6(3):2013, doi:10.4271/2013-24-0119.

[23] De Bellis, V., Marelli, S., Bozza, F., and Capobianco, M., "Advanced Numerical/Experimental Methods for the Analysis of a Waste-Gated Turbocharger Turbine," SAE Int. J. Engines 7(1):2014, doi:10.4271/2014-01-1079.

[24] Serrano, J., Arnau, F., Novella, R., and Reyes-Belmonte, M., "A Procedure to Achieve 1D Predictive Modeling of Turbochargers under Hot and Pulsating Flow Conditions at the Turbine Inlet," SAE Technical Paper 2014-01-1080, 2014, doi:10.4271/2014-01-1080.

[25] Schorn, N., "The Radial Turbine for Small Turbocharger Applications: Evolution and Analytical Methods for Twin-Entry Turbine Turbochargers," SAE Int. J. Engines 7(3):2014, doi:10.4271/2014-01-1647.

[26] Cavina, N., Borelli, A., Calogero, L., Cevolani, R. et al., "Turbocharger Control-Oriented Modeling: Twin-Entry Turbine Issues and Possible Solutions," SAE Int. J. Engines 8(5):2015, doi:10.4271/2015-24-2427.

[27] Hribernik, A., Dobovišek, Z., and Černej, A., "Determination of Twin-Turbine Discharge Coefficients Under Partial Admission Conditions," SAE Technical Paper 930192, 1993, doi:10.4271/930192.

[28] Brinkert N., Sumser S., Schulz A., Weber S., Fieweger K. and Bauer H.-J., Understanding the twin-scroll turbine-flow similarity. ASME Turbo Expo, GT2011-46820, 49:2207–2218, 2011.

[29] Fredriksson C. F., Xuwen Qiu, Baines N. C., Müller M., Brinkert N. and Gutmann C., Meanline Modeling of Radial Inflow Turbine With Twin-Entry Scroll. ASME Turbo Expo 2012,doi:10.1115/GT2012-69018

[30] Aymanns R., Scharf J., Uhlmann T., Pischinger S.,Turbocharger Efficiencies in Pulsating Exhaust Gas Flow, MTZ, Vol. 73, 07-08/2012.

[31] Lückmann D., Uhlmann T., Kindl H., Pischinger S., Separation in Double Entry Turbine Housings at Boosted Gasoline Engines. MTZ, Vol. 74, 10/2013

[32] Uhlmann, T., et al. "Development and Matching of Double Entry Turbines for the Next Generation of Highly Boosted Gasoline Engines." 34th International Vienna Motor Symposium. 2013.
[33] Macek, J., Vítek, O., Burič, J., and Doleček, V., "Comparison of Lumped and Unsteady 1-D Models for Simulation of a Radial Turbine," SAE Int. J. Engines 2(1):173-188, 2009, doi:10.4271/2009-01-0303.
[34] Vítek, O., Macek, J., and Polášek, M., "New Approach to Turbocharger Optimization using 1-D Simulation Tools," SAE Technical Paper 2006-01-0438, 2006, doi:10.4271/2006-01-0438.
[35] Macek, J. and Vítek, O., "Simulation of Pulsating Flow Unsteady Operation of a Turbocharger Radial Turbine," SAE Technical Paper 2008-01-0295, 2008, doi:10.4271/2008-01-0295.
[36] Macek, J., Vávra, J., and Vítek, O., "1-D Model of Radial Turbocharger Turbine Calibrated by Experiments," SAE Technical Paper 2002-01-0377, 2002, doi:10.4271/2002-01-0377.
[37] Vávra, J., Macek, J., Vítek, O., and Takáts, M., "Investigation of Radial Turbocharger Turbine Characteristics under Real Conditions," SAE Technical Paper 2009-01-0311, 2009, doi:10.4271/2009-01-0311.

