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# EXPERIMENTAL INVESTIGATION OF AN EFFICIENT METHOD FOR MEASURING TURBOCHARGER MAPS

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## ABSTRACT

The recording of turbocharger maps is usually ensured through measuring points on constant speed lines at a quasi-steady operating point of the turbocharger. Operating points can be controlled by the parameters hot gas mass flow and gas temperature on the turbine side of the turbocharger as well as the output air flow resistance at the compressor side. Because of the simultaneous usage of the controls, long settling times are required to reach a turbocharger operating point that can be assumed to be stationary.

The present paper takes up that even transient measured characteristic operation points are comparable to stationary measured ones. Influences from a transient operation mode on characteristic diagrams for compressor and turbine are investigated experimentally. By transient operation for t/c map measurement, the possibility of a significant time saving is expected compared to that of quasi-steady operating points.

## 1. INTRODUCTION

It is almost impossible to think of developing a combustion engine without turbocharging in recent times. Due to the need of higher efficiency turbocharging is a good way of decreasing pollutant emission while maintaining constant driving performance. To satisfy the drastically intensified exhaust emission regulations the requested nominal power needs to be realized using a small cylinder capacity of the combustion engine that has to use appropriate turbocharging pressure ratios.

Using turbocharger test benches, also known as hot gas test benches, turbochargers can be analysed in a wide range of characteristic parameters. Characteristic curve maps can be derived from the measured values that allow for information about the operating behaviour and provide input parameters for process simulations. Also, the maps are needed for tuning of exhaust gas turbocharger and combustion engine. During the measurement, the motor environment is simulated by the test bench. [1]

The characteristic maps are usually acquired during steady operating states. Maps for compressors and turbines are determined in discrete operating points. These maps usually show the dependency between pressure ratio or efficiency and the flow-rate. Each of the measurement points inside the map is set by controlling the gas mass flow and the output gas flow resistance along a line of constant rotational speed. Furthermore, the temperature at the turbine input is held constant during the measurement. Each operating point is depending on several operating parameters. Interdependent closed-loop controllers work simultaneously to achieve the desired operating points. After a distinct settling time a steady state is assumed.

The treatises of Grigoriadis [2] and Müller [3] both suggest that fluctuation of the pressure during the work cycle does not significantly affect the measured operating points. For that reason, it is investigated if characteristic maps are comparable when measured in steady and unsteady states. The resulting reduction of the required time to gather the characteristic data would be an economical advantage.

# 2. MEASURING TURBOCHARGER MAPS QUASI-STEADY

## 2.1 Basic construction of the hot gas test bench

Figure 1 shows a schematic of the test bench used to gather the data shown in this paper. There are two separated circuits, the turbine and the compressor circuit, which are thermodynamically coupled by the turbocharger that is highlighted in blue in the schematic. To ensure as accurate and reproducible data acquisition as possible the gas conducting tubes around the compressor are installed straightly. Also for that reason, temperature and pressure sensors are located within areas for calming the mass flow.

