Friction and Heat Transfer Effects on Turbocharger Modeling

Dominik Lückmann¹, Christof Schernus², Tolga Uhlmann², Björn Höpke¹, Carolina Nebbia³

¹ Institute for Combustion Engines (VKA), RWTH Aachen University
² FEV GmbH, Aachen
³ FEV Italia S.r.l.

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Turbine Operation Area at WOT and Load Step

![Graph showing turbine operation area at WOT and load step. The graph plots Turbine Pressure Ratio against Reduced Turbine Speed. There are two distinct regions: WOT for \( n_{\text{eng}} = 1000-5500 \text{ min}^{-1} \) and Load Step for \( n_{\text{eng}} = 1300 \text{ min}^{-1} \).]
Standard Hot Gas Measurement Range

- Standard Measurement (Open Loop)
  - $T_3 = 600 \, ^\circ\text{C}$
  - WOT $n_{\text{eng}} = 1000-5500 \, \text{min}^{-1}$
  - Load Step $n_{\text{eng}} = 1300 \, \text{min}^{-1}$
  - Measurement Range Below $0.5 * n_{\text{TC, max}}$

- Engine Torque $M$
  - WOT $n_{\text{eng}} = 1000-5500 \, \text{min}^{-1}$
  - Load Step $n_{\text{eng}} = 1300 \, \text{min}^{-1}$
  - Below $0.5 * n_{\text{TC, max}}$

- Engine Speed $n$

Reduced Turbine Speed $n_{\text{TC}} \cdot T^{0.5} / \text{min}^{-1}/K^{0.5}$

Turbine Pressure Ratio / -
Calculation of the Turbine Efficiency

Turbine efficiency as a function of turbine outlet temperature

\[ \eta_{T,\text{is}} = \frac{P_T}{P_{T,\text{is}}} \neq \frac{\dot{m}_T \cdot (h_3 - h_4)}{\dot{m}_{\text{is}} \cdot (h_3 - h_{4,\text{is}})} \]

\[ \dot{Q}_T \neq 0 \]

Turbine efficiency definition using compressor power

\[ \eta_{T,\text{net}} = \eta_{T,\text{is}} \cdot \eta_{m,\text{TC}} = \frac{P_V = P_T - P_F}{P_{T,\text{is}}} \approx \frac{\dot{m}_T \cdot (h_2 - h_1)}{\dot{m}_{\text{is}} \cdot (h_3 - h_{4,\text{is}})} \neq f(T_4) \]

\[ \dot{Q}_V \approx 0 \]

Turbine Net Efficiency is a function of

\[ \rightarrow \text{Aerodynamic turbine performance} \]
\[ \rightarrow \text{Compressor heat flux} \]
\[ \rightarrow \text{Bearing friction losses} \]

\[ \rightarrow \text{Mach similarity does not apply to turbine net efficiency maps} \]
\[ \rightarrow \text{Heat flux, friction losses and aerodynamic has to be separated} \]
Content

- Introduction
- Impact of Compressor Heat Flux on TC Maps
- Impact of Bearing Friction Losses on TC Modeling
- GT-Power TC Modeling
- Results of a Simple Friction and Turbine Heat Transfer Model
- Summary
Heat Flux into the Compressor Coolant Temperature Variations

\[ \eta_{T,\text{is}} \ast \eta_{m,\text{TC}} = \frac{\dot{m}_V (h_{2,\text{tot}} - h_{1,\text{tot}})}{\dot{m}_T (h_{3,\text{tot}} - h_{4,\text{is},\text{st}})} \]

Standard measurement range down to approx. 0.4 - 0.5 * \( n_{\text{ATL, max}} \) due to a dominant heat flux into the compressor at lower speeds.

