Národní centrum kompetence inženýrství pozemních vozidel Josefa Božka

3-WP06 High Efficiency Turbochargers for Large-Bore ICEs

Coordinator of the WP:

Brno University of Brno (BUT), Pavel Novotný

Participants of the WP:

Czech Technical University (CTU), Oldřich Vítek
PBS Turbo (PBST), Jiří Klíma

Main Goal of the WP

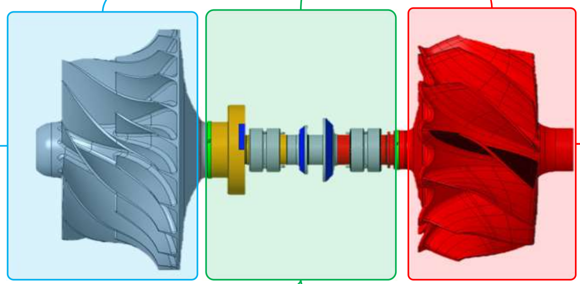
Research on new ways to improve the overall efficiency of turbochargers with application in Large-Bore internal combustion engines.

Deliverables:

3-WP06-001: Turbocharger with implemented measures to increase the mechanical efficiency (PBST, BUT, CTU)
3-WP06-002: Software for heat transfer estimation in turbocharger rotor system (BUT, PBST)
3-WP06-003: Report on Milestones – Large turbochargers (PBST, BUT, CTU)

3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Main goal of WP:
Research on new ways to improve the overall efficiency of turbochargers with application in large-bore internal combustion engines.



Compressor wheel–central housing interaction: **disc friction**

Efficient bearings: **air-bearings**

Electrically assisted turbocharging: **e-turbo, e-booster**

Turbine safety: **vibration** and **fatigue**

Unconventional fuels: **hydrogen (H_2), ammonia (NH_3)**

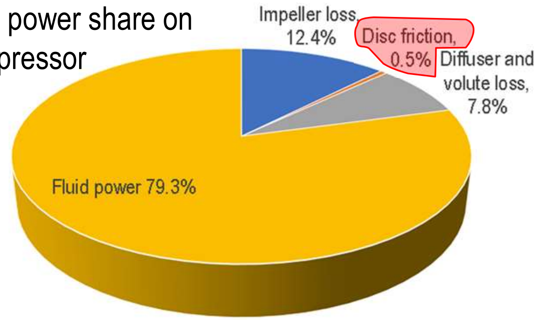
Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Compressor disc friction

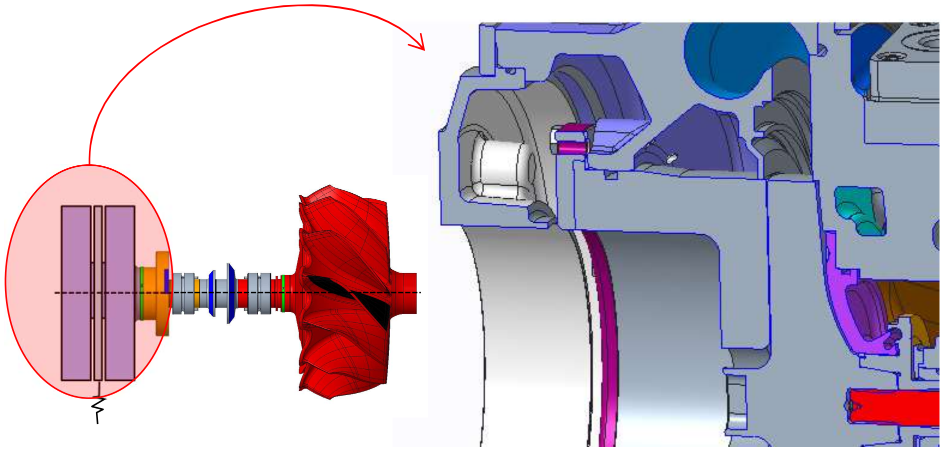
- Based on analytical and CFD predictions and literature review, the power loss due to compressor wheel friction (smooth version) is about 0.5% of the shaft power input.
- Experimental test program proposed to validate friction losses of smooth and non-smooth versions.
- Investigation to non-smooth variants including effects of surface treatment.

Test no.	Rotor	Stator
1	Ra 0,4	Ra 0,4, smooth, gap 0,5; 1,3; 2,1; 3
2	Ra 0,4	Ra 6,3, smooth, gap 0,5; 1,3; 2,1; 3
3	Ra 0,4	Ra 0,4, open bolts, gap 0,5; 1,3; 2,1; 3
4	Ra 6,3	Ra 6,3, smooth, gap 0,5; 1,3; 2,1; 3
5	Ra 6,3	Ra 6,3 open bolts, gap 0,5; 1,3; 2,1; 3
6	Ra 6,3	Painted, open bolts, gap 0,5; 1,3; 2,1; 3

Average power share on the compressor



Application on TCR16 turbocharger



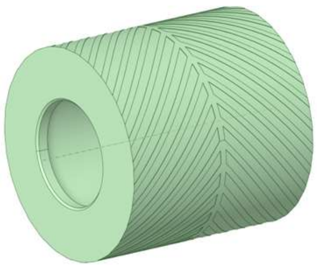
Ing. Klíma, Dr. Vacula, prof. Novotný

Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

New ways to significantly reduce mechanical losses

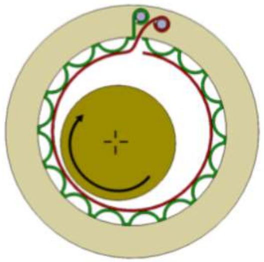
- Computational models of aerodynamic bearings based on commercial CFD software are used. Some of the special versions, e.g. airfoil bearings can not be efficiently solved because commercial solution is not available!
- RaDYN program extended by solution of compressible 2D Reynolds equation and elasto-aerodynamics and thermal effects.
- Solution of herringbone/helical grooving bearings, airfoil bearing.

PSOL130 solver developed!