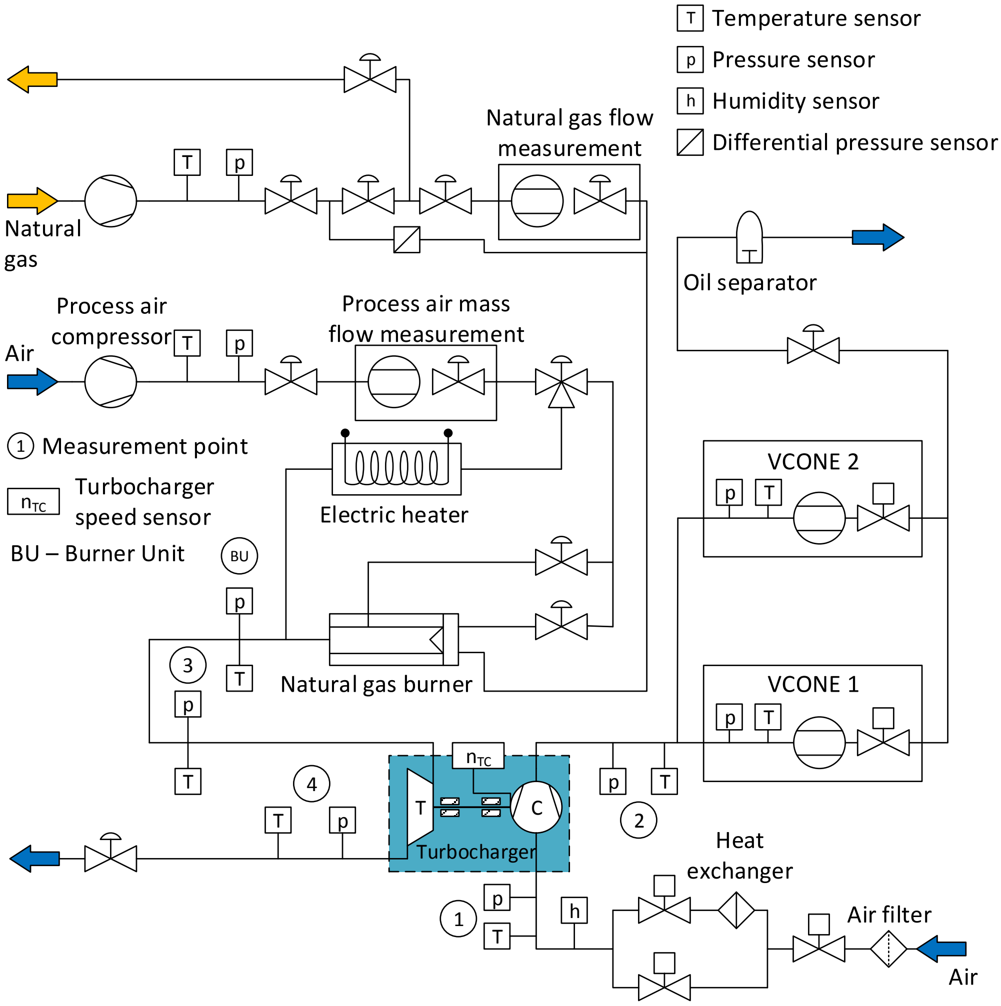



Figure 1: Hot gas test bench gas flow chart of Technische Universität Ilmenau

The gas flow in the turbine circuit starts at the process air compressor which enables for controlling the burning unit within a wide range of mass flow. One part of the process air is conducted along with precompressed natural gas in the burning chamber. The other part is mixed with the hot gas leaving the combustion chamber. Mass flow and temperature of the continuous gas flow out of the burning unit are controlled using the "temperature and pressure measurement point (BU). Before entering the turbine, the temperature and pressure are again measured at point (3). Also, there is a measurement point (4) located after the turbine exit to determine the output pressure. Separated by a relatively large distance there is another measurement point after a diffusor to determine the temperature. Even though all tubes are well isolated this causes a noticeable measurement uncertainty as it was shown in [4]. Before leaving the gas conducting tubes the gas flow passes a throttle that can be used to simulate exhaust back pressure.

The air conditioning unit of the compressor unit sucks in air from the test laboratory and cools it down to the compressor input air temperature if required. A throttle enables for lowering the compressor input pressure below the surrounding pressure to simulate pressure loss by tubes and high altitude driving. Before entering the compressor temperature, pressure and humidity are measured. After leaving the compressor, again temperature and pressure are acquired. The determination of the mass flow is done using a V-cone tube with an appropriate diameter. An electrically controllable valve is used for adjusting the compressor output pressure. While closing the valve the pressure rises and gas flow decreases which simulates a load like a combustion engine.

## 2.2 Turbocharger mapping procedure

Before the survey of a turbocharger map by an automatic test run starts, the minimum number of measurement points for the compressor and turbine maps are set. Each characteristic curve is limited by the first measurement point at the surge line and the last measurement point at the choke line. The remaining number of measurement points is distributed equidistantly on the speed line.

The automatic test run starts with setting the turbocharger operating point by controlling the turbine inlet temperature ($T_3$-controller) to a value of $600°\mathrm{C}$, the turbine inlet mass flow ($\dot{m}_3$-controller) and the compressor inlet temperature ($T_1$-controller) to a value of $20°\mathrm{C}$.

Afterwards, the output airflow resistance at the compressor side is adjusted to a predefined value using the electric valve VP2. Also, the turbocharger speed control is activated. After the settling time of the speed control the surge line detection is enabled. This is achieved by closing the valve VP2 in small steps of 0.1% per second until surge occurs.

Surge leads to fluctuation of pressure and temperature at compressor inlet and outlet, as well as variation of turbocharger speed. Surge is detected if turbocharger speed and compressor inlet and outlet pressure all exceed the tolerance range which depends on turbocharger speed. To increase the accuracy of surge detection this process is carried out several times using smaller rates for each iteration. The measurement data of the last iteration is used to determine the last measurement point on the speed line. These points on each speed line result in the surge line in the turbocharger map.

The first measurement point on each speed line is defined by the minimum permitted compressor efficiency. Combined these points result in the choke line. All measurement points are set by controlling the mass flow ($\dot{m}_2$-controller) and discretely adjusting the position of the VP2 valve. After reaching the operation point a settling time of 20s is introduced to assure quasi-steady-state. One measurement cycle is considered to be quasi-steady if the stability criteria do not exceed the tolerance range for at least 60s within a time period of 100s. Tolerance criteria are turbocharger speed, compressor mass flow, compressor efficiency, temperature at compressor and turbine inlet, oil pressure and temperature and also coolant flow and temperature.