- \( T_3 = 600 \, ^\circ\text{C} \)
- \( T_{\text{Oil}} = 90 \, ^\circ\text{C} \)
- \( T_{\text{CWT}} \):
  - w/o CW

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Heat Flux into the Compressor
Coolant Temperatur Variations

With lower coolant temperature the heat flux into the compressor is reduced → $\eta_T$
Heat Flux into the Compressor Coolant Temperatur Variations – Total Turbocharger Efficiency

→ Negligible Impact of the compressor heat flux on the aerodynamic performance

→ Conditions to separate
  → Aerodynamic performance
  → Heat flux to compressor fulfilled

\[ T_3 = 600 \, ^\circ\text{C} \]
\[ T_{\text{Oil}} = 90 \, ^\circ\text{C} \]
\[ T_{\text{CWT}}: \]
- w/o CW
- 115 °C
- 90 °C
- 40°C
Heat Flux into the Compressor
Calculation of the Heat Flux

Specific heat flux to compressor $q_C / \text{kJ/kg}$

Compressor mass flow rate / $\text{kg/s}$

- $n_{\text{red}} = 2150 \text{ min}^{-1} \text{K}^{0.5}$
- $T_3 = 600 \degree \text{C}$
- $T_{\text{oil}} = 90 \degree \text{C}$
- w/o CW

Model Based Approach (Sirakov, Casey)$^3$

Experimental Approach (Scharf)$^1$

„FVV TC-Wärmeströme“ CFD (Heuer)$^2$

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$^1$ Extended Turbine Mapping and Engine Simulation, Dissertation, Scharf

$^2$ TC-Wärmeströme, FVV Abschlussbericht, Bohn, Heuer, Moritz, Wolff

$^3$ Evaluation of Heat Transfer Effects on Turbocharger Performance, ASME GT2011-45887, Sirakov, Casey
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Impact of Bearing Friction Losses on TC Modeling

Friction Measurement

**Friction and Heat Transfer Effects on Turbocharger Modeling**

- $F_A = 0 \text{ N}$
- $T_{\text{Oil}} = 90 \degree \text{ C}$
- $p_{\text{Oil}} = 4 \text{ bar (abs.)}$

**Graph:**
- TC Friction Power Loss / W vs. TC Speed / 1/min
- Oil Temperature / \degree \text{ C}
- Thrust Load / N

- $120,000 \text{ 1/min}$
- $80,000 \text{ 1/min}$
- $40,000 \text{ 1/min}$

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Impact of Bearing Friction Losses on TC Modeling

\( n_{\text{eng}} = 1500 \text{ RPM, WOT} \)

\[ n_{\text{red}} = \frac{n_{\text{TC}}}{\sqrt{T_{\text{Turbine Inlet}}}} \]
Impact of Bearing Friction Losses on TC Modeling

\( n_{\text{eng}} = 1500 \text{ RPM, WOT} \)

\[
n_{\text{red}} = \frac{n_{\text{TC}}}{\sqrt{T_{\text{Turbine Inlet}}}}
\]

\[
n_{\text{TC, Mapping}} = n_{\text{red}} \sqrt{873.15 \text{ K}}
\]

\[
\text{Error} = \frac{\int (P_{\text{Friction}}(n_{\text{TC, GT-Power}}) - P_{\text{Friction}}(n_{\text{TC, Mapping}})) d\alpha}{\int P_{\text{Turbine}} d\alpha} = 5.35 \%
\]
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Isentropic Adiabatic Turbine Efficiency

Friction and Heat Transfer Effects on Turbocharger Modeling

Net turbine efficiency

\[ \eta_{T, is} \cdot \eta_{m, TC} = \frac{\dot{m}_V (h_{2, tot} - h_{1, tot})}{\dot{m}_T (h_{3, tot} - h_{4, is, st})} \]
Isentropic Adiabatic Turbine Efficiency

Isentropic efficiency

\[ \eta_{T, is} = \frac{\dot{m}_V (h_{2, tot} - h_{1, tot}) + P_F}{\dot{m}_T (h_{3, tot} - h_{4, is, st})} \]

Net turbine efficiency

\[ \eta_{T, is} \eta_{m, TC} = \frac{\dot{m}_V (h_{2, tot} - h_{1, tot})}{\dot{m}_T (h_{3, tot} - h_{4, is, st})} \]
Isentropic Adiabatic Turbine Efficiency

**Isentropic adiabatic efficiency**

\[
\eta_{T,\text{is,ad}} = \frac{\dot{m}_V(h_{2,\text{tot}} - q_C - h_{1,\text{tot}}) + P_F}{\dot{m}_T(h_{3,\text{tot}} - h_{4,\text{is,st}})}
\]

