Contents of Work Package 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03: Solutions for Flow Component/System Testing and Analysis

Coordinator of the WP

České vysoké učení technické v Praze, Ing. Petr Hatschbach, CSc., doc. Ing. Jiří Vávra, Ph.D., prof. Ing. Jiří Fürst, Ph.D.

Participants of the WP

EATON – doc. Ing. Jiří Vávra, Ph.D.

ŠKODA AUTO – Ing. Ladislav Adámek

Main Goal of the WP

Novel test bench architecture for testing of hydrogen management components for fuel cells with innovative closed loop design to testing of high hydrogen flowrates with a small hydrogen supply unit only. The test bench also include temperature, pressure and gas composition conditioning. Virtual prototype – digital twins of test bench.

Improved design of restrictor attached to the input of the turbocharger compressor optimized by experimental investigation and advanced numerical simulations. This will increase efficiency of turbocharger and in overall reduce CO2.

Partial Goals for the Current Period

Test bench P&ID design, 1-D thermodynamics simulations, preliminary 3D CAD design

Design of experimental equipment for restrictor testing. Simulation of flow fields with respect to experimental verification

Contents of Work Package 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03: Solutions for Flow Component/System Testing and Analysis

Official 4-WP03 Deliverables:

- 4-WP03-001 | **Test bench for hydrogen fuel cell system components**,
  G-funk, XII./2025, CTU 0.5; EATON 0.5
- 4-WP03-002 | **Optimized restrictor of the compressor for turbocharged high-power SI ICE**,
  G-funk, XII./2025, CTU 0.5; SKODA AUTO 0.5
- 4-WP03-003 | **Database of subsonic flow simulations**,
  O, XII./2025, CTU 0.95; SKODA AUTO 0.05

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-001: Test bench for hydrogen fuel cell system components

PEMFC BoP – Fuel Loop

The Fuel loop architecture varies based on hydrogen storage and fuel delivery control strategy, but **must ensure reliable fuel delivery** at requested:

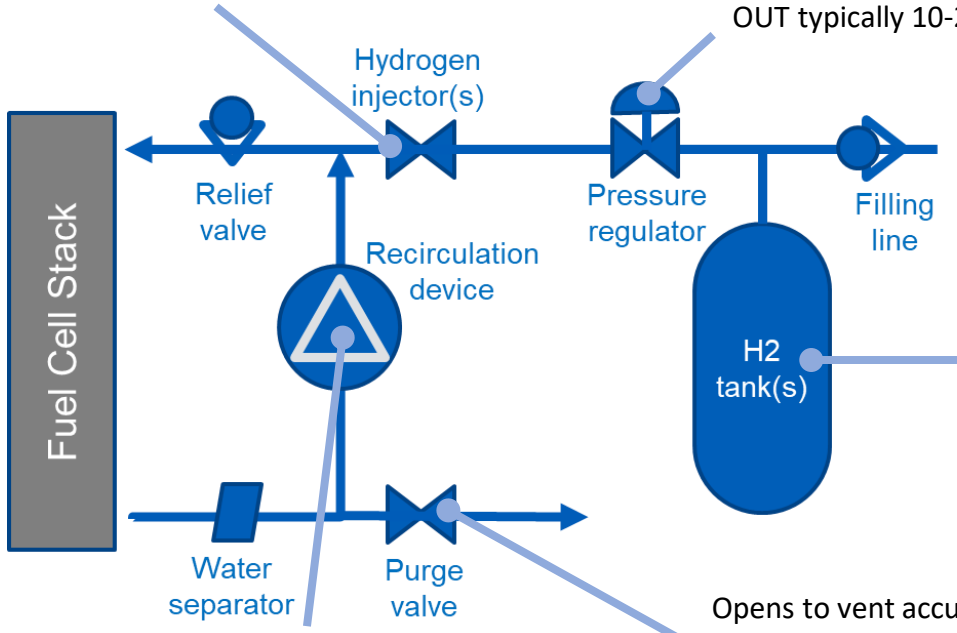
Mass flow: 1.5x more hydrogen then needed is pushed through the stack to ensure sufficient hydrogen is always available across the entire stack; Lambda goes up to 5 for very low loads when only a little amount of hydrogen is consumed - flow must be maintained to ensure proper water management. (Water diffuses from the air to the fuel side.)

Pressure: Pressure at both sides of the stack should be kept at same levels (with tolerance) to avoid mechanical damage of the membrane and catalyst layer.