Author's Publications Related to the Thesis

[38] Vitek O., Macek J., Zak Z. (2017). Chap. 9, The Physical Model of a Radial Turbine with Unsteady Flow Used for the Optimization of Turbine Matching. In E. G. Giakoumis, Turbochargers and Turbocharging: Advancements, Applications and Research. NY USA: Nova Science Publishers, Inc. ISBN: 978-1-53612-239-8

[39] ZAK, Z., EMRICH, M., TAKATS M., MACEK, J.: In-Cylinder Heat Transfer Modelling. In: MECCA Journal of Middle European Construction and Design of Cars. 2016, vol.14, no.3, p.2-10. ISSN (Online) 1804-9338, DOI: https://doi.org/10.1515/mecdc-2016-0009

[40] ZAK, Z., MACEK, J., HATSCHBACH, P.: Evaluation of Experiments on a Twin Scroll Turbocharger Turbine for Calibration of a Complex 1-D Model. In: MECCA Journal of Middle European Construction and Design of Cars. 2016, vol.14, no.3, p.11-18. ISSN (Online) 1804-9338, DOI: https://doi.org/10.1515/mecdc-2016-0010.

[41] ZAK, Z., MACEK, J., HATSCHBACH, P.: Measurement of Twin Scroll Turbine Performance Under Steady Flow. In: Proceedings of XLVII. Conference of ICE Research Depts. of Czech and Slovak Universities. KOKA 2016. Brno: Brno University of technology, Faculty of mechanical engineering, Institute of automotive engineering. 2016.

[42] ZAK, Z., HVEZDA, J., MACEK, J., EMRICH, M., TAKATS M..: User Model in GT-SUITE. In: Proceedings of XLVII. Conference of ICE Research Depts. of Czech and Slovak Universities. KOKA 2016. Brno: Brno University of technology, Faculty of mechanical engineering, Institute of automotive engineering. 2016.

[43] Zak Z., Macek J., Vitek O., Emrich M., Takats M., Hatschbach P., Vavra J.: Physical Model of a Twin Scroll Turbine in GT-SUITE. 2015 European GT Conference. Frankfurt am Main. 2015

[44] MACEK, J., ZAK, Z., VITEK, O.: "Physical Model of a Twin-scroll Turbine with Unsteady Flow," SAE Technical Paper 2015-01-1718, 2015, doi:10.4271/2015-01-1718.

[45] ZAK, Z., VITEK, O., MACEK, J.: Application of a Radial Turbine 1-D Model. In: MECCA Journal of Middle European Construction and Design of Cars. 2013, vol. 11, no. 1, p. 1-8. ISSN 1214-0821, ISSN 1804-9338 (Online)

[46] ZAK, Z., HVEZDA, J., EMRICH, M., MACEK, J., CERVENKA, L.: Utilization of Multi-zone Model Results in SI Engine Modeling. In: MECCA Journal of Middle European Construction and Design of Cars. 2012, vol. 10, no. 2, p. 23-30. ISSN 1214-0821.

[47] POHORELSKY, L., ZAK, Z., MACEK, J., and VITEK, O., "Study of Pressure Wave Supercharger Potential using a 1-D and a 0-D Approach," SAE Int. J. Engines 4(1):1331-1353, 2011, doi:10.4271/2011-01-1143.
[48] MACEK, J., VITEK, O., ZAK, Z.: "Calibration and Results of a Radial Turbine 1-D Model with Distributed Parameters," SAE Technical Paper 2011-01-1146, 2011, doi:10.4271/2011-01-1146.
[49] MACEK, J., VITEK, O., POHORELSKY, L., ZAK, Z.,: Pressure Wave Supercharger 0-D Model. In: MECCA Journal of Middle European Construction and Design of Cars. 2011, vol. 9, no. 1, p. 32-39. ISSN 1214-0821.
[50] MACEK, J., VITEK, O., POHORELSKY, L., ZAK, Z.,: Simulating Boost Pressure System by Differential or Algebraic Equations Model. In: MECCA Journal of Middle European Construction and Design of Cars. 2010, vol. 8, no. 3 and 4, p. 26-34. ISSN 1214-0821.
[51] POHORELSKY, L., ZAK, Z., MACEK, J., VITEK, O.: Study of Pressure Wave Supercharger Potential using a 1-D Approach. In: MECCA Journal of Middle European Construction and Design of Cars. 2010, vol. 8, no. 2, p. 5-13. ISSN 1214-0821.
[52] ZAK, Z.: The Influence of Turbocharger System on Compression Ignition Engine Efficiency. Diploma Thesis (Master degree) D2008 - M 12, Faculty of Mechanical Engineering, Czech Technical University in Prague, Prague 2008.