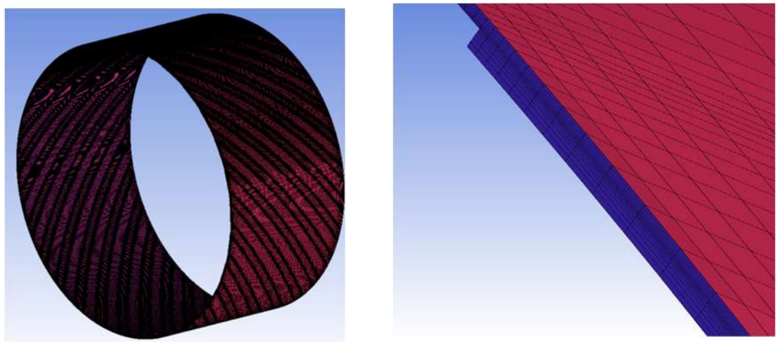
5% deviation from the ANSYS CFX was achieved, and a significantly better solution time ratio of 1000:1 was achieved

PSOL160 solver developed!



Commercional alternative for solution of aeroelastic bearing is not available!

ANSYS CFX: 3D CFD hexa mesh of herringbone grooving bearing (symmetrical model)



RaDYN: In-house developed program for elasto-aerodynamic problems

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial z}\right)-\frac{\omega D}{4}\frac{\partial(\rho h)}{\partial x}-\frac{\partial(\rho h)}{\partial t}=0$$

$$\frac{\partial}{\partial \alpha}\left(\frac{\xi}{\bar{\eta}}\frac{\partial P^2}{\partial \alpha}\right)+\frac{\partial}{\partial \gamma}\left(\frac{\xi}{\bar{\eta}}\frac{\partial P^2}{\partial \gamma}\right)-\omega_d P\Lambda\frac{\partial H}{\partial \alpha}+2\dot{\varepsilon}P\Lambda\cos(\alpha-\delta)-\omega H\Lambda\frac{\partial P}{\partial \alpha}-2H\Lambda\frac{\partial P}{\partial t}=0$$

Iterative GausSeidel pseudo-transient solution, thermal effects, elastic deformations for compliant bearing effects.

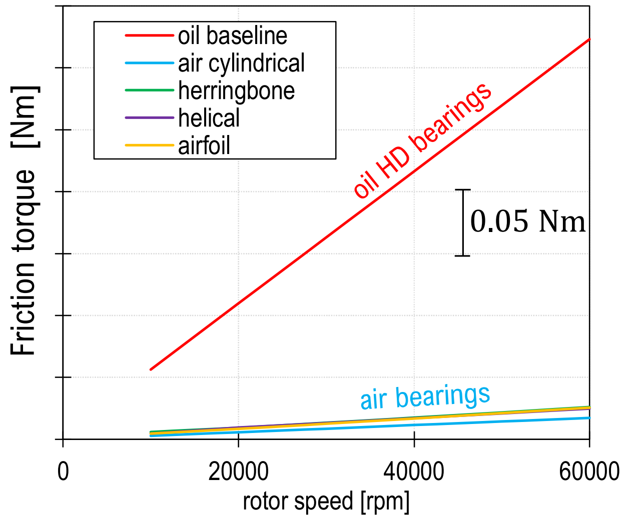
prof. Novotný

Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

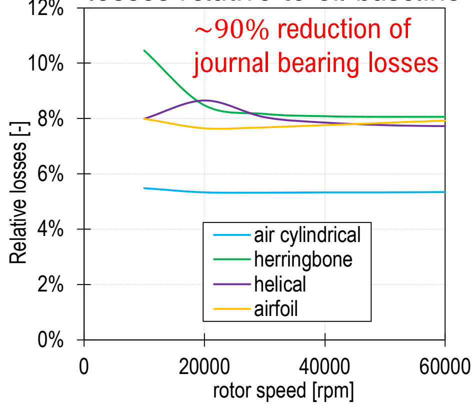
Application of air journal bearings in TCR10-size compatible turbocharger

- The use of air bearings represents a significant reduction in mechanical losses!

journal bearing friction torque vs. rotor speed



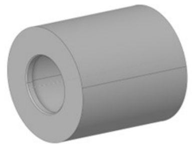
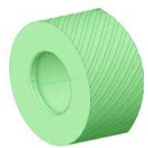
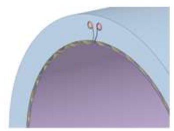
losses relative to oil baseline



Potentially ~90% reduction in mechanical losses from journal bearings!

- There are still disadvantages to air bearings, primarily rotor instability at high speeds and high wear during rotor start-up and stop-down.

Application on TCR10 turbocharger

serial bearing (TCR10)	
cylindrical air bearing	
herringbone grooving air bearing	
helical grooving air bearing	
airfoil bearing	

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Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Turbine blade vibrations

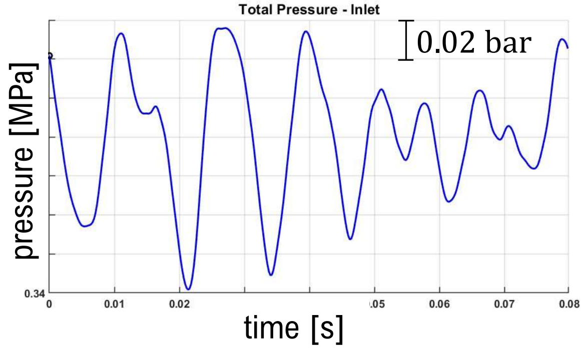
- Analysis of ICE-based time variable operating conditions at turbine inlet. Input time-variable quantities were evaluated for pseudo-transient behaviour.
  → The cycle was evaluated using minimum and maximum values.

