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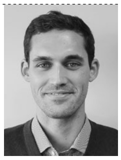

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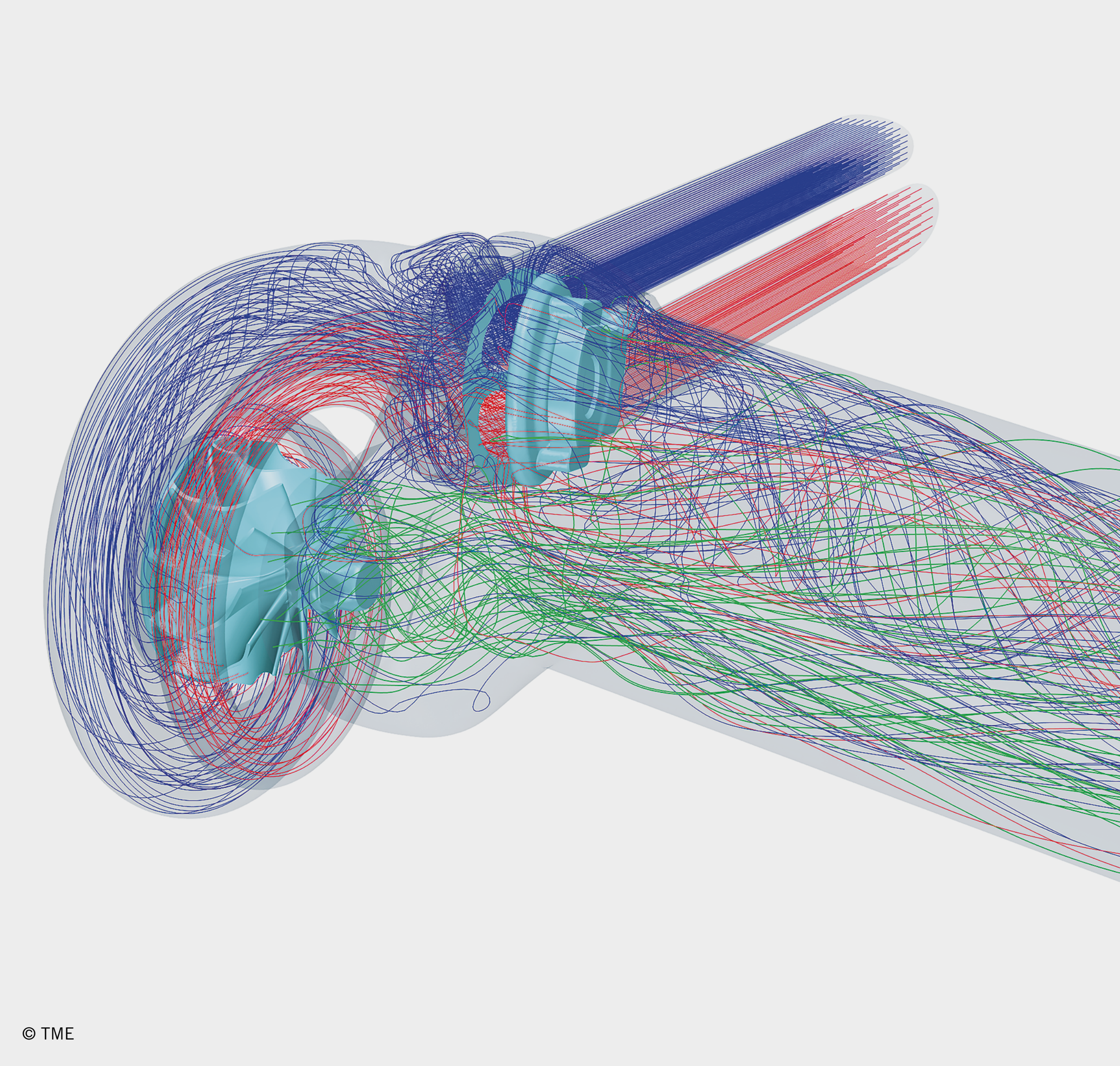
Investigation into Wastegate Channel Interaction of Twin-scroll Turbines

Optimal modeling of exhaust gas turbochargers contributes to the improvement of predictive 1-D engine process calculations. In order to be able to consider flow influences at twin-scroll wastegate channels, the FVV research project “Investigation Twin-scroll Turbines” (FVV-No. 1264) was initiated. The results of the project, which was carried out at RWTH Aachen University, represent an important extension for map-based modeling approaches.