If a quasi-steady-state is detected the actual measurement starts for a time of 20s. The mean values of all parameters are stored. During this process again the stability criteria are observed. If one of the stability criteria is out of range the measurement is marked as unsteady.

This procedure is repeated for every speed line. The overall measurement time for 10 points is about one hour.

## 2.3 Stability of quasi-steady operation points

Figure 2 shows the interdependency between the controllers for turbocharger speed and mass flow of the burning unit for quasi-steady-state measurement. Furthermore, the turbine inlet temperature control is implemented as a cascaded controller together with the burner outlet temperature controller and is dependent on the turbine inlet mass flow.

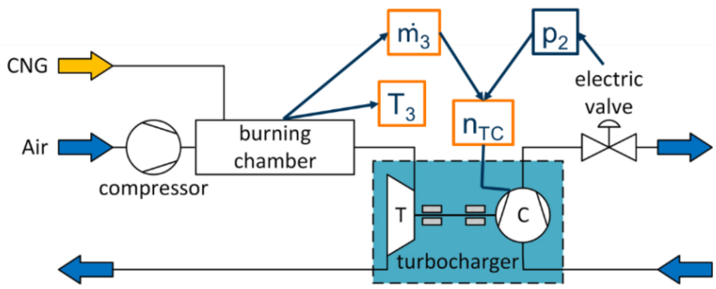



Figure 2: Interdependent controller during turbocharger mapping

If setting the turbocharger operation point could be done without a given turbocharger speed, i.e. only with the turbine inlet mass flow controller, the $n_{TC}$ controller can be eliminated. This would decouple the control circuits of compressor and turbine (Figure 3). Since this reduces the complexity of the control it can be assumed that the settling time decreases.

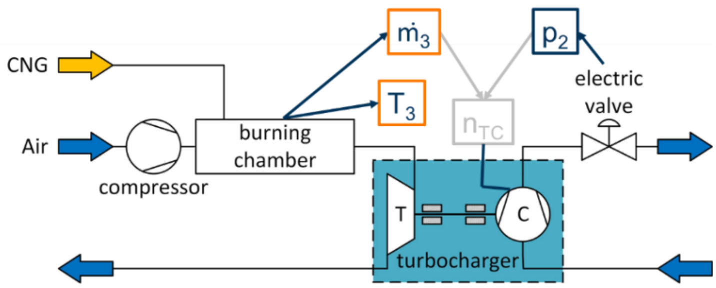



Figure 3: Measuring turbocharger maps without $n_{TC}$-controller

For validation of this hypothesis the deviation of the characteristic values is studied using different types of control. For comparison three operation points were chosen whose position at the reference map of a car turbocharger is shown in Figure 4. Each of these points is studied both with open-loop and closed-loop-control.

The measurements of the points which are measured quasi-steadily have been carried out at a turbine inlet temperature of 600°C. The first quasi-steady point is measured with the standardized turbo charger speed control (TCSC). The turbine mass flow has been set according to the turbocharger speed of the reference measurement point. The newly defined procedure is a open-loop control for the turbine flow rate (TIMFC).

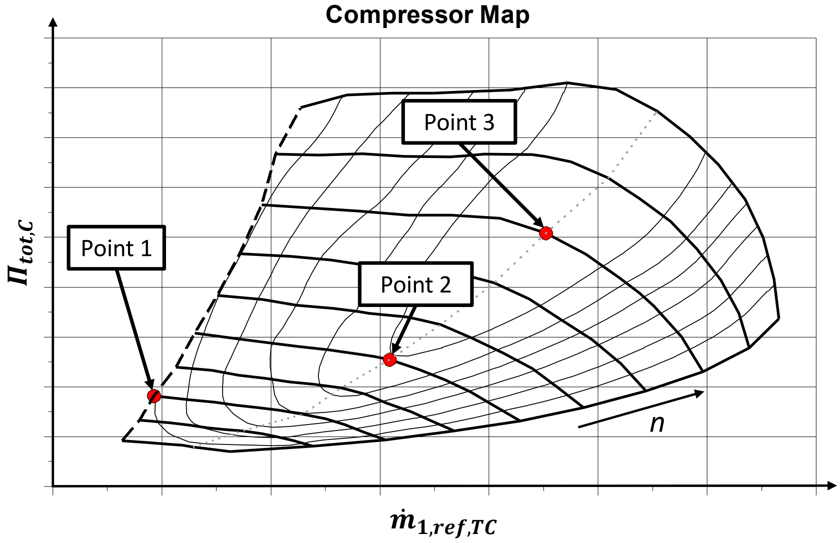



Figure 4: Quasi-steady measurement points

The quasi-steady operating points measured without the turbocharger speed control show few deviations of relevant values. Exemplary, Figure 5 displays the deviations at the quasi-steadily measured point 1 which is located on the surge line. The minimum deviation offers the possibility to create more accurate mean values with less measurement time. It can therefore be assumed that recording turbocharger maps can be done faster and more accurate without the turbocharger speed control.

