DEVELOPMENT AND COMMISSIONING OF A NEW TURBOCHARGER TEST FACILITY

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ABSTRACT

A new turbocharger (TC) test facility has been developed, built and commissioned at the Institute of Thermal Turbomachinery and Machinery Laboratory (ITSM) of the University of Stuttgart. This paper presents the setup and gives a short overview of the realized components and an analysis of the reproducibility of the results.
The objective of this test facility is to compare turbochargers of different sizes using the same test rig. As such, influences of different test rigs on the behavior and measurements of the turbochargers can be avoided. To enable the testing of different sized turbochargers, the test facility can provide turbine mass flows between 0.013 and 1.2 kg/s. The test rig is built up with a water-cooled combustion chamber operated with propane to simulate the exhaust gas. The combustion chamber can achieve exhaust gas temperatures up to 1200°C with a maximum pressure of 6 bar.

The design of the turbocharger test facility and its functioning as well as some measurements and an outlook on further investigations are addressed in this paper.

INTRODUCTION

Investigations into topics of turbomachinery are always connected with numerical and practical research. Hence, the Institute of Thermal Turbomachinery ITSM located at the University of Stuttgart decided to extend the testing laboratory with a turbocharger test bench in 2007. With the existing knowledge regarding development, numerical calculations and testing of steam turbines, the gap to close for smaller machines was assessable and the next logical step was to improve research and to extend consolidated knowledge. Lecture courses and the offer for practical projects for students was also adapted and updated. The proximity to the automotive industry is an additional benefit, but not the determining factor. To be independent from financial influences, the development of the TC test rig and the build-up was funded as a research project.

NOMENCLATURE

a	gas speed, m/s
c_u	circumferential velocity component, m/s
h	enthalpy, J/kg
$\dot{m}$	mass flow, kg/s
p	pressure, bar
u	circumferential speed, m/s
A	cross section of the pipe, m²
B	Greitzer parameter, -
L	length of the pipe, m
P	power, kW
T	temperature, K
V	volume, m³
Δ	difference, -
η_m	mechanical efficiency
CC	combustion chamber
ITSM	Institute of Thermal Turbomachinery and Machinery Laboratory, Germany
PLC	programmable logic controller
TC	turbocharger

Subscripts

t	turbine
c	compressor
f	fuel
1	inlet
2	outlet

BASIC PRINCIPLE

As usual, before making a decision, an analysis of the actual needs in research and industry was performed by the persons responsible at the institute. The analysis of testing possibilities for smaller machines showed that the available industrial test benches have limits and unavoidable impacts on accuracy and power output. The objectives for the new test bench are not only measuring standard maps for TCs, but rather further development techniques and validity prove of existing correlations. As a result, a test bench with high accuracy in temperature and control strategies was needed. The range of interesting machines spans from TCs for downsized internal combustion engines to turbine stages for micro gas turbine applications including waste heat recovery systems using a turbo engine.

As there was no suitable test stand to carry out the planned investigation, the decision was made to develop a new test bench. Starting with a new concept of a combustion chamber (CC), the whole test bench and all auxiliary systems are designed to accommodate the high demands. Possible back pressure and maximum temperature of the combustion chamber, maximum temperature and mass flow of the exhaust system and the accuracy of the control system used open up new testing possibilities. The aim of this project was always to provide the most realistic testing conditions possible for the devices investigated on the test bench. Several technical add-on systems are installed or certain possibilities prearranged. A simulation of the volume behind the compressor for surge phenomena regarding automotive applications or the possibility of pressurizing or depressurizing the compressor without a closed loop system or a choke actuator at the inlet are only two upgrades which are not standard in the industry. The possibilities for research, especially on TCs, without system limitations can be tested and investigated at the ITSM. In the following chapters, this paper describes the set-up of a unique TC test bed, the auxiliary systems which are needed to enable testing, accuracy and range of testing conditions and first research results of developed. With the conclusion, a development road map is given to account for future planned developments at the test bed.