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1 INFLUENCE OF WASTEGATE OPENING

Current methods of modeling exhaust Turbochargers (TC) are based on maps that are measured on a TC hot gas test bench when the Wastegate (WG) is completely closed. However, the WG is open across a broad range of the engine map for a turbocharged engine, as shown schematically in **FIGURE 1**. What influence the opening has on the power conversion at the turbine as well as on the modeling in the 1-D engine process calculation requires a general statement.

Twin-scroll turbines have two WG channels that are decoupled from each other. Depending on the position of the WG flap on the channels, different geometric flow cross-sections arise for its opening angle. This has a direct impact on the exhaust backpressure in the two sections of the exhaust manifold and, in turn, on the residual gas content in the connected cylinders. In addition, opening the WG changes the flow condition at the turbine impeller inlet. Precise knowledge of the flow condition is a prerequisite for modeling twin-scroll turbines [1]. For this purpose, a method for the acquisition of a WG characteristic at the combustion chamber test bench is to be derived. The research project was carried out at the Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) at RWTH Aachen University.

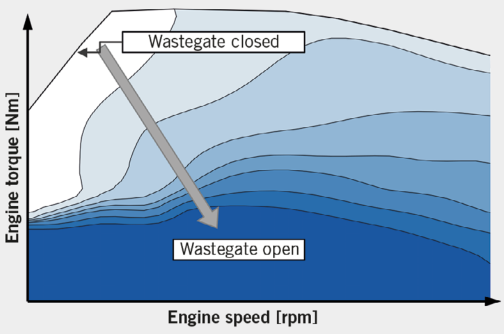

FIGURE 1 Schematic diagram of the WG position in an engine map as a function of engine speed and torque (© TME)

2 ISENTROPIC FLOW CROSS-SECTION

Preliminary investigations have shown that the WG in a turbine cannot be fully mapped by means of a throttle equation. Rather, the isentropic flow cross-section $A_{s,\,WG}$ is dependent on the turbine pressure ratio, especially for small opening angles, so that it is introduced to characterize the WG flow. It relates to the state variables pressure p and temperature T in the measurement pipes upstream and downstream of the turbine. It is important to note that only the mass flow $\dot{m}_{WG}$, passing through the WG is considered in the calculation. For a mono-scroll turbine, $A_{s,\,WG}$ is determined by Eq. 1, where in the other equations the index 3 describes the condition of the turbine upstream and 4 downstream:

Eq. 1 $$A_{s,\,WG} = \frac{\dot{m}_{WG}}{c_s\,\rho_s}$$

Here, the density ρ_s and the specific heat capacity c_s are described by Eq. 2 and Eq. 3, respectively, with the total static pressure ratio Π_{WG} and $\Pi_{critical}$ resulting from Eq. 4; R stands for the gas constant and k for the compressibility:

Eq. 2 $$\rho_s = \rho_3 {*} \max(\Pi_{WG};\, \Pi_{critical})^{\frac{1}{\kappa_3}}$$

Eq. 3 $$c_s = \sqrt{\left(\frac{2\kappa_3}{\kappa_3 - 1}\right) R_T\, T_3 \,\left(1 - \max(\Pi_{WG},\, \Pi_{critical})^{\frac{\kappa_3 - 1}{\kappa_3}}\right)}$$

Eq. 4 $$\Pi_{WG} = \frac{p_4}{p_3} \text{ or } \Pi_{critical} = \left(\frac{2}{\kappa_3 + 1}\right)^{\frac{\kappa_3}{\kappa_3 - 1}}$$