- Analysis of blade-vane interaction using CFD – FEM one-way coupled approach

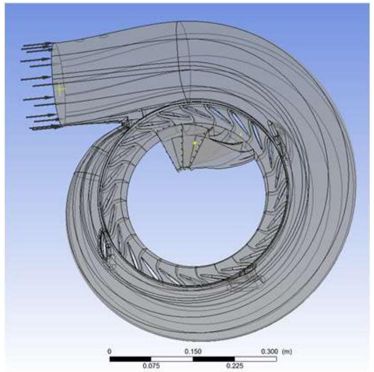
- Turbine blade stresses under pseudo-transient operating conditions

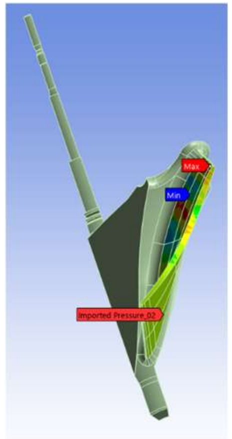
Pseudo-transient simulations show some inaccuracy and therefore it is necessary to validate by a fully transient approach for the entire duty cycle for evaluation stress.

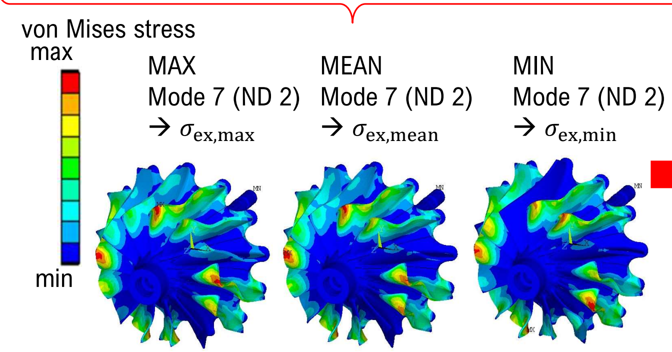
Application:
20-cylinder ICE
Engine speed 1500 rpm
TC rotor speed 38450 rpm



CFD-FEM computational models for a simulation of the entire duty cycle







→ unsymmetrical stress cycle → turbine blade fatigue evaluation

prof. Píštěk

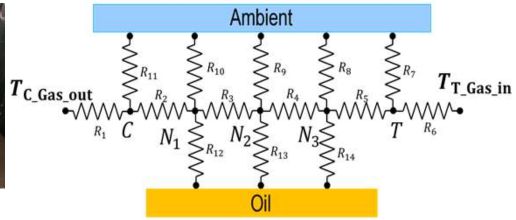
Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

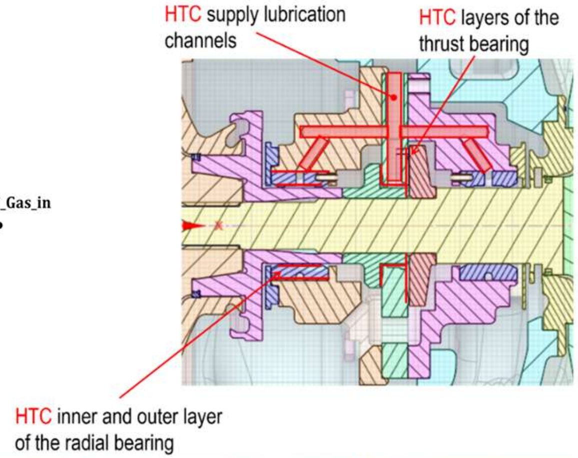
Software for heat transfer estimation in turbocharger rotor system

- The software contains a **database** of heat transfer coefficients for important locations in the turbocharger.
- Input signals: gas temperatures at compressor/ turbine inlet/ outlet, pressures, water/air temperatures etc.
- Suitable values are selected on the basis of characteristic geometric properties and operating conditions.
- The software can also be used just to determine the **HTC** values, which the user then inputs into external FEM/CFD models.

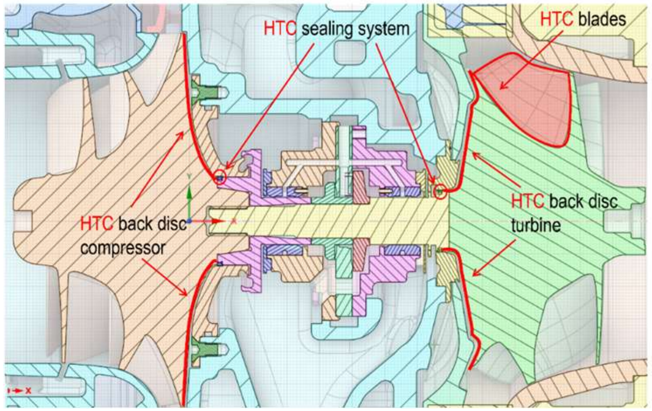
Heat transfer coefficients on important rotor parts, heat flux through the rotor system a shaft temperatures are the results.

measurement on turbocharger ⟺ calibration ⟺ 1D model of the turbocharger





Location	Correlation relationship
Sealing rings	$\mathrm{Nu} = 0.476\left(\frac{H}{\delta}\right)^{-0.56}\mathrm{Re}^{0.8}Pr^{0.4}$
Back of the wheel	$\mathrm{Nu} = 0.08G^{-0.07}\mathrm{Re_j}^{0.5}\mathrm{Re_w}^{0.25}$
Wheel blade	$\mathrm{Nu} = 0.0296\mathrm{Re}^{0.8}\mathrm{Pr}^{0.33}$
Lubrication channels	$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}$
Radial bearing	$\mathrm{Nu} = 0.65\mathrm{Ta}^{0.226}\mathrm{Pr}^{0.333}$
Cylindrical housing surface	$\mathrm{Nu} = 0.53(\mathrm{Gr\,Pr})^{0.25}$
Annular housing surface	$\mathrm{Nu} = 0.667(\mathrm{Gr\,Pr})^{0.25}$