THE TEST BENCH

As mentioned before, the main objective of designing the ITSM turbocharger test rig was to ensure comparability between different TCs under the same testing conditions. To achieve this objective, the following points were identified and have to be fulfilled by the test facility:

- mass flow range up to 1.2 kg/s
- pressures up to 6bar at CC outlet
- temperatures up to 1200 °C at CC outlet
- high temperatures at low mass flow rates
- high accuracy and reproducibility for mass flow (+/- 2%) and temperature (+/- 2%)
- safety
- variability for different TC applications

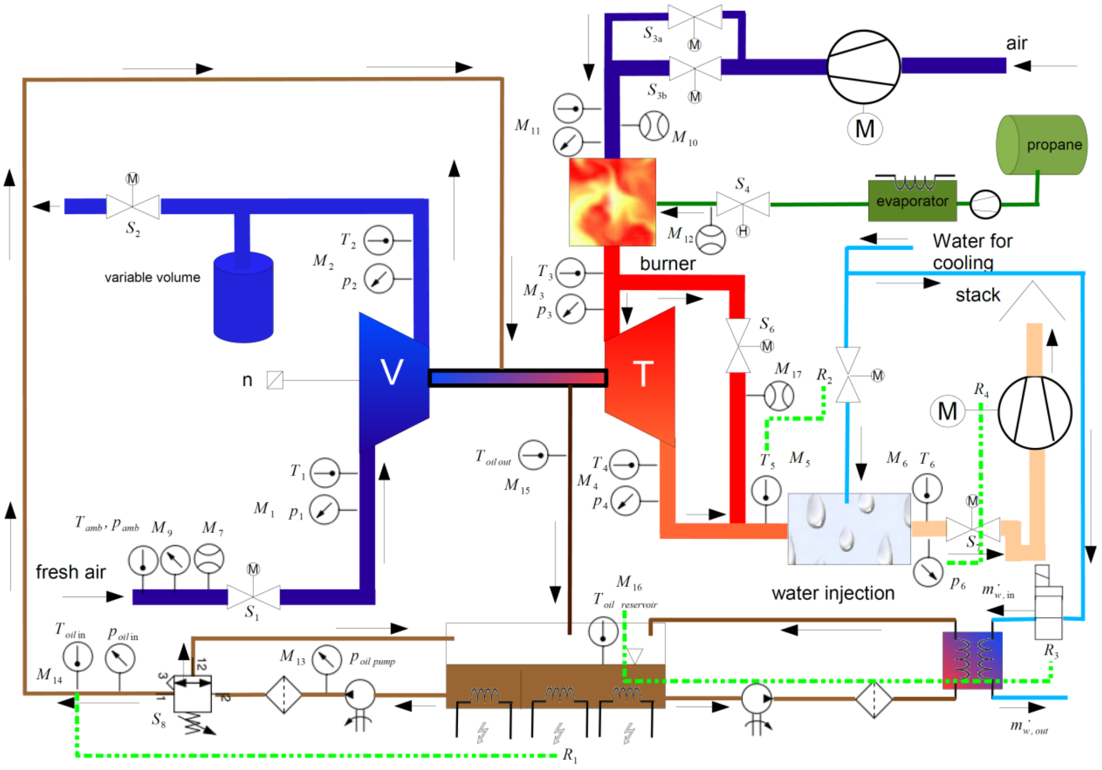

Figure 1: Schematic diagram of the ITSM turbocharger test facility

The demand for accuracy and reproducibility should be scrutinized further. All measurements are always affected by inaccuracies of the measurement technique itself. In some cases, the position at which the measurements are conducted is important. For example, there are different temperature distributions over the pipe cross section. Apart from the impact of the different temperatures on the cross section, the temperature measured is also influenced by the angular momentum in the flow, which can be caused through deflections of the previous flow path. All these factors will cause fluctuations of the measured values. Fluctuations in the designed test facility should be smaller than 2%. Additionally, it is crucial that the test rig reproduces the same operation point. When comparing two measurements, the difference of the mean values over a time period should be smaller than 2% as well.

In the following section, the test facility which has been developed and built up by Mr. Sebastian Challand [1] is described and discussed with respect to the requirements specified above.

Figure 1 shows the setup of the TC test rig. The concept is based on a divided system where the compressor and turbine flow paths are separated. This permits to measure the compressor and the turbine of the TC over a wider area of operation. Disconnecting the compressor flow path from the turbine flow path provides some degree of latitude for more intensive studying of the compressor and turbine separately. Due to this, the description of the test rig will be divided in a compressor side, turbine side as well as a combustion chamber part.