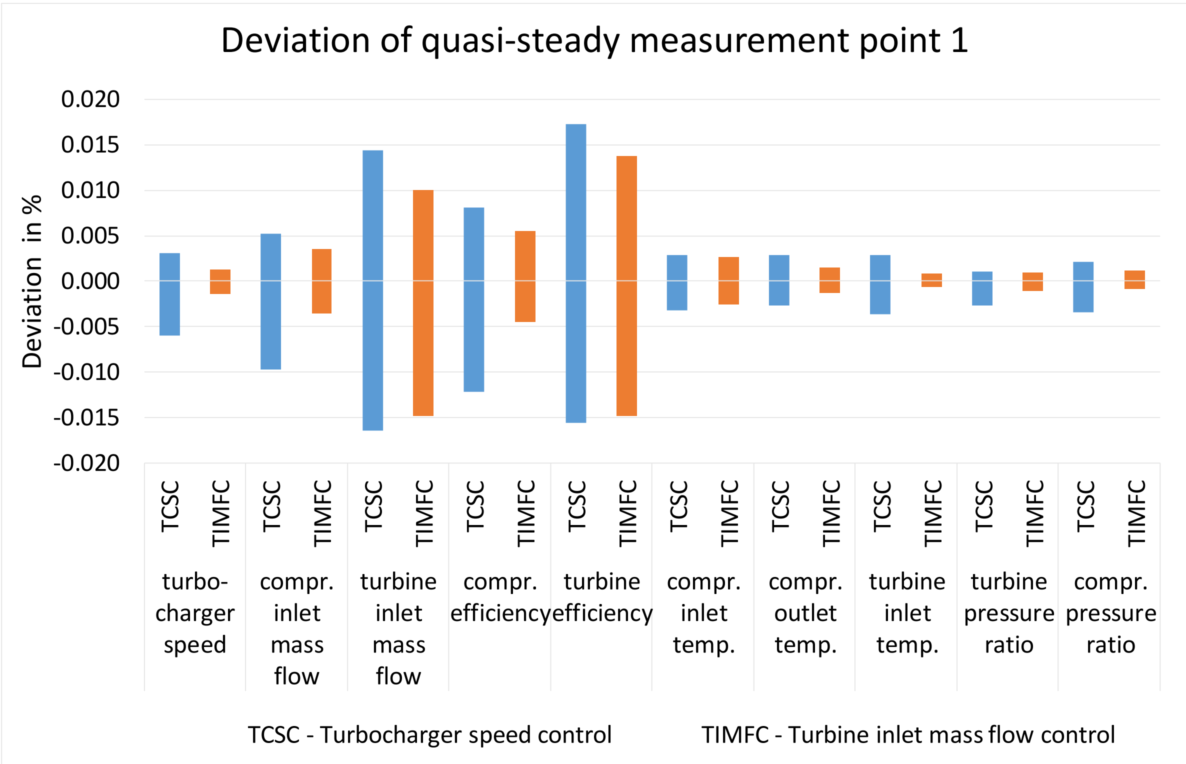



Figure 5: Quasi-steady measurement point 1

## 3. UNSTEADILY MEASURED TURBOCHARGER MAPS

### 3.1 Influence of the rotor inertia

Recording turbocharger maps without a turbocharger speed control offers the possibility to measure in transient mode. In this case care has to be taken that the influence rotor inertia due to a change in speed ($d\omega_{TC}/dt$) does not influence the measured data. For evaluating the influence equation (3.1) [5] is used which describes the power balance of the turbocharger shaft without bearing friction ($P_{BF} = 0$).

$$\frac{d\omega_{TC}}{dt} = \frac{P_T + P_C}{\omega_{TC} \cdot J_{TC}} \tag{3.1}$$

In quasi-steady-state there is no turbocharger speed change and the compressor and turbine power is in total equal to zero ($P_T + P_C = 0$). As a result of measurement inaccuracy at quasi-steady-state resulting from the turbine outlet temperature measurement point the calculated compressor power (equation (3.2) [5]) differs significantly from the turbine power (equation (3.3) [5]). Consequently, an acceleration power dependent on the operation point is determined.

$$P_C = \dot{m}_1 \cdot \Delta h_1 = \dot{m}_1 \cdot c_{p,1} \cdot (T_2 - T_1) \tag{3.2}$$

$$P_T = \dot{m}_3 \cdot \Delta h_3 = \dot{m}_3 \cdot c_{p,3} \cdot (T_4 - T_3) \tag{3.3}$$

The influence of rotor inertia increases along with the turbocharger speed. The influence is at its maximum when turbocharger speed changes at a high speed range with minor acceleration power. Figure 6 shows the compressor power at a high turbocharger speed over compressor mass flow.