For twin-scroll turbines, a distinction must be made between WG channels 1 and 2. To evaluate the flow quality, $A_{s,\,WG}$ is often compared to a geometric cross section. The latter is required in particular for calculating the flow coefficient α_{WG} of a WG channel. It is performed in the same way as for the inlet/outlet valve – **FIGURE 2** compares both geometries. Thus, α_{WG} can be determined according to Eq. 5:

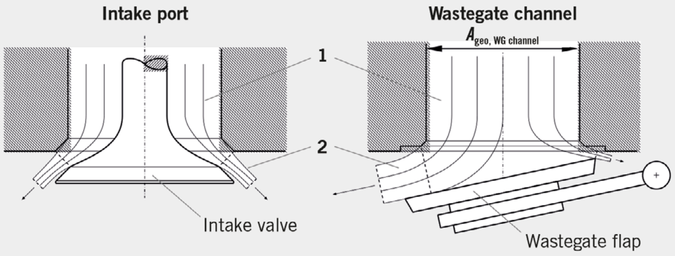

FIGURE 2 Analogy between the determination of the flow coefficient for intake and exhaust valve (left) and WG channel (right); condition before (1) and after (2) throttle [2] (© TME)

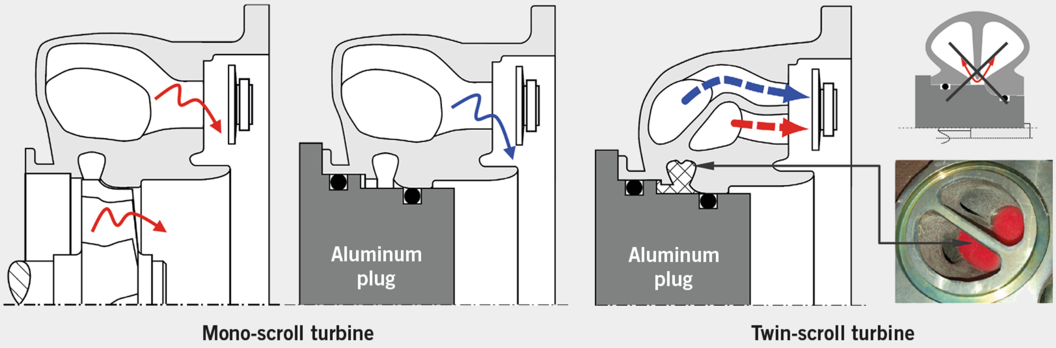

FIGURE 3 Air path in mono-scroll (left) and twin-scroll (right) turbine housing: mono-scroll with aluminum plug; twin-scroll additionally blocked with silicone (© TME)

Eq. 5 $\alpha_{\mathrm{WG}} = \frac{A_{\mathrm{s,\,WG}}}{A_{\mathrm{geo,\,WG}}}$

For the geometric cross-section of the WG channel, a distinction must be made between the cross-section inside the channel $A_{\mathrm{geo,\,WG\,channel}}$ and the cross-section between WG flap $A_{\mathrm{geo,\,WG\,flap}}$ and the WG seat. Depending on the WG opening angle the smaller cross-section will be used for reference.

3 MEASUREMENTS ON THE TC HOT GAS TEST BENCH

Since the conventional measurement procedure for a mono-scroll WG TC with an open WG does not allow the division of the turbine mass flow between the impeller and WG channel, **FIGURE 3** (left), the test sample ATL1 is modified accordingly in addition to the conventional measurement. The flow passes through the turbine housing only. An aluminum plug at the bearing housing connection blocks the area where the turbine impeller would otherwise be located. The plug is also designed to block the air path of the impeller downstream, so that the air can be discharged only via the WG channel once it has entered the turbine volute. Since all the relevant pressures in the measurement pipes upstream and downstream of the turbine as well as $\dot{m}_{\mathrm{WG}}$ through the WG channel are known, $A_{\mathrm{s,\,WG}}$ can be calculated by means of Eq. 1.