Compressor Side of the Test Bench

The compressor side of the test rig consists of a suction pipe which is split in three different sized pipes each equipped with a mass flow meter to achieve a high precision mass flow measurement over the whole operation range of the TCs. In this case, the three pipes are DN100, DN250 and DN300 with a mounted turbine meter in each pipe. The smallest pipe is used for mass flows from 25-400 m³/h, the second suction pipe is used for mass flows between 160 and 2500 m³/h and the biggest suction pipe is used for a range of 400-4000m³/h. The benefit of the parallel arrangement is that the inlet pipe does not have to be switched during the measurements of a single TC. This ensures the reproducibility and accuracy of the compressor mass flow measurements under the same inlet conditions.

The TCs typically used for automotive applications have a design mass flow rate of about 0.15 kg/s, while trucks, commercial and off-road vehicles go up to 0.6 kg/s or higher. This corresponds to a mass flow ranging from 450 m³/h (for passenger cars) to 1800 m³/h (for trucks). This shows that the established facility can provide the mass flows for the compressors for all TCs currently used in automotive applications and also for small marine or stationary applications. The mass flow meters in the suction pipes are turbine meters with a high accuracy and reproducibility in the chosen mass flow range of the pipes. Tests have shown that the errors in accuracy and reproducibility of the turbine meters are smaller than 1% in the chosen area of operation. Figure 2 shows the accuracy of the three turbine meters in the suction pipes of the compressor. The data was measured while testing a TC so that the error of accuracy is the sum of the turbine meter error and the fluctuations of the mass flow caused by the TC itself.

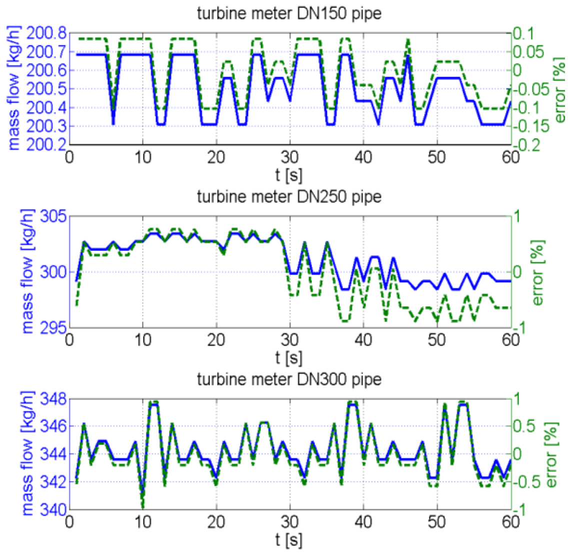

Figure 2: accuracy of the turbine meters in the compressor suction pipe

The suction pipes are connected to a filtering box which filters particles greater than 10 µm. The installed filters are changeable to decrease the particle size with finer filters if needed. This prevents damage to the TC from particles in the air. This further provides a constant temperature because the air which is filtered by the system comes from a great hall which maintains nearly the same temperature over the year. The humidity of the air is measured in the hall and can be used for calculations and comparability of the measurements.

The connection from the suction pipe to the TC compressor has a variable design. Usually, the test rig uses connection pipes 5 times the length of the compressor inlet diameter for steadying the flow. In this case the connection pipes are built longer to place pressure and temperature probes in the flow path. After these probes, the distance to the compressor inlet is designed to be 10 times the diameter of the compressor inlet for steadying the flow disturbed by the pressure and temperature probes. The temperature probes can be calibrated at the ITSM to further increase the accuracy of the measurements.

The compressor outlet side is also connected to a flow-steadying section. After that, there are some measurement probes for pressure and the temperature detection. Apart from the static pressure probes, there is the possibility to use piezo resistive pressure probes for detecting the surge margin and transient flow effects. The pressure probes will be mounted in the pipes depending on the requirements of the TC to be tested.

Downstream of the measurement probes, the flow pipe is split into two pipes, one bigger and one smaller pipe. Each pipe is equipped with a valve the opening angle of which can be controlled between 0% and 100% open. With the valves, it is possible to measure the whole compressor map without changing the setup of the test rig. The valves are used to control the rotational speed of the TC for exactly adjusting a specific operation point.