Composition: Besides water, nitrogen also diffuses from the air to the to fuel side and because it does not react, it accumulates in the loop. Water and nitrogen are heavier than hydrogen, 9x and 14x respectively, and influence the system operation significantly.

Precise control of injected fuel can be proportional valve or one/multiple injectors.

Controls intermediate pressure downstream the tank(s) – IN 10-700 bar, OUT typically 10-200 bar



700 bar compressed hydrogen storage

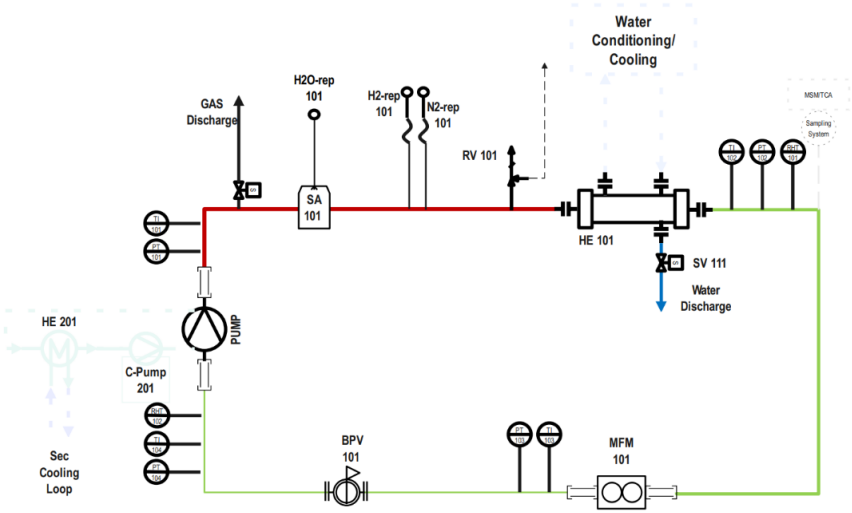
Opens to vent accumulated nitrogen and water (and hydrogen) from the fuel loop.

Excess fuel is not exhausted to the atmosphere, but recirculated back to stack. Stack pressure drop must be overcome to maintain stable circulation

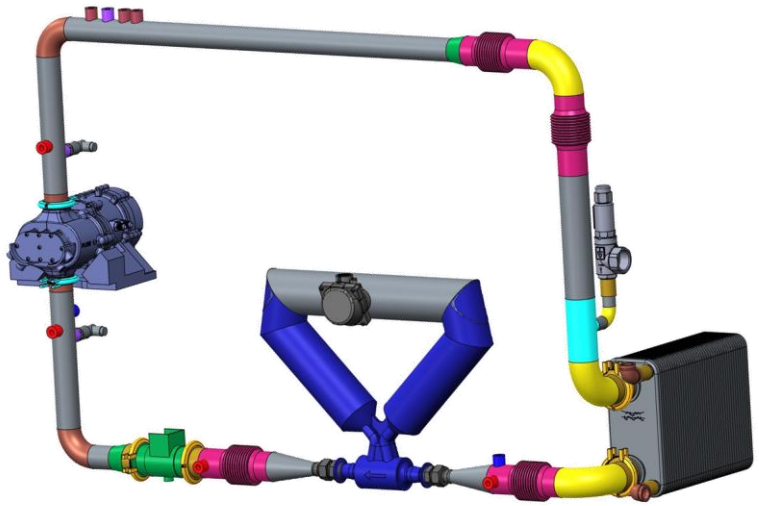
Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-001: Test bench for hydrogen fuel cell system components

P&ID design of a HRB testing loop



Preliminary 3D CAD Design of a HRB testing loop



Core components defined

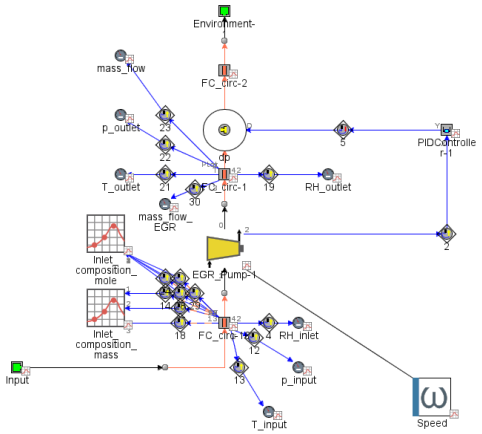
- HRB – based on current EGR pump
- Mass flow meter – low density of mixture and high flow rate
- HE sizing
- Throttle valve
- Humidification – detailed description needs student participation - Thesis
- Condensed water separation
- Sensors (p, T, Rh)