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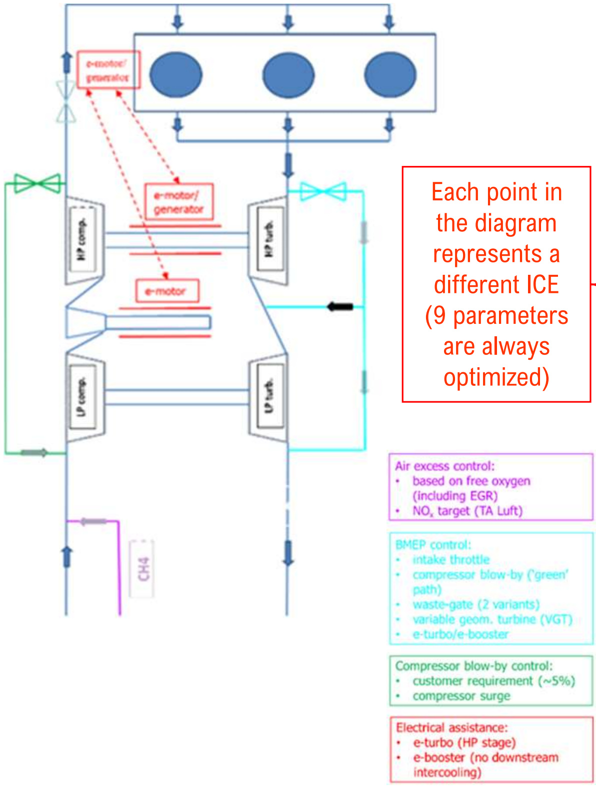
Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Electric assistance for turbochargers and boosters

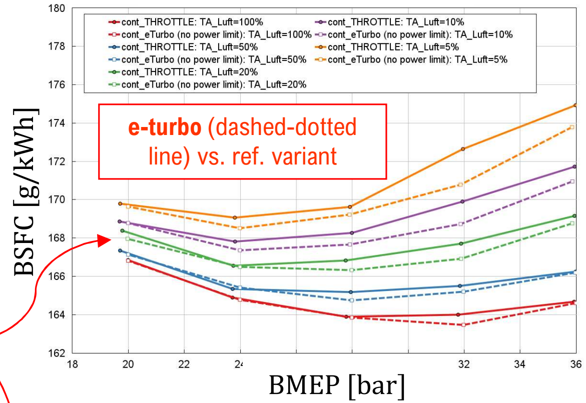
- Large-scale optimizations under steady state conditions to minimize BSFC, operated at constant NOx level based on TA Luft.
- Transient performance is always verified
  - → Load change from BMEP of 12 bar to 32 bar at constant engine speed.
- Sensitivity studies: influence of BMEP control, e-assistance application, NOx level, fuel composition (CH_4, H_2, NH_3), ambient conditions, etc.

E-turbo could slightly improve BSFC under operating conditions, it requires very high boost pressure → high BMEP and/or low NOx level. **E-booster is always worse** → missing intercooling and additional pressure loss are the main reasons.

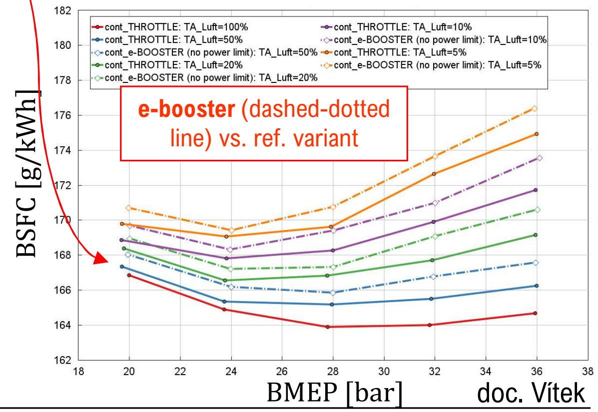
Application on two-stage turbocharged gas V20 ICE



e-turbo at HP stage



e-booster between LP and HP stage, no intercooling



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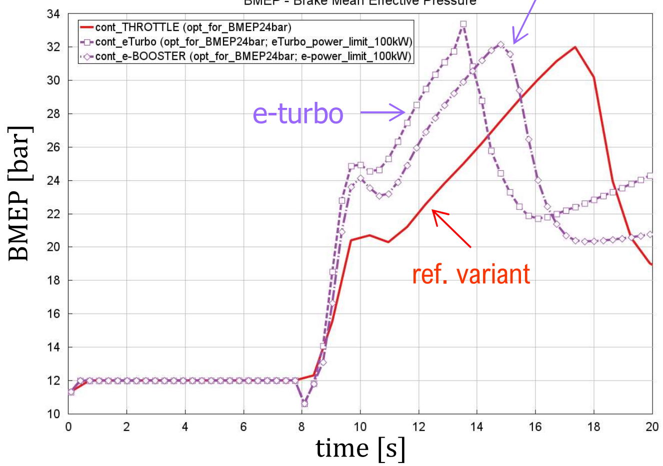
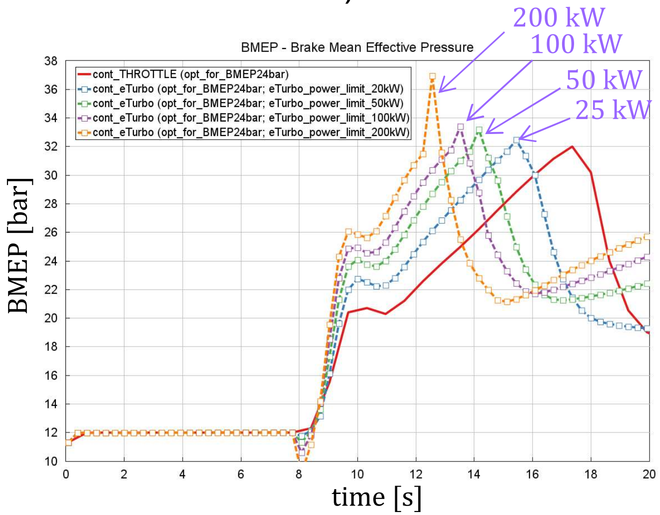
Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Electric assistance for turbochargers and boosters in transient conditions

- E-assistance power level is reasonable (below 100kW) => 2-stage group requires support from e-machine (=> no energy harvesting).