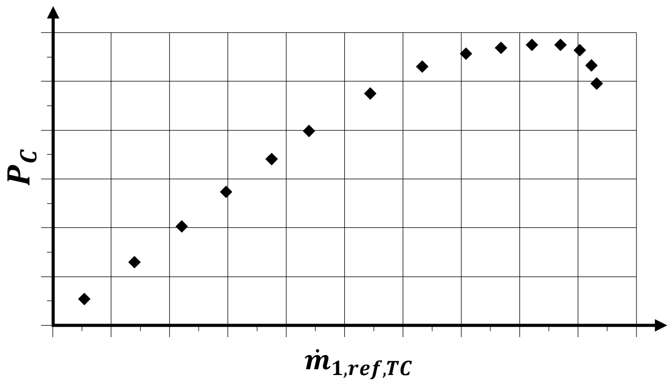



Figure 6: Acceleration power over compressor mass flow of a turbocharger speed line

Starting at the surge line, acceleration power rises with increasing mass flow. In proximity of the choke line it then falls abruptly. The maximum permitted acceleration power is determined to be 5% of the minimum compressor power at the respective turbocharger speed. The inertia of the reference turbocharger is assumed as $J_{TC} = 2 \cdot 10^{-5}\text{kgm}^2$ which has been proposed by [6].

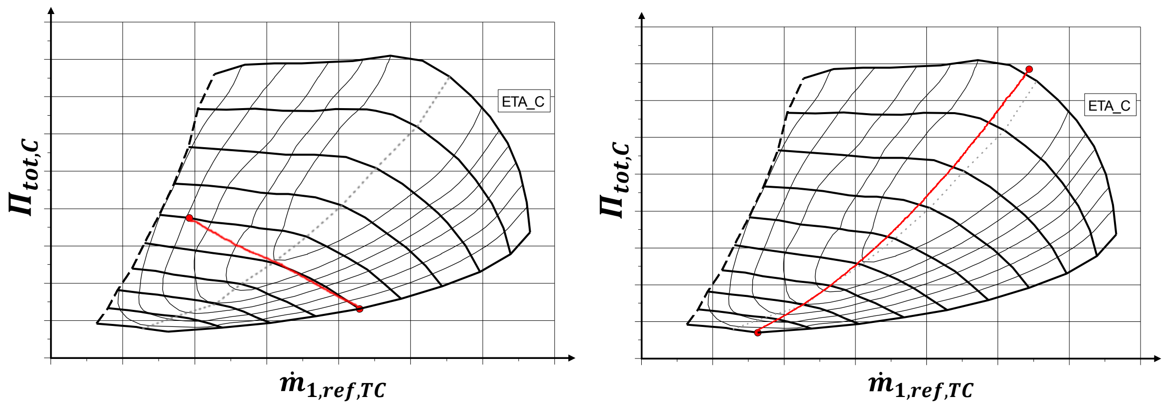
$$\frac{d\omega_{TC}}{dt} = \frac{P_{acc.,perm}}{2 \cdot \pi \cdot n_{TC} \cdot J_{TC}} = 611\frac{\text{rad}}{\text{s}^2} = 6832\ \text{rpm/s} \tag{3.4}$$

Equation (3.4) generates the maximum permitted turbocharger speed change of $\dot{n}_{TC} = 6832\,\mathrm{rpm/s}$ for the reference turbocharger. This value considers the worst case and shall therefore never be exceeded during transient measurements.

### 3.2 Open-loop-control strategies and the influence on relevant values

A transient turbocharger operation mode is possible using either an open-loop-control of the VP2-valve position with a constant turbine inlet mass flow or an open-loop-control of the turbine inlet mass flow with a constant VP2-valve position. On the basis of the reference turbocharger map the first and last measurement points are determined.

Figure 7a shows the course of measurement by adjusting the VP2-valve position at a constant turbine inlet mass flow with a slope of 0.05% per second. During the measurement time of 5 minutes the turbocharger speed changes in the range from 155000 rpm to 140000 rpm. The results from the measurement with variation of the turbine inlet mass flow are shown in Figure 7b. Changing the turbine inlet mass flow at a constant VP2-valve position also changes the turbine inlet temperature. This implies that a slope of 0.0001 kg/s per second is required. During a measurement time of about 10 min the turbocharger speed ranges from 80000 rpm to 220000 rpm which is equal to the maximum speed range of the reference turbocharger.



a - variation of VP2-valve position b - variation of turbine inlet mass flow

Figure 7: Unsteady measurement without speed controller

For both measuring principles the turbocharger speed change is substantially lower than the maximum permitted turbocharger speed change calculated in equation (3.4). As a result the influence of the rotor inertia moment is negligible.