Software References

[SW 1] ZAK, Z.: Models of turbocharger test beds in GT-SUITE [Software], CTU in Prague, Faculty of Mechanical Engineering, Library of software 12201, 2017
[SW 2] ZAK, Z.: Software for evaluation of the experimental data measured on the turbocharger test bed [Software], CTU in Prague, Faculty of Mechanical Engineering, Library of software 12201, 2017
[SW 3] ZAK, Z.: Full 1-D unsteady model of a radial centripetal turbine with twin scroll in GT-SUITE [Software], CTU in Prague, Faculty of Mechanical Engineering, Library of software 12201, 2017
[SW 4] ZAK, Z.: Models of the experimental diesel engine John Deere 6068 in GT-SUITE (single cylinder model for TPA included) [Software], CTU in Prague, Faculty of Mechanical Engineering, Library of software 12201, 2017

Author's Additional Publications

[53] FÜRST, J., ZAK Z.: CFD Analysis of a Twin Scroll Radial Turbine. In: Proceedings of Experimental Fluid Mechanics 2017. EFM 2017. Mikulov. Czech Republic

[54] ZAK, Z., VITEK, O., MACEK, J.: Application of Radial Turbine 1-D Model. In: Proceedings of XLIII. Conference of ICE Research Depts. of Czech and Slovak Universities. KOKA 2012. Roztoky: Czech Technical University in Prague. 2012.

[55] ZAK, Z., HVEZDA, J., EMRICH, M., MACEK, J., CERVENKA, L.: Utilization of Multi-zone Model Results in SI Engine Modeling. In: Proceedings of XLIII. Conference of ICE Research Depts. of Czech and Slovak Universities. KOKA 2012. Roztoky: Czech Technical University in Prague. 2012.

[56] POHORELSKY, L., ZAK, Z., MACEK, J., VITEK, O.: Study of Pressure Wave Supercharger Potential using 1-D Approach. In: KOKA 2010. Liberec: Technical University of Liberec. 2010. p. 114-123. - ISBN 978-80-7372-632-4

[57] MACEK, J., VITEK, O., POHORELSKY, L., ZAK, Z.: Simulating Engine Boost Pressure Systems by Differential or Algebraic Equations Models - Pros and Cons. In: Proceedings of XLIst Conference of ICE Research Depts. of Czech and Slovak Universities. KOKA 2010. Liberec: Technical University of Liberec. 2010. p. 85-103. - ISBN 978-80-7372-632-4

Citations of Author's Work

[44] Cited by:

1) Chiong, M. S., Rajoo, S., Romagnoli, A., Costall, A. W., & Martinez-Botas, R. F. (2016). One-dimensional pulse-flow modeling of a twin-scroll turbine. Energy, 115, 1291-1304.

[46] Cited by:

2) Shree, V., and Ganesan, V. "Thermodynamic Modelling of Combustion Process in a Spark Ignition Engine and its Numerical Prediction." Combustion for Power Generation and Transportation. Springer Singapore, 2017. 317-366.

[47] Cited by:

3) Singh, J. and Agrawal, V., "Coding, Evaluation, Comparison, Ranking and Optimum Selection of Supercharger," SAE Technical Paper 2016-01-0293, 2016, doi:10.4271/2016-01-0293.
4) Bharath, A. N. "Optimization of the air handling system of a multi-cylinder light duty engine running on reactivity controlled compression ignition-A simulation study." PhD diss., The University of Wisconsin-Madison, 2016
5) Davidson, C. K. Actuated control parameters to reduce vehicle emissions and fuel consumption at isolated intersections. Master thesis. University of Idaho, 2013.

[48] Cited by:

6) Galindo, J., et al. "Development and validation of a radial variable geometry turbine model for transient pulsating flow applications." Energy Conversion and Management 85 (2014): 190-203.
7) J. Galindo, H. Climent, A. Tiseira, L.M. García-Cuevas, Effect of the numerical scheme resolution on quasi-2D simulation of an automotive radial turbine under highly pulsating flow, Journal of Computational and Applied Mathematics, Volume 291, 2016, Pages 112-126, ISSN 0377-0427

Resumé

Disertační práce popisuje vývoj metodiky, která nevyužívá stacionární mapy turbíny pro simulace radiální dostředivé turbíny se dvouvstupovou skříní. Stacionární mapy turbíny nejsou v celém procesu použity.