Transient response (load change from 12 to 32 bar of BMEP)





Transient response is significantly faster for both e-assistance variants (e-turbo is always slightly faster).

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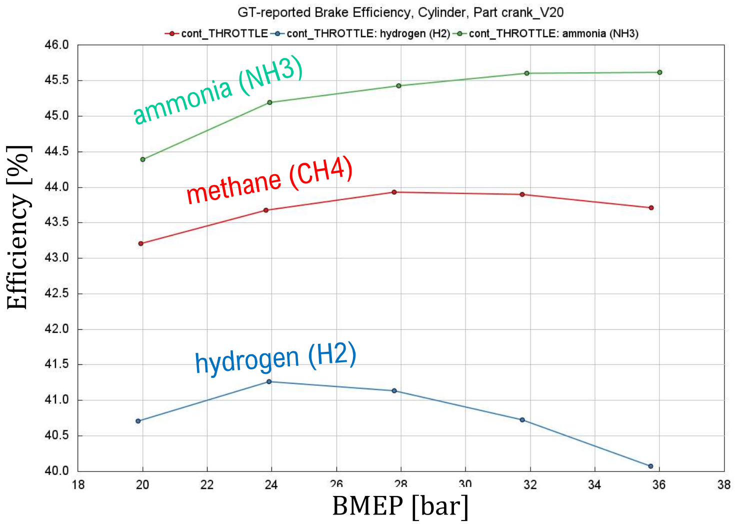
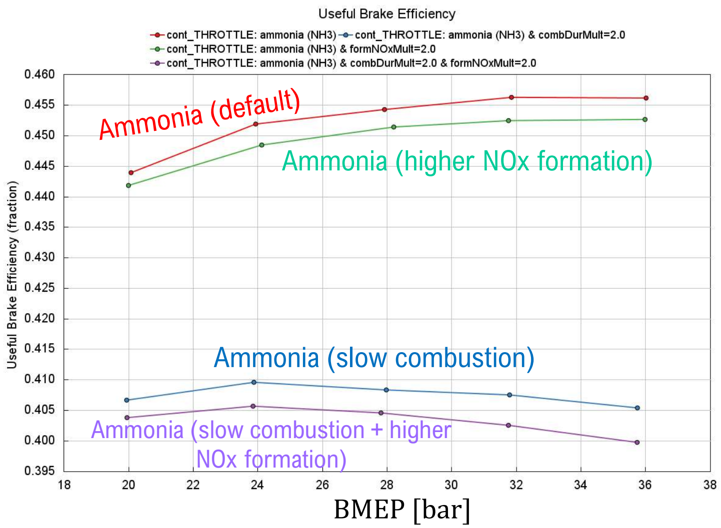
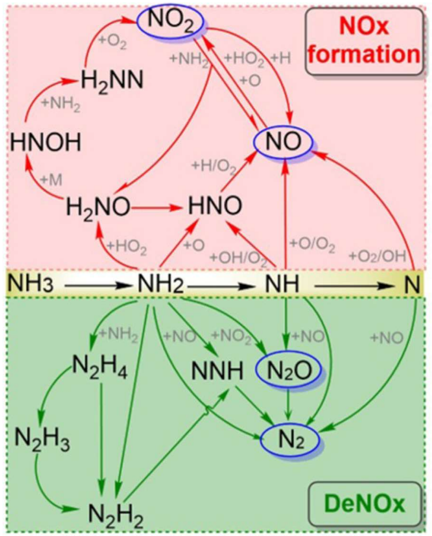
Activities in 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Application of alternative fuels (ammonia, methane, hydrogen)

- Ammonia burns very slowly, and its combustion process leads to significantly larger NOx formation => experiments (3-WP07) are planned for 2025.
- Detailed 3-D CFD calculations (LES + 'reduced' chemical kinetics) were performed to estimate combustion duration and NOx formation.







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Fulfillment of goals and deliverables of 3-WP06: High Efficiency Turbochargers for Large-Bore ICE

Current State of Deliverables and Fulfillment of Goals

- 3-WP06-001: Turbocharger with implemented measures to increase the mechanical efficiency (PBST, BUT, CTU) – in progress & no major delays
- 3-WP06-002: Software for heat transfer estimation in turbocharger rotor system (BUT, PBST) – in progress & no major delays
- 3-WP06-003 | Report on Milestones - Large turbochargers, O-ostatní, VI./2026, PBST 0.1; CTU 0.9 – in progress & no major delays

Dissemination of results

- VITEK, O., MACEK, M., KLIMA, J. AND VACEK, M. Application of Electrically Assisted Turbocharging for the Case of Large-Bore Gas SI ICE. 55th international scientific conference of Czech and Slovak universities and institutions focused on research and teaching methods related to ICEs, alternative powertrains and transport. Liberec, TUL, 2024. ISBN 978-80-7494-711-7.
- NOVOTNÝ, P.; VACULA, J.; KUDLÁČEK, P.; KOCMAN, F. Prediction of gas leakage through the turbocharger sealing system. 55. mezinárodní vědecká konference zaměřená na výzkumné a výukové metody v oblasti vozidel a jejich pohonů. 1. Liberec: Technická univerzita v Liberce, Fakulta strojní, Katedra vozidel a motorů, 2024. p. 92-100. ISBN: 978-80-7494-711-7.

Fulfillment of goals and deliverables of 3-WP06: High Efficiency Turbochargers for Large-Bore ICE

List of Due Deliverables and Their Added Value

- Highly efficient turbomachinery with improved efficiency and high-power density for different application targets: light/heavy duty vehicles, fuel cells, trucks, buses, railway vehicles at side branches and power co/generation units.
- Oil-free bearings (air bearings) can open the way for the application of turbochargers for fuel cell-based power units.
- Estimate of thermodynamic potential of different solutions in terms of improved efficiency, faster transient response and lower pollutants. Increased knowledge allows closer contact with customer and increases PBST competitiveness on the market.