For validation the deviation of those values which should in theory not be affected by transient operation mode is shown in Figure 8. The calculated deviations are within the range of the stability criteria of a quasi-steady turbocharger operation mode. In fact, deviations are much lower than necessary to reach the stability criteria.

Finally, it can be concluded that the transient turbocharger operation mode does not have any indirect influence on relevant values. That implies that the transient operation mode with an open-loop-control of the VP2-valve position or the turbine inlet mass flow is in principle possible.

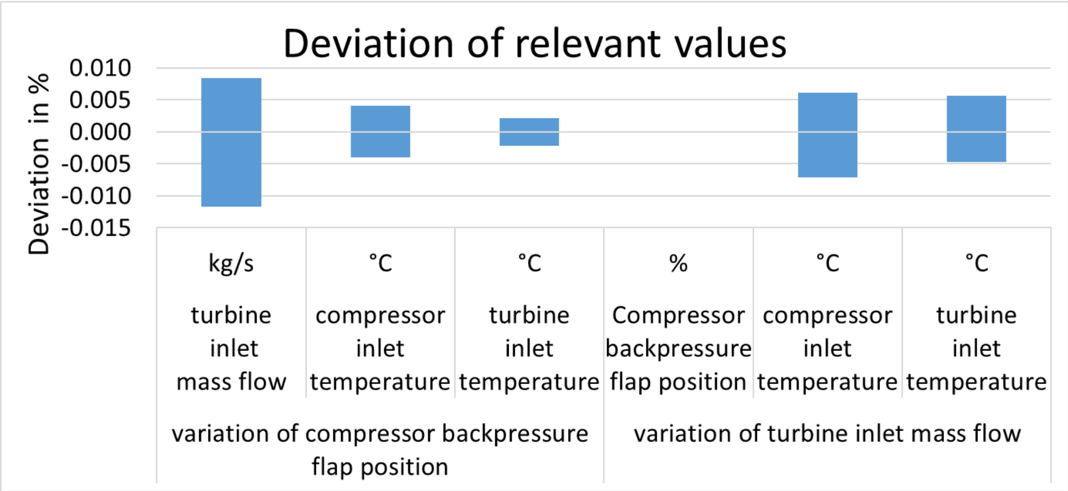


Figure 8: Deviation of relevant values by transient measurement without speed controller

## 4. TRANSIENT MEASURED TURBOCHARGER OPERATION POINTS

To analyse the comparability of the two different possibilities of measuring the characteristic map an exemplary test run using a ramp function for the position of the electric valve VP2 at constant mass flow $\dot{m}_3$ has been carried out.

To estimate the direction in which the VP2 valve is actuated the same measurement procedure is conducted with increasing and decreasing opening of the valve. Hence, one measurement run approaches surge the other choke. Three operation points have been chosen for comparison whose position inside the characteristic map is shown in Figure 9.

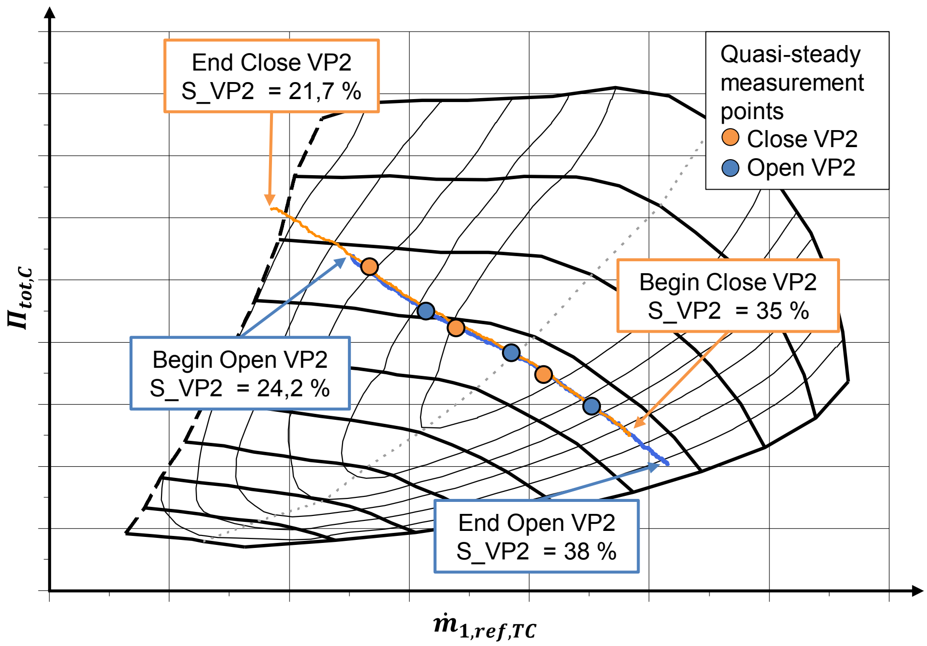


Figure 9: Position from the unsteady measurement at the compressor map

The automatic measurement procedure is conducted using a constantly controlled mass flow at a turbine inlet temperature of 600°C. Oil and water temperature have been initially set to 90°C. Each measurement is done at an opening rate of valve VP2 of 0.05% per second and repeated twice to achieve information about reproducibility.