**Isentropic efficiency**

\[
\eta_{T,\text{is}} = \frac{\dot{m}_V(h_{2,\text{tot}} - h_{1,\text{tot}}) + P_F}{\dot{m}_T(h_{3,\text{tot}} - h_{4,\text{is,st}})}
\]

**Net turbine efficiency**

\[
\eta_{T,\text{is}} \cdot \eta_m,\text{TC} = \frac{\dot{m}_V(h_{2,\text{tot}} - h_{1,\text{tot}})}{\dot{m}_T(h_{3,\text{tot}} - h_{4,\text{is,st}})}
\]
GT-Power Turbocharger Modeling

Separate modeling of

→ Aerodynamic turbine performance
→ Bearing friction losses

improves the simulation quality
GT-Power Turbocharger Advanced Modeling

Extended turbine maps

Extended compressor map

Bearing friction losses

Turbocharger Heat Flux Model

Thrust Load

TC Friction Power Loss / W

TC Speed / 1/min

Oil temperatur / °C

Mech. Power

Compress. hous.

Shaft hous.

Shaft

Coolant

Oil

Turbine hous.

Comp. hous.

Comp.

Turb.
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Impact of Turbocharger Inlet Oil Temperature on Load Steps

Friction model enables turbo engine modeling in cold-start and warm-up scenarios

- Lower turbo speed and slower acceleration
- Increased backpressure by higher power consumption
  - PMEP
  - BSFC
Impact of Turbocharger Inlet Oil Temperature on Load Steps

Friction model enables turbo engine modeling in cold-start and warm-up scenarios

- Lower turbo speed and slower acceleration
- Increased backpressure by higher power consumption
  - PMEP
  - BSFC
- Delayed engine response in
  - Drive-away
  - Tip-in from low part load

![Graph showing the impact of turbocharger inlet oil temperature on load steps.](image)

Small Turbocharged Gasoline Engine
Load Steps at 1400 RPM

- IMEP @ 2 sec / bar
- TC oil inlet temperature / °C

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Simple Heat Transfer Model

\[ \dot{Q}_T = \dot{m}_T h_{3,tot} - (\dot{m}_V (h_{2,tot} - q_c - h_{1,tot}) + P_F) - \dot{m}_T h_{4,tot} \]

Hot gas measurements

T \_3 Variations

Turbine Volute

Heat input rate

Turbine mass flow rate

specific turbine heat flux

turbine inlet temp.
Simple Heat Transfer Model

Hot gas measurements

\[ T_3 \text{ Variations} \]

\[ \dot{Q}_T = \dot{m}_T h_{3,\text{tot}} - (\dot{m}_V (h_{2,\text{tot}} - q_C - h_{1,\text{tot}}) + P_F) - \dot{m}_T h_{4,\text{tot}} \]

\[ \text{specific turbine heat flux} \]

\[ \text{turbine mass flow rate} \]

\[ \text{turbine inlet temp.} \]

\[ \dot{m}, T \]

\[ \text{Turbine Volute} \]

\[ \text{heat input rate} \]

\[ \text{error} = \frac{T_{\text{sim}} - T_{\text{engine testbench}}}{T_{\text{engine testbench}}} \times 100\% \]

\[ \text{Turbine outlet temp. / °C} \]

\[ \text{error} = 7.5\% 1.3\% \quad 3.6\% 0.6\% \]

\[ \text{engine measurement} \quad \text{w/o heat flux model} \quad \text{with heat flux model} \]

Friction and Heat Transfer Effects on Turbocharger Modeling
Summary

- Due to the measurement methodology the calculation of the turbine (net) efficiency and compressor efficiency is impacted by the heat transfer to the compressor and the bearing friction losses.
- The heat transfer into the compressor has no impact on the aerodynamic performance of the compressor.
- This enables a separation of
  - Compressor heat flux
  - Aerodynamic Performance
  and combined with a bearing friction measurement allows to create TC Maps that apply the Mach similarity.
- On this basis advanced heat transfer models or bearing friction loss models can been introduced (decrease of IMEP @ 2 sec by 1 bar Oil temp. 90 → 50 °C).
- The shown simple turbine heat transfer model shows already good results. (error reduction in turbine outlet temperature by 80 %)
Thank you for your attention!

Dominik Lückmann¹, Christof Schernus², Tolga Uhlmann², Björn Höpke¹, Carolina Nebbia³

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