One of the interesting parts in testing TCs for automotive applications is to measure and detect the specific behavior of the compressor for the same TC in different cars. Greitzer [2,3] showed that the surge behavior of a system is connected to the volume behind the compressor.

$$B = \frac{u}{2a}\sqrt{\frac{V}{AL}} \qquad \text{(Eq. 1)}$$

He postulated the B-parameter, shown in equation 1, which is a factor for evaluating the surge margin of a compressor by considering the volume behind the compressor. By assuming that the gas speed is equal to the rotational speed of the TC, the equation can be simplified to equation 2.

$$B_0 = \frac{1}{2}\sqrt{\frac{V}{AL}} \qquad \text{(Eq. 2)}$$

The B_0-parameter is used to calculate the surge margin of a given compressor outlet system. High B_0-parameters tend to move the surge margin to lower compressor mass flow rates while smaller B_0-parameters move the surge margin to higher mass flow rates.

In fact, each car-model has a unique suction pipe geometry and volume behind the compressor. The surge margin of the same TC compressor will occurs at different mass flow rates. In some cases this will lead to the use of the TC in an unstable region for some car applications. Table 1 shows different volumes downstream of the TC compressors for different TC applications.

engine application	volume behind compressor in application [liter]
V12 Biturbo	97.3
FPT F1C (small trucks)	12.5
Cursor 13 (small marine, agriculture)	67.9
Cursor 13 VTG (utility vehicle)	39.1
Cursor 9 VTG (utility vehicle)	29.9
VW TDI common-rail	9.9
Smart CDI	4.0

Table 1: Volumes between the TC-compressor and engine cylinder [3]

To simulate the different suction pipe volumes at the TC test rig, a variable surge volume has been developed and installed as part of a student project [4]. The variable surge volume can be adjusted steplessly between 0 liter and 100 liter, the concept of the variable surge volume is shown in Figure 3. Thanks to the stepless volume adjustment, the behavior of the same TC compressor can be simulated in different car applications without changing the test bench.

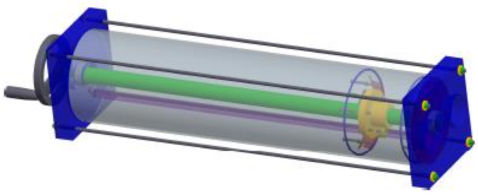

Figure 3: Variable surge volume

To determine the rotational speed of the TC, an eddy current measurement system is placed in the volute of the compressor and connected to the controlling system of the test bench.

Turbine Side of the Test Bench

The TCs at the new test facility at the ITSM are driven by hot gas. The hot gas is produced by a combustion chamber which is fired with propane. The main achievement of driving a TC test rig with gas compared to oil is the wide spectrum of the combustion chamber operation map without changing the setup. An additional benefit is the purity of the produced hot air. Exhaust gas which contains sooty particles can affect or even damage the measurement equipment. The exhaust gas in the presented test facility is produced by a combustion chamber which will be discussed separately later in this paper. If sooty particles in the exhaust gas are needed, for example when measuring the failure behavior of VTG TCs, the particles can be injected in a separate injection step or generated by an admission injection with gasoline into the combustion chamber. The injector can also be used to inject water or steam to simulate higher humidity levels in the exhaust gas.

The compressed air for the combustion process is delivered by a screw compressor with a maximum power of 400 kW. The screw compressor delivers at 6 bar compressed air into a storage volume of 13 000 l to provide a constant pressure even if mass flows change rapidly. The maximum mass flow of the screw compressor is limited to 1 kg/s. This results in a limitation of the maximum possible mass flow for the test facility. Including the losses in the pipe route from the screw compressor to the test facility, the maximum possible mass flow is limited to 0.9 kg/s. The facility itself is already prepared to achieve higher mass flow rates up to 1.2 kg/s by replacing the screw compressor with a more powerful device.

The compressed air is dried by an air dryer installed between the screw compressor outlet and the storage volume. This conditions the delivered air to 20° C and a relative humidity of 30%.