The measurement points for steady-state measurement have been chosen according to the results of transient analysis. Due to the control regime the average value for a measurement time of 20s does not exactly match the desired values. It is possible that this results in deviations between both measurement modes.

The turbocharger speed is at each valve position independent of the measurement direction. The values turbine mass flow $\dot{m}_3$ and turbine inlet temperature $T_3$ show only few deviations during transient measurement which is a result of the simplified control concept. As a consequence of the constantly controlled turbine mass flow $\dot{m}_3$ over the range of VP2 position the turbine inlet temperature control is able to keep the temperature within a small range of values. Differences between steady and transient measurement are not noticeable. Also, compressor inlet and outlet pressure ($p_1$ and $p_2$) and therefore the compressor pressure ratio $\Pi_C$ and compressor mass flow $\dot{m}_1$ show no significant deviation between both measurement modes.

Figure 10 shows the behaviour of compressor outlet temperature $T_2$ depending on a change of VP2 position. In this transient measurement a noticeable difference between both measurement directions can be seen. Low mass flow leads to an increase in the temperature $T_2$.

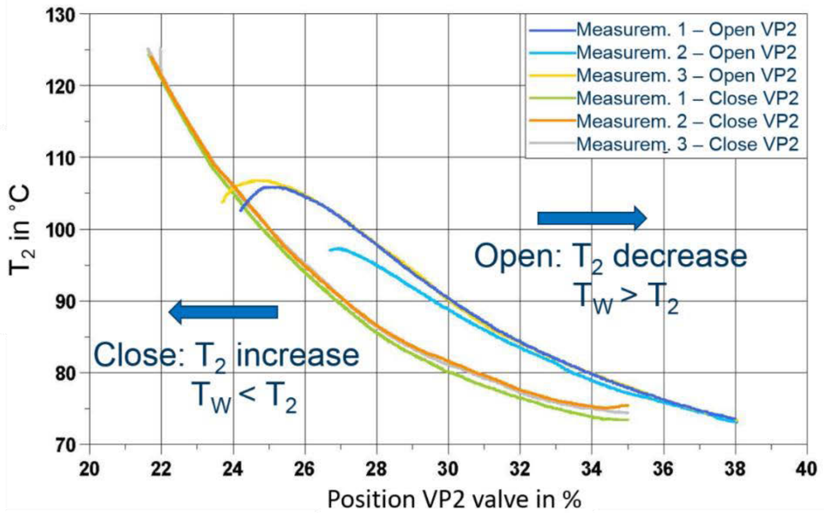



Figure 10: Time curve of compressor outlet temperature at the unsteady measurement

The deviation in temperature behaviour depending on the measurement direction indicates that temperature measurement suffers from lag. After leaving the compressor the fluid travels through a tube with a length of about 1.3m before passing the measurement point at compressor outlet. The tube in between is an insulated steel tube which is connected to the outlet by silicone tubes and adapters. If the fluid temperature raises quickly the tube wall needs some time to heat up as well while cooling the fluid before its temperature is measured. The opposite effect occurs for quickly dropping fluid temperature. In this case the fluid is heated between outlet and measurement position.

Computing the compressor and turbine efficiency this results in an overestimation in case "Close VP2" and an underestimation in the other case. The difference between both values is more than 10%.

Normally, hot gas test benches are designed for steady-state measurements with adiabatic states. To overcome the problem another temperature sensor has been installed as close to the compressor outlet as possible (Figure 11).

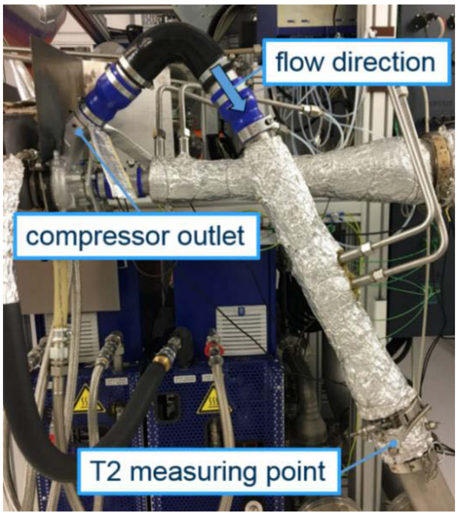



Figure 11: Additional $T_2$ measuring point at compressor outlet

After installing the additional measuring point, the aforementioned measurement procedure has been repeated. As can be seen in Figure 12 the newly introduced temperature sensor shows a significantly reduced deviation between both measurement directions due to reduced lag. However, the compressor outlet temperature is higher as expected in case "Open VP2". It is assumed that in this case the initial temperature of the tubes is more dominant than the actual lag.