To measure the WG flow in twin-scroll turbines, the volutes are filled with silicone in advance to prevent cross flow at the dividing wall, **FIGURE 3** (right). As a result, it is also possible to directly infer the WG mass flows when measuring test sample ATL2. Thus, a calculation of $A_{\mathrm{s,\,WG}}$ for each scroll according to Eq. 1 is also possible here.

In order to quantify the individual mass flows in the two scrolls, a special dual-burner setup is used, in which each scroll is

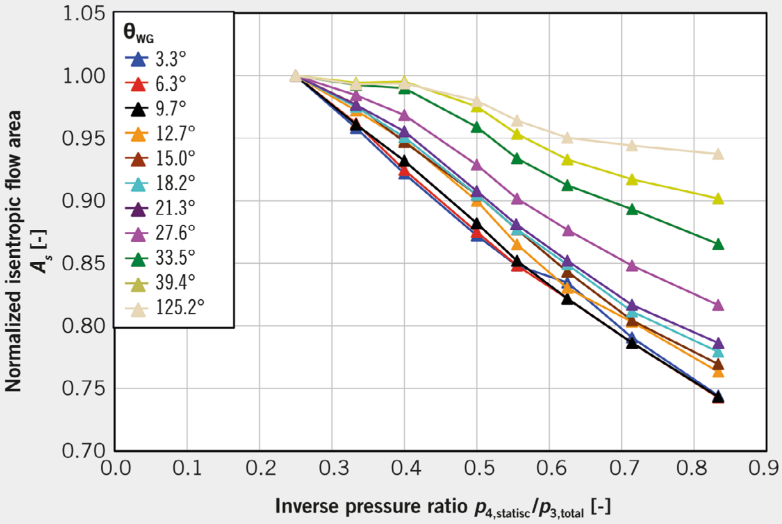

FIGURE 4 Pressure dependency of $A_{\mathrm{s,\,WG}}$ of a mono-scroll turbine at angle opening θ_{WG} in each case (© TME)

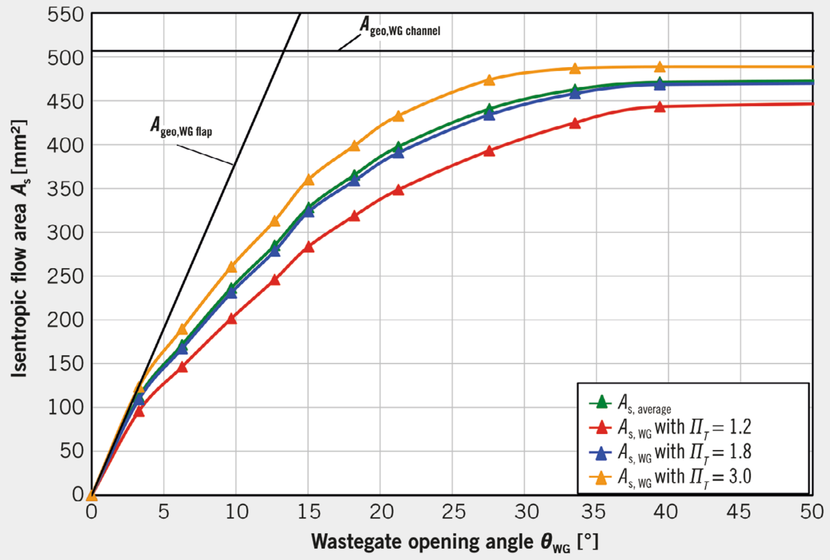

FIGURE 5 Geometric and isentropic cross-sections of flow plotted over the WG opening angle θ_{WG} (© TME)

connected to a separate mass flow source. Thus, $\dot{m}_{WG}$ is known for each scroll. By using a two-flow measuring pipe upstream of the turbine, p and T are determined at the WG channel inlet. The condition downstream of the WG is measured in the same way as the mono-scroll turbine in the measurement pipe downstream of the turbine. In order to overcome the limitations of the measurements (for example, a minimum mass flow of burners), additional investigations have been performed with 3-D models using Computational Fluid Dynamics (CFD). The comparison between measurement and simulation shows good agreement, so only the simulation results are discussed here.