Assessment of the Contribution of Deliverables

- Thermodynamics of very high boosted ICEs with low NOx level – (3-WP05), 3-WP07, (4-WP08), (4-WP06).
- Transient response and low mechanical losses – (3-WP05), (4-WP08), (4-WP06).
- Fuel Cells super-/turbocharging – 4-WP06

Current contribution of 3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Assessment of the Formal/Administrative Goals of the Work Package

	PBST	BUT	CTU
Finances (reporting/spending)	OK	OK	OK
Commercialization (the whole organization)	OK	OK	OK
Deliverables	OK	OK	OK

3-WP06: High Efficiency Turbochargers for Large-Bore ICEs

Thank you for your attention

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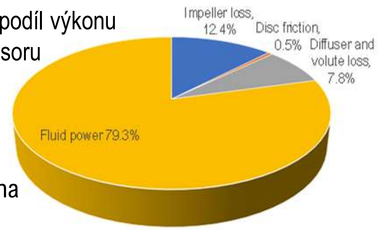
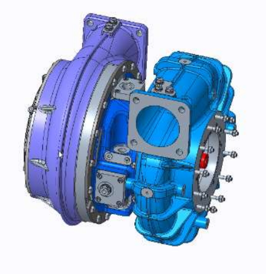
Výsledky dosažené 2024–2025 za 3-WP05: Vysoce účinná turbodmychadla pro velké motory

PBST: Ventilační ztráty

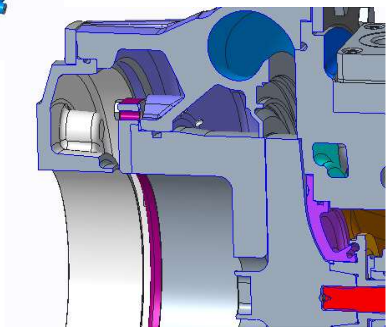
Průměrný podíl výkonu na kompresoru



Použití na turbodmychadlo TCR16

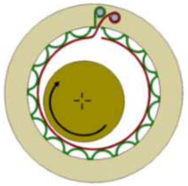


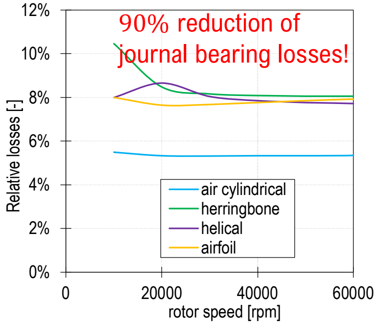
Experimentální testovací program navržený pro ověření ztrát třením.



BUT: Mechanické ztráty, bezolejová ložiska, přestup tepla

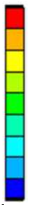
PSOL130 vyvinut řešič pro drážkovaná ložiska.
PSOL160 vyvinut řešič pro aeroelastické mazání.





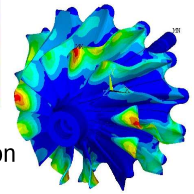
Analýzy napětí a únavy lopatek turbín

max

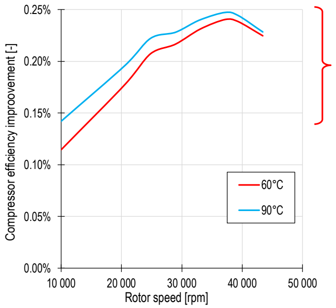


min
napětí von Mises

MAX
Mode 7 (ND 2)



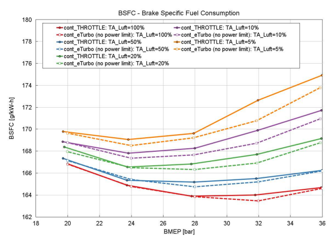
Snížené tření disku kompresoru o 40 %

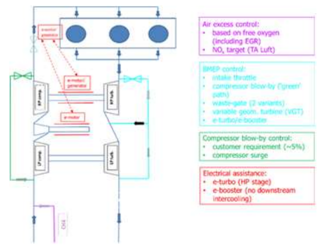


účinnost je snížena o 0.12 ÷ 0.25 %

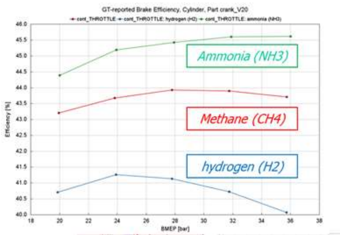
CTU: termodynamika, paliva, přechodové chování turbodmychadla

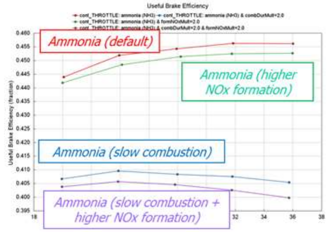
Přeplňování turbodmychadlem s posilovačem E-(e-turbo, e-booster)

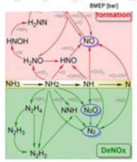


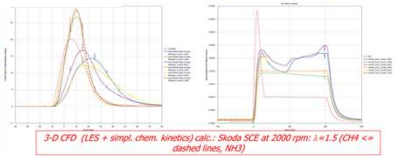


Různá paliva (metan, vodík, amoniak)





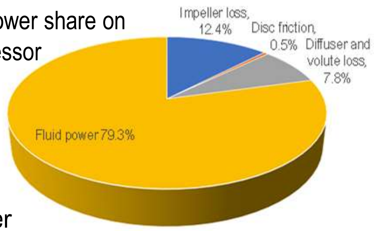




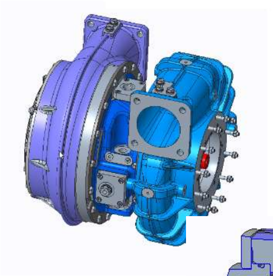
Results 2024–2025 under 3-WP05: Future Automotive Boosting Solutions