Due to the compressed and conditioned air, both hot and cold TC measurements are possible. For the cold measurements, only the compressed air is used to run the TC turbine by passing the combustion chamber without passing a combustion process. The TC turbine thereby expands the compressed air to ambient pressure and drives the compressor of the TC. For the hot measurements, the compressed air delivered is used to run a gas-burning process inside the combustion chamber.

At the test facility itself the flow path of the compressed air is split into two parts. The first flow path of the compressed air is directed to the combustion process while the second part is used to control the temperature of the flame. This principle is comparable to a burning process in a gas turbine where the annular mass flow is used as secondary air to cool the system. To achieve a high accuracy in controlling and measuring, the compressed air mass flows of the two flow paths are further split into two parallel pipes with different diameters. Similar to the compressor suction side, there is a greater and smaller pipe each equipped with a mass flow meter to realize the required accuracy of the mass flow rate measurements. All mass flow meters on the turbine side of the test facility are Coriolis mass flow meters which have an error of accuracies lower than 1%.

As mentioned before, the ITSM turbocharger test rig uses propane as fuel to fire the combustion chamber. The propane is stored in a 6400 l tank with a maximum pressure of 12 bar. The liquid propane is evaporated by a 35 kW evaporator operating at 75 °C with a maximum output of 200 kg/h. To prevent the evaporated gas from condensing, the pipes leading to the test rig are heated. The gas mass flow is controlled and measured in the same way as the air mass flow. The flow path is again split into two different sized pipes equipped with mass flow meters corresponding to the pipe diameter. To meet the safety standards of propane applications, there are several valves installed to prevent gas leakage. There is also a leakage control installed which continuously observes the pressure in the gas pipe. If there is a leak in the gas pipe, the pressure will drop and the manometers will detect it. This leads directly to a shutdown of the gas pipe and the CC. The TÜV and chimney sweeper have confirmed the acceptability of the gas system.

The turbine inlet and outlet are prepared with pressure and temperature probes. The probes are mounted in the flow pipes within a distance of about 10 times the pipe diameter to ensure a steady flow. The swirl behind the turbine makes measurements of the thermodynamic values directly downstream the turbine impossible. The temperature probes are selected to withstand high temperatures and pressures, and deliver a high accuracy over the whole temperature range. Thus, the temperature probes can be easily changed and matched to the temperature region of the measurements. The pressure probes are positioned at four points circumferentially and mechanically connected to measure the mean pressure of the flow. Figure 4 shows a typical variable measurement pipe used at the TC test rig.

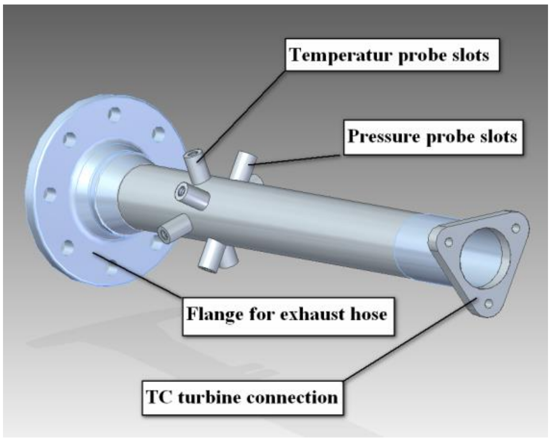

Figure 4: Measurement pipe at TC turbine outlet

The exhaust duct of the turbine is connected to a flex hose to allow for compatibility to different TCs. The flex hose as well as the stack are designed to withstand high temperatures to meet the demand of the maximum testing temperature of TCs. The hose is designed to endure temperatures up to 800 °C under constant operation. To prevent flue gas condensation, the hose is made of stainless steel and has the largest possible diameter to reduce the back pressure.

TCs are usually equipped with an oil supply. This oil cools the hot turbine side and reduces the heat transfer to the compressor side. At the same time, it lubricates the bearing. To create constant conditions for measuring the TC, test facility oil supply has a water driven heat exchange to cool the oil and a heating system with two electrical heating coil.

For the same reason, the testing room is equipped with an outlet to remove hot air as well as smoke from the testing room to keep the ambient conditions nearly constant.