Pro popis chování turbíny při libovolné úrovni ostřiku oběžného kola, byl vyvinut specifický testovací stav turbodmychadel s oddělenými sekcemi před turbínou. Testovací stav umožňuje dosáhnout libovolné úrovně ostřiku oběžného kola pomocí škrcení v sekcích nebo zavřením jedné sekce. Vybraná dvouvstupová turbína byla měřena za stacionárních podmínek na zmíněném testovacím stavu s otevřenou smyčkou. Požadovaný počet pracovních bodů turbíny je v případě přístupu nevyžadujícího mapy relativně nízký v porovnání s klasickými stacionárními mapami, které jsou generovány pro každou úroveň ostřiku oběžného kola. Turbína byla měřena při plném, parciálním a extrémním parciálním ostřiku se zavřenou sekcí. Stacionární experimentální data byla vyhodnocena vyvinutým programem.

Nestacionární plně 1-D model turbíny se dvěma sekcemi byl vyvinut v GT-SUITE. Model celé turbíny se spirálami, míšením proudů v rozváděcím ústrojí, rotorem turbíny, netěsnostmi a výstupní trubkou musí být kalibrován za stacionárních podmínek v souladu s daty naměřenými na testovacím stavu turbodmychadel. Plně kalibrovaný model turbíny se dvouvstupovou skříní je poté připraven pro nestacionární simulace s modelem spalovacího motoru.
Přeplňovaný šestiválcový vznětový motor vybavený dvouvstupovou turbínou byl podrobně testován v ustálených stavech a přechodových režimech. Cílem měření bylo získání dat pro ověření chování modelu turbíny za silně pulzačních podmínek.

Model experimentálního spalovacího motoru byl vyvinut a kalibrován dle experimentálních dat. Stacionární stavy a také přechodové režimy motoru byly simulovány pomocí modelu motoru s plně 1-D modelem turbíny. Výsledky simulací byly porovnány s experimenty.

Ucelená metodika využívající přístupu bez stacionárních map turbíny byla validována a ověřena simulacemi spalovacího motoru s plně 1-D modelem turbíny za skutečných podmínek, změřených na přeplňovaném spalovacím motoru. Výsledky byly také porovnány s klasickým přístupem založeným na mapách.

Summary

A 1-D Unsteady Model of a Twin Scroll Radial Centripetal Turbine for Turbocharging Optimization

The thesis describes the development of methodology, which utilizes the map-less approach in simulation of a radial centripetal turbine with twin scroll. The steady flow turbine maps are not utilized during the entire process.

For the description of the turbine performance under arbitrary level of the impeller admission, a specific turbocharger test bed with separated sections upstream of a turbine was developed. The test bed enables to achieve arbitrary level of the impeller admission via throttling in sections or closure of one section. A selected twin entry turbine was measured under steady flow conditions on the mentioned test bed with open loop. The required number of turbine working points in case of map-less approach is relatively low in comparison with the classical steady flow maps, which are generated for each level of the impeller admission. The turbine was measured at full, partial and extreme partial admission with closed section. The steady flow experimental data were evaluated by the developed software.

An unsteady full 1-D model of a turbine with twin scroll was developed in GT-SUITE simulation environment. The model of the whole turbine with scrolls, mixing of flows at nozzle ring upstream of the impeller, turbine wheel, leakages and outlet pipe has to be calibrated under steady flow in compliance with the data measured on the turbocharger test bed. The fully calibrated twin scroll turbine model is then prepared for the unsteady simulation with the internal combustion engine model.

A turbocharged six cylinder diesel engine equipped with the twin scroll turbine was properly measured at steady states and transients. The goal of the measurement was to obtain data for verification of the turbine model behaviour under highly pulsating flow conditions.

The model of the experimental internal combustion engine was developed and properly calibrated by experimental data. The engine steady states and also transient operation conditions were simulated by means of the engine model with full 1-D turbine. The simulation results were compared with experiments.

The comprehensive methodology utilizing the map-less approach was validated and verified by the engine simulation with full 1-D turbine model under real conditions, measured on the turbocharged internal combustion engine. The results were also compared with the classical map based approach.