PBST: Ventilation losses

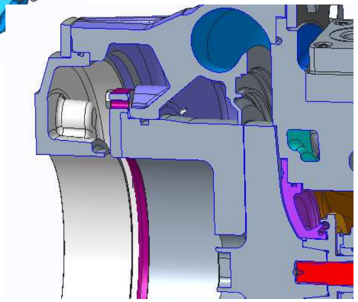
Average power share on the compressor



Application on TCR16 turbocharger

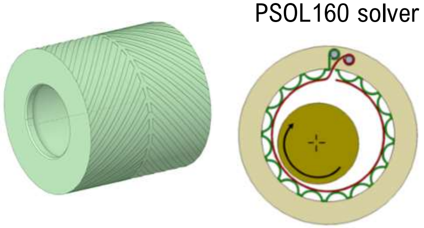


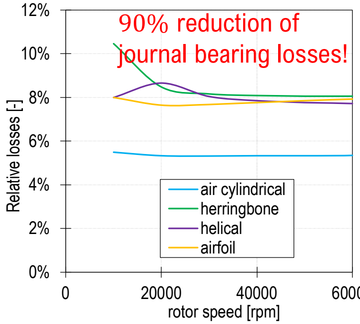
Experimental test program proposed to validate friction losses.



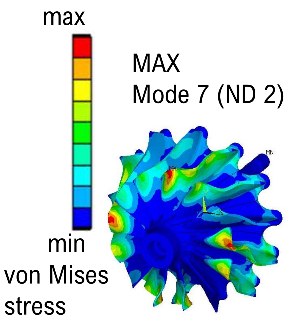
BUT: Mechanical losses, oil-free bearings, heat transfers

PSOL130 solver for grooved bearings developed.
PSOL160 solver for aeroelastic lubrication developed.

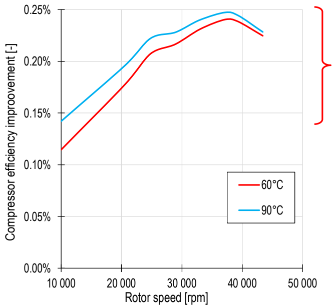




Turbine blade stress and fatigue analyses

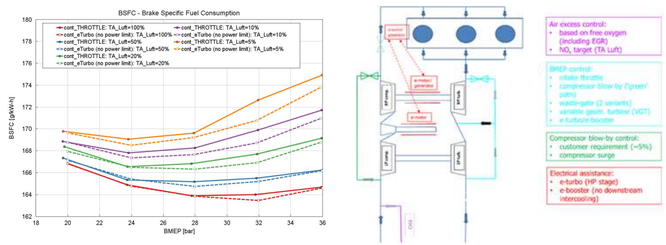


If reduced compressor disc friction by 40% efficiency is reduced by 0.12 ÷ 0.25 %

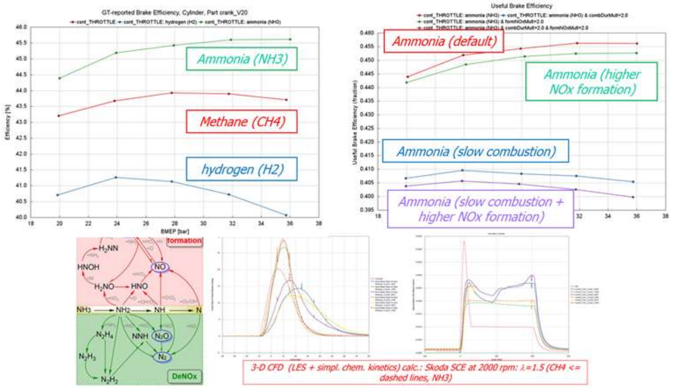


CTU: thermodynamics, fuels, turbocharger transient behavior

E-assisted turbocharging (e-turbo, e-booster)



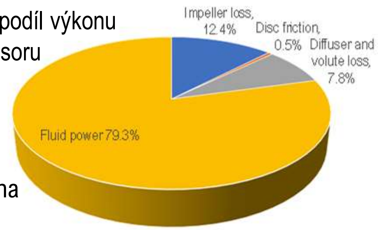
Different fuels (methane, hydrogen, ammonia)



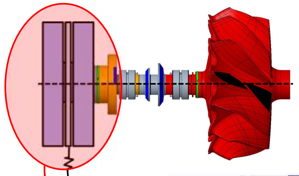
Výsledky 2024 za 3-WP05: Vysoce účinná turbodmychadla pro velké motory

PBST: Ventilační ztráty

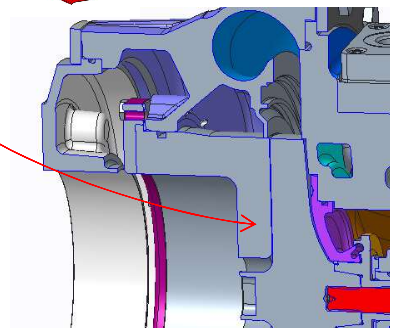
Průměrný podíl výkonu na kompresoru



Použití na turbodmychadlo TCR16

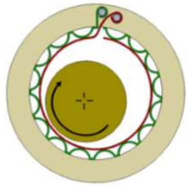


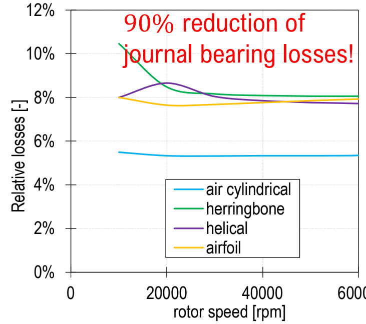
Experimentální testovací program navržený pro ověření ztrát třením.



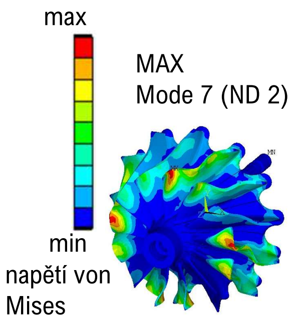
BUT: Mechanické ztráty, bezolejová ložiska, přestup tepla

PSOL130 vyvinut řešič pro drážkovaná ložiska.
PSOL160 vyvinut řešič pro aeroelastické mazání.