Combustion Chamber

As mentioned before, the combustion chamber (CC) is based on a burner gun and has two different flow paths for the cold air. The flame is controlled from the end of the combustion chamber where the burner gun is placed. It is equipped with three different flame detectors to secure the safety of the system. The three flame detectors are used to observe the flame. Because of the changing size and form of the flame there is a need for three watchers. If none of the three flame detectors receives a signal, the system will shut down automatically. The flame detectors had to be placed in the back of the CC because of the jacket cooling system.

One of the advantages of the combustion chamber is its water cooled jacket. It ensures that the casing temperature of the combustion chamber stays – even with the maximum temperature of 1200 °C – below 70 °C. The cooling system is based on a closed water circuit with a heat exchanger to the conventional water circuit of the Institute. On the one hand, the water cooling reduces the size of the chamber compared to an air cooled chamber; on the other hand, it reduces the component load of the casing. In commonly used combustion chambers, the chamber is cooled by the circumferential mass flow. This leads to a minimum mass flow which has to be adjusted by setting a specific temperature, otherwise, the mechanical load of the CC will increase. By using a water cooled jacket, the circumferential mass flow of cold air can be dramatically decreased which leads to higher maximum temperatures at low mass flow rates. A further benefit is that the water cooled system also reduces the temperature in the test room compared to a common CC. The effect of temperature on the efficiency calculation of the TC is therefore reduced. Additionally, the casing of the combustion chamber is too cold to be a source of ignition for possible gas leakage. To observe the cooling system, there are three mass flow meters placed in the cooling cycle which ensure a sufficient cooling flow. At low cooling mass flow rates, the system will automatically shut down the combustion chamber.

One of the biggest challenges in running TC test rigs with hot gas is testing small TCs at high temperatures. For these tests, the CC has to deliver small mass flows at high temperatures. The flame of the combustion process needs a certain mass flow rate to reach a specific temperature. This causes a minimum line of use in the operation map of the combustion chamber. The maximum propane mass flow under full load is about 110 kg/h while the evaporator, as mentioned before, is designed to reach maximum mass flow rates up to 200 kg/h. This oversizing gives the possibility to increasing the maximum power of the combustion chamber, without changing the evaporator. The maximum power of the CC is about 1MW. The maximum temperature of 1200 °C can be reached under continuous operation. It is possible to reach higher temperatures up to 1400 °C for short durations.

For controlling the inlet air and the gas flow into the combustion chamber, there are several high precision pneumatic valves which can adjust the degree of opening of the valves within 2500 steps between closed and open. As a result, the operating points can be adjusted with high precision. This fulfills the temperature precision requirements where the error has to be smaller than 2%. To increase the reproducibility of the measurements, the selected valves have a hysteresis smaller than 1%.

SOFTWARE AND CONTROLLING THE TEST FACILITY

The controlling of the test bench is realized through a PLC from Siemens. The PLC is separated into two independent PLC systems, each with an individual CPU and control panel. One of the PLC systems controls the combustion chamber while the other one controls the rest of the test bench. The control circuits are implemented in the PLC to ensure the safety of the test rig even if the controlling PC crashes.

The operation panel to regulate the parameters of the test rig is built with LabVIEW which makes it possible to operate the mass flow rate and temperature of the combustion chamber. The same program is used for controlling the valve positions at the compressor outlet side. The functioning of the controlling will be described in the following.

The compressor and the turbine of a TC application are connected in two ways. The first is given by the continuity equation (Eq. 3).

$$\dot{m}_c + \dot{m}_f = \dot{m}_t \qquad \text{(Eq. 3)}$$

The second connection is the mechanical connection of the shaft defined by the power balance equation (Eq. 4).

$$P_c = -\eta_m P_t \quad \textbf{(Eq. 4)}$$

Further, the power of the turbine is defined by the equation 5,

$$P_t = \dot{m}_t \Delta h_t = \dot{m}_t (u_{t2} c_{ut2} - u_{t1} c_{ut1}) \quad \textbf{(Eq. 5)}$$

and the compressor power is defined by equation 6.

$$P_c = \dot{m}_c \Delta h_c = \dot{m}_c (u_{c2} c_{uc2} - u_{c1} c_{uc1}) \quad \textbf{(Eq. 6)}$$