4 PRESSURE RATIO DEPENDENCY

FIGURE 4 presents the respective calculated values for $A_{s,\ WG}$ versus the inverse turbine pressure ratio of a mono-scroll turbine. For better comparability, each value is normalized by the maximum cross-section of the corresponding WG position. As expected, $A_{s,\ WG}$ increases under constant pressure ratio conditions and wider opening WG. The relative change between two pressure ratios becomes smaller as the WG opens further. One interesting aspect here is that, for a constant WG position, $A_{s,\ WG}$ increases as the pressure ratio decreases (and the driving pressure gradient over the WG increases). Accordingly, a pressure dependency of $A_{s,\ WG}$ can be observed, as is the fact that it is much more pronounced at small opening angles. The pressure dependency for the smallest opening angle is calculated here at 25 % between the highest and lowest measured pressure ratio.

A primary objective of the new WG modeling method in the 1-D engine process simulation is to be able to use the WG opening angle as an output variable. In **FIGURE 5**, for each of the three turbine pressure ratios Π_T = 1.2; 1.8 and 3, $A_{s,\ WG}$ is plotted versus the opening angle θ_{WG}. In addition, for each measured WG position, the mean value over all pressure ratios is plotted, whereby a maximum deviation of around 10 % with respect to the average value can be specified. The geometric cross-sections $A_{geo,\ WG\ channel}$ and $A_{geo,\ WG\ flap}$ show up as the maximum limit in **FIGURE 5**. Following Eq. 5, these can be used to calculate the flow coefficient α_{WG}. Since the smaller geometric cross-section must always be used for calculations, the channel cross-section is used as a reference from an opening angle of θ_{WG} = 13°. This results in a maximum flow coefficient for the wide open WG of α_{WG} = 0.93.

5 INTERACTION OF THE WG DOWNSTREAM FLOW

In order to understand the experimental results of the twin-scroll WG investigations on the test bench in more details, a 3-D CFD investigation was performed based on CAD data. Since all physical quantities can be determined at any point in the simulation, the mass flows through the WG channels can be clearly determined despite the impeller and scroll interaction at the dividing wall. It is therefore possible to calculate the isentropic cross-sections of flow of both WG channels $A_{s,\ WG,\ i}$.

For the analysis of twin-scroll WG turbines, a different visualization method is used in the following: It aims to show whether and how the discharge from one WG channel affects the discharge from the other channel. The advantage of the turbine interaction map is that, by means of the scroll pressure ratio Π_{scroll} and the average turbine pressure ratio $\Pi_{T\ averaged}$ span an area where $A_{s,\ WG,\ i}$ can be plotted as another quantity on a third axis.

FIGURE 6 shows the results for scroll 1 over the entire turbine operating range for a constant opening angle θ_{WG} = 8° (the results for scroll 2, not shown here, are analogous). For illustration, a sample engine pulse has been incorporated in the turbine interaction map for illustrative purposes. As expected, the values under single admission of this scroll on the right in the diagram are the biggest at $A_{s,\ WG,1}$ = 234 mm². In this flow condition, the fluid flows only from scroll 1 to the turbine outlet. In an ideal situation in which the two WG outlets are not located right next to each other, but are routed separately to the surroundings, no