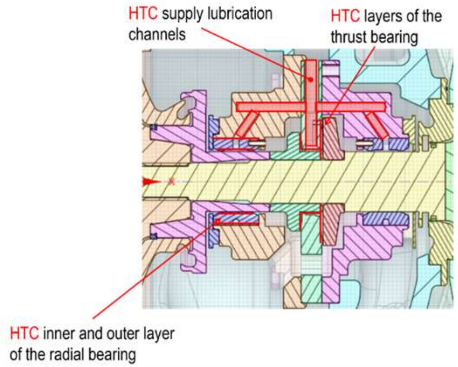




Analýzy napětí a únavy lopatek turbín

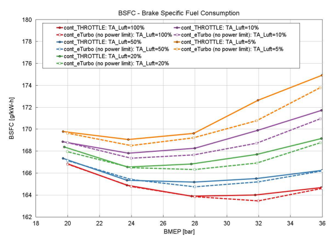


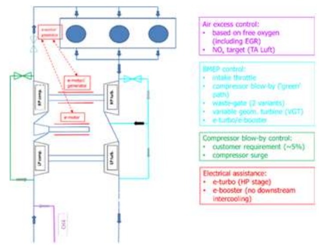
Přenos tepla v turbodmychadle



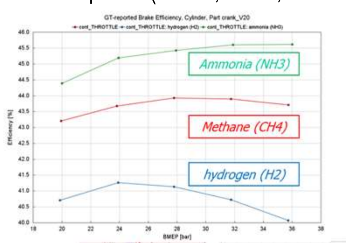
CTU: termodynamika, paliva, přechodové chování turbodmychadla

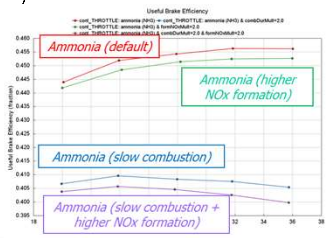
Přeplňování turbodmychadlem s posilovačem E-(e-turbo, e-booster)

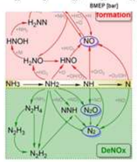


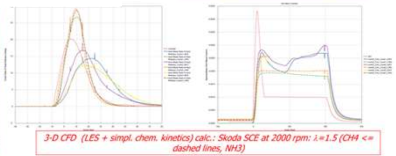


Různá paliva (metan, vodík, amoniak)





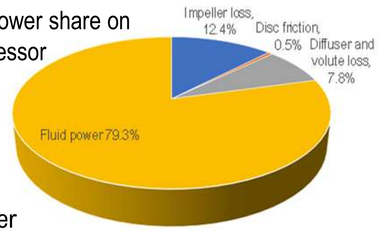




Results 2024 under 3-WP05: Future Automotive Boosting Solutions

PBST: Ventilation losses

Average power share on the compressor



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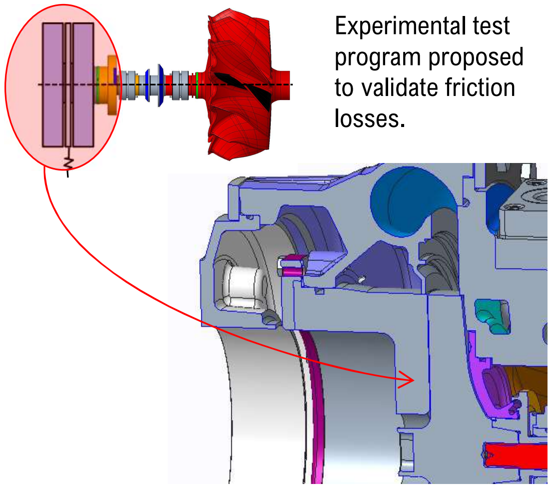

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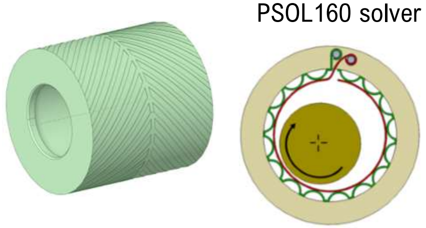
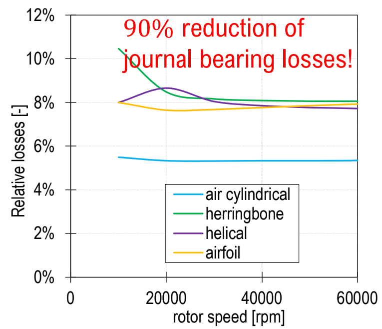
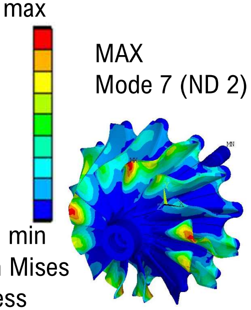




Turbine blade stress and fatigue analyses

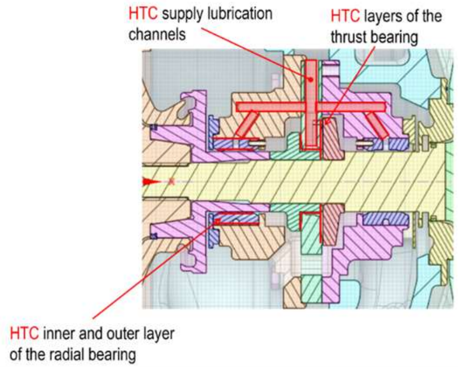
max



min
von Mises stress

MAX
Mode 7 (ND 2)

Heat transfer in turbocharger



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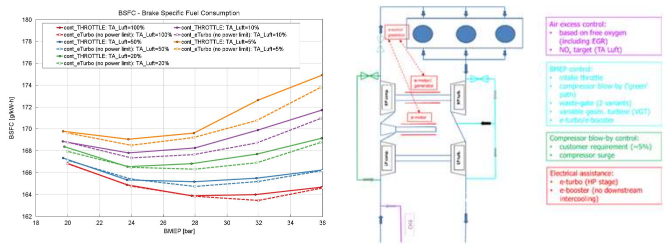

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