By substituting Eq.4 and Eq.5 in Eq.7 and assuming that there is no swirl in the flow at the inlet of the compressor resp. at the outlet of the turbine, equation 7 can be derived.

$$\dot{m}_c u_{c2} c_{uc2} = \eta_m \dot{m}_t u_{t1} c_{ut1} \quad \textbf{(Eq. 7)}$$

u_{c2} and u_{t1} are connected by the geometries of the turbine and the compressor, while usually the mass flows $\dot{m}_c$ and $\dot{m}_t$ are linked by Eq. 3. At the test rig presented, the flow paths of the turbine and the compressor are separated, and Eq. 3 has not been considered. The delivered power of the turbine can be increased by increasing the mass flow or/and the temperature of the CC. This will increase $\dot{m}_t$ and the rotational speed at the same time. Due to the power equilibrium (Eq. 7) $\dot{m}_c$ will rise. The compressor mass flow $\dot{m}_c$ can further be influenced by changing the opening degree of the valves behind the compressor outlet. By opening these valves, $\dot{m}_c$ will increase, while the rotational speed will decrease. Furthermore, this will decrease the power delivered from the turbine. Closing the valves will have the reverse effect.

Apart from the operating systems, a measurement record system is implemented in LabVIEW to plot the thermodynamic and operation values of the TC. The program can record the data continuously as well as single points. For the recording of single points, the system waits until the thermodynamic values of the compressor and turbine are stable. To reduce the measuring error, the system records the mean value over a declared time starting once the stability criteria are reached.

REPRODUCIBILITY AND ACCURACY

As mentioned before, reaching a high accuracy and reproducibility is one of the main objectives of this test rig. This is essential to reach comparability between different sized TCs and to analyze the influences of the flow effects especially in small TCs. Because, of this, the accuracy and the reproducibility of the thermodynamics of the combustion chamber are addressed in the following.

Figure 5 shows the temperature and the mass flow delivered by the combustion chamber. The measurements were taken on two different days, the mass flow was set to 600 kg/h and the temperature to 600 °C. The accuracy of the single measurement series is lower than 2% for both measurement series. Comparing the mean error of the two measurements shows that there is nearly no difference between them. For this example, the error of reproducibility of the mass flow and the temperature by considering the mean value over 60s is far below 1%.

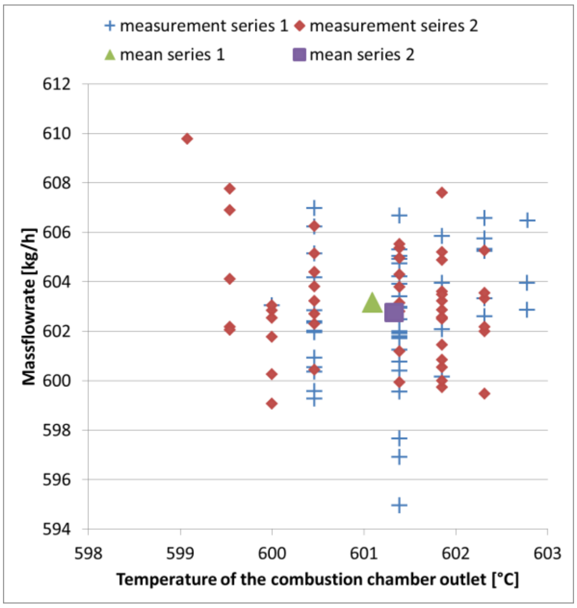

Figure 5: Reproducibility and accuracy of temperature and mass flow

This meets the objective declared at the beginning of the development. For further studies, has to be considered the reproducibility of the operation maps measured with the new test facility. For these objectives, tests with the same TC have been made at different days. Figure 6 shows the flow pressure ratio over the flow coefficient measured for a rotational speed of 100.000 rpm of the TC compressor.