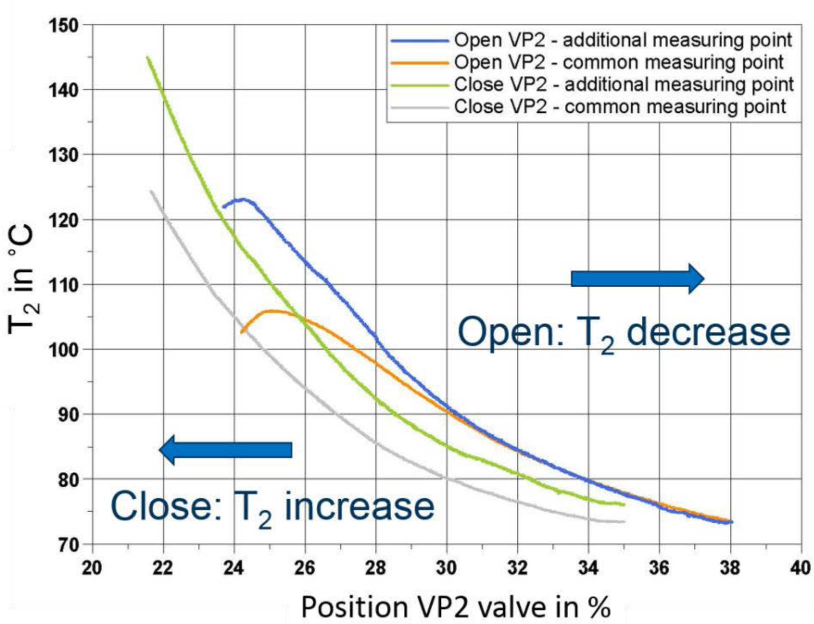



Figure 12: Comparison time curve of compressor outlet temperature at the additional and common measuring point

The preceding results suggest that an additionally introduced measurement point enables for more accurate measurement results but still, further investigation is needed to study whether the deviation is small enough to assure convincing data for derivation of the turbocharger map.

## 5. CONCLUSIONS

In this work the comparability between characteristic turbocharger maps measured either in quasi-steady or unsteady state is investigated. Eliminating the need for a quasi-steady-state significantly reduces the time to record the turbocharger map. The comparability is shown by experimental studies exemplarily.

Measurements carried out without turbocharger speed control showed less deviation of the characteristic values in a representative map compared to the classical approach. Therefore, it is assumed that measuring operation point without constraining to curves of constant rotational speed leads to higher accuracy while being more time-efficient. To verify this claim transient operating states without constant speed have been investigated. A noticeable influence of the rotor's inertia could be excluded. The influence of different control regimes towards the behaviour of the turbocharger during transient measurement was observed. The results showed that measurement data stayed constant which indicates that steady-state is not required. The deviation of the characteristic values has been much lower than it had to be to satisfy the stability criteria. This means that transient measurement is in principle possible to use for acquiring characteristic maps of turbochargers.

For the purpose of evaluating the measurement results of both transient and steady-state method an exemplary measurement using a ramp function gradually adjusting the position of valve VP2 has been carried out while maintaining constant mass flow at the turbine inlet. The results of this attempt showed errors in temperature measurement that occurred because of a high influence of the tube's wall temperature in transient mode. An additional temperature sensor has been installed in higher proximity to the turbine inlet to reduce this error. Although this approach reduced the error significantly it still has to be examined whether the deviation is small enough to achieve convincing map measurement.

## REFERENCES

[1] Ingenieurgesellschaft Auto und Verkehr,"Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven," Vieweg + Teubner, Wiesbaden, 2012.
[2] Grigoriadis P.,"Experimentelle Erfassung und Simulation instationärer Verdichterphänomene bei Turboladern von Fahrzeugmotoren," Dissertation, Technische Universität Berlin, 2008.
[3] Müller D.,"Einfluss der Anordnung und des Betriebs von Abgasturboladern auf deren Pumpgrenze," Dissertation, Hannover, 2008.
[4] Pfeffer K., "Experimentelle Untersuchung und Analyse der Einflussparameter auf Turboladerkennfelder," Projektarbeit, Technische Universität Ilmenau, FG Energieeffiziente Fahrzeugantriebe, 2016.
[5] Pucher H., and Zinner K.,"Aufladung von Verbrennungsmotoren: Grundlagen, Berechnungen, Ausführungen," Springer Vieweg, Berlin, Heidelberg, 2012.
[6] Jahn M., ,"Modellierung der Rotordynamik eines Abgasturboladers," Diplomarbeit, Technische Universität Ilmenau, FG Technische Mechanik, 2007.

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