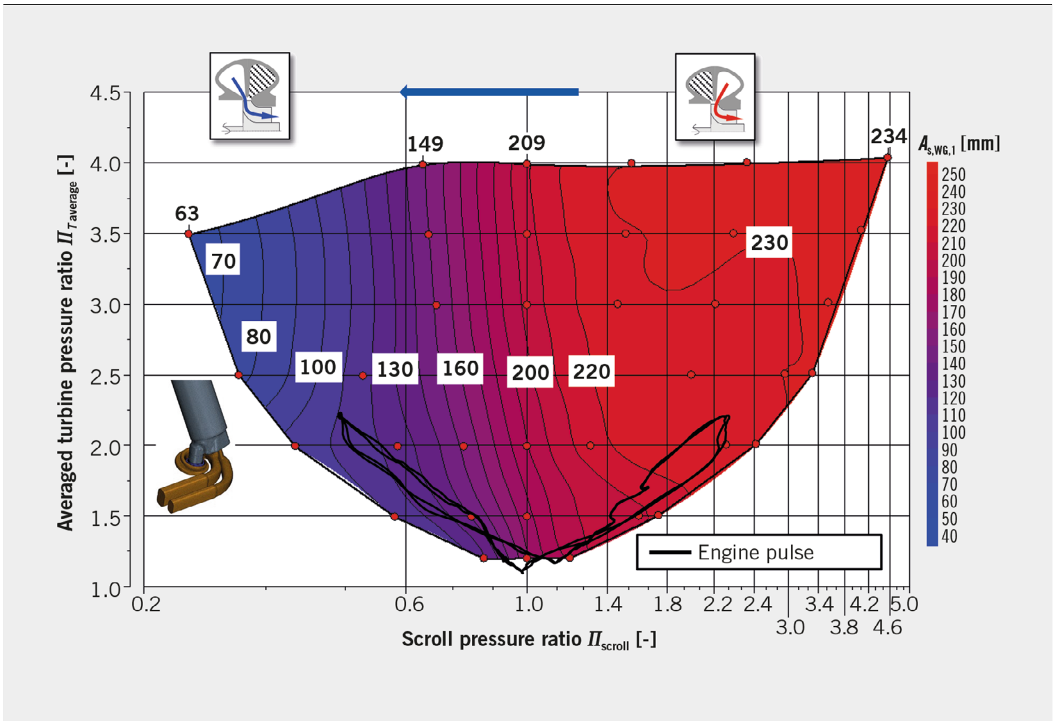

FIGURE 6 3-D CFD model with impeller: $A_{s,\ WG,1}$ as a contour diagram in the turbine interaction map for θ_{WG} = 8° (© TME)

influencing effects should be observed. In practice, this is not the case and the WG discharges can come into contact with and influence each other.

This effect becomes clear under unequal admission. In areas in which more mass flows through scroll 1 than scroll 2, the isentropic area of flow $A_{s,\ WG,1}$ is still relatively high, although a reduction during higher unequal admission can already be observed. By the near-vertical contours it becomes clear that the change of $A_{s,\ WG,\ 1}$ from the scroll pressure ratio Π_{scroll} becomes dominant and the change through $\Pi_{T\ averaged}$ is minimal. Already in the area under equal admission (Π_{scroll} = 1), the values for $A_{s,\ WG,1}$ decrease significantly as the flow through the second scroll increases. They drop sharply to $A_{s,\ WG,\ 1} = 63\ mm^2$. It can therefore be assumed that a discharge from WG channel 2 impedes the discharge from WG channel 1.

In principle, it was shown that it is possible to determine the isentropic flow cross-sections of both WG channels with the test bench setup presented here. These can be provided as a look-up table for the 3-D CFD gas exchange simulation. In this way, the WG flow can be better modeled and thus its influence on engine operation, for example through the residual gas behavior, can be more accurately predicted.

6 SUMMARY

Two different test bench setups were investigated for a mono-scroll turbine (with and without impeller) in order to determine the isentropic flow cross-section efficiently and non-destructively. A pressure ratio dependency of up to 25 % could be demonstrated, which is why the flow behavior cannot be represented by a simple throttle equation.

A measurement and simulation methodology was developed for a twin-scroll test sample to calculate the isentropic flow cross-section of both WG channels. A strong interaction of the WG downstream flow of twin-scroll turbines due to blocking of the downstream flow under unequal admission was demonstrated. 1-D modeling approaches to account for these effects in the gas exchange simulation were developed and validated with measurements/3-D CFD simulations. As a result, the 1-D models can now additionally output the WG opening angle, which is important, for example, for fast application processes in engine calibration.

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