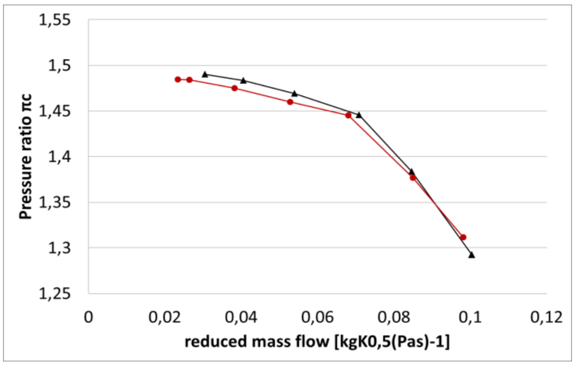

Figure 6: Reproducibility of compressor map - pressure ratio

It is obvious that the error of the reproducibility for the corrected mass flow and the pressure ratio are smaller than 1%. The corrected mass flow is therefore calculated from the mass flow, temperature and pressure at compressor inlet with equation 8.

$$\dot{m}_{cor} = \dot{m}_c \frac{\sqrt{T}}{p} \qquad \text{(Eq. 8)}$$

Measuring the efficiency of a TC compressor is strongly influenced by the ambient conditions. The heat transfer from the hot turbine side to the compressor will decrease the efficiency of the compressor. The ambient temperature in the testing room will also influence the efficiency significantly. Figure 6 compares the efficiency of the TC compressor measured on the two different days.

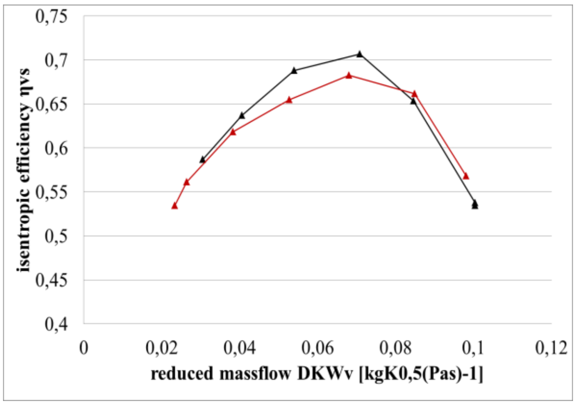

Figure 7: Reproducibility of compressor map - efficiency

The comparison shows a good correspondence over a wide mass flow range. Only in the mid-range the maximum error in the efficiency is about 5% which is mainly caused by the differences in the heat transfer between the turbine and the compressor.

CONSLUSION

Table 2 summarizes the key data of the presented TC test facility.

temperature range	20°C - 1200°C (1400°C short)
maximum pressure	6 bar absolute
mass flow range	0.013-0.9 kg/s (CC already prepared for 1.2 kg/s)
combustion chamber	propane-fired, water-cooled casing
mean error of accuracy of mass flow and temperature	< 1%
mean error of reproducibility of mass flow and temperature	< 1%
possible applications	small passenger car up to small marine TCs

Table 2: Summery of the TC test facility key data

By comparing the data shown in table 2 with the requirements at the beginning, it can be noted that the test facility established meets and even exceeds the requirements,, especially with regard to the accuracy and reproducibility. The mass flow range can be achieved by replacing the screw compressor because the combustion chamber is already prepared to reach the requested mass flow rates. For automotive TC applications, the test rig can even deliver the requested mass flow rates with the current setup. The water-cooled casing significantly increases the safety and reliability of the combustion chamber by reducing the temperature and mechanical load compared to air-cooled CCs.

FURTHER INVESTIGATIONS ON THE TEST FACILITY

Further investigations will concentrate on transient effects in TCs. Additionally, the test rig will become a closed loop setup to extend the measurements of the performance maps of the compressor. A closed loop setup uses the compressed air from the TC compressor and loops that air back to the compressor inlet. The already compressed air will be further compressed and reaches higher compressor outlet pressures. This extends the compressor performance map to higher pressures which results in a moving of the surge margin to lower mass flows at the same pressure ratio [5]. At the presented test rig, a closed loop system can be realized by using the compressed air from the screw compressor. The benefit of using the compressed air from the screw compressor instead of the TC compressed air is that the pressure for the compressor inlet is independent from the current state of the TC compressor. It is also possible to use higher inlet pressures to investigate the behavior of the compressor wheel under such rough conditions.

It is also conceivable to implement a thermoshock test application by switching the mass flow for the TC turbine between the hot exhaust gas from the combustion chamber and the cold compressed air from the screw compressor.

Future research will also record the fluttering of the blades by using tip timing systems.

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