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

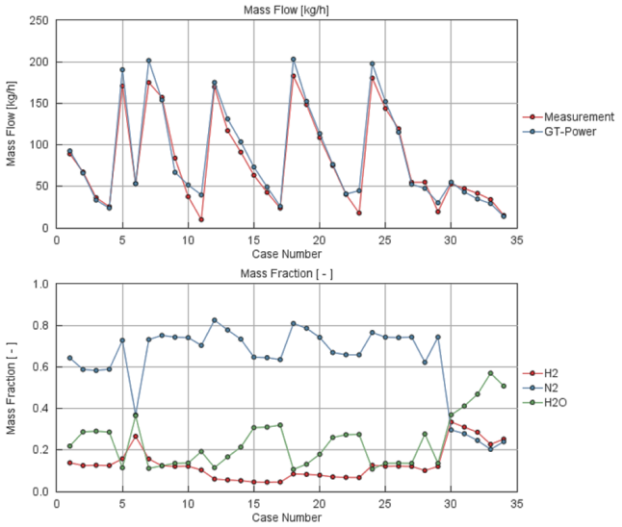
4-WP03-001: Test bench for hydrogen fuel cell system components

1D thermodynamics simulations, working conditions assessment (physical limits specifications)

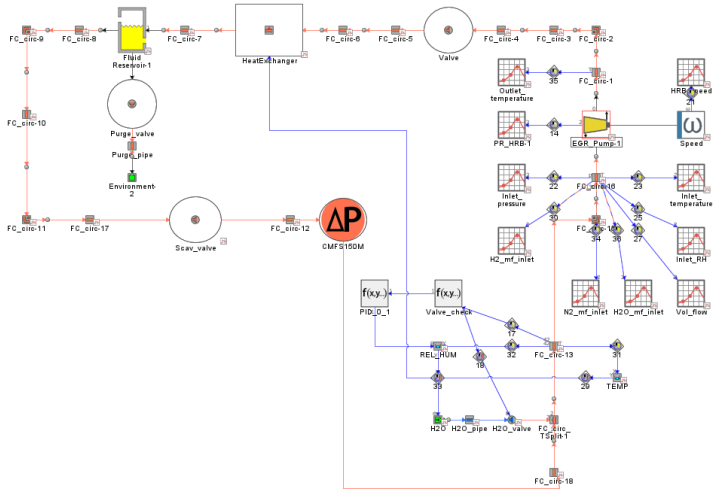
- HRB maps available for air only, tests in open loop test bench performed with H2, N2 and H2O mixtures (within the range HRB typical working conditions)
- Mathematical model describing performance differences between ICE and FC behavior
- DoE points definition, description of saturated gas mixture behavior and control system definition



1D GT-Power model to verify the accuracy of the HRB map for mixtures of different composition



Comparison measurement vs. simulations



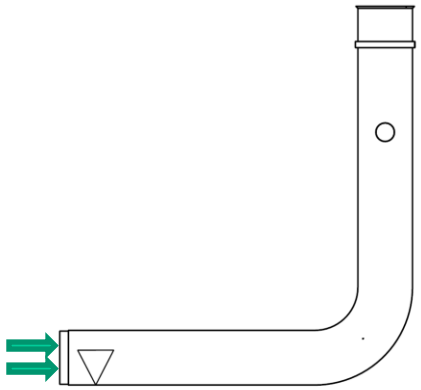
1D GT-Power model of complete circuit with all devices

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

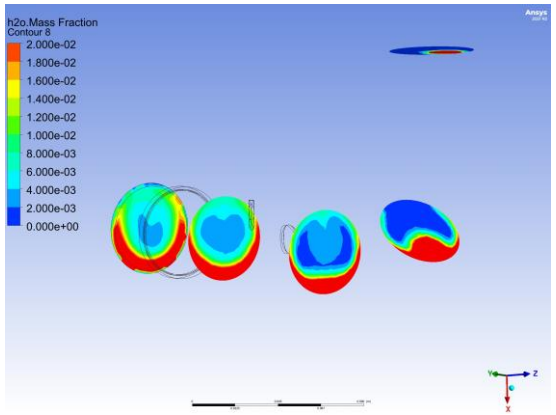
4-WP03-001: Test bench for hydrogen fuel cell system components

3D CFD (proof of concept) simulations of water injection into the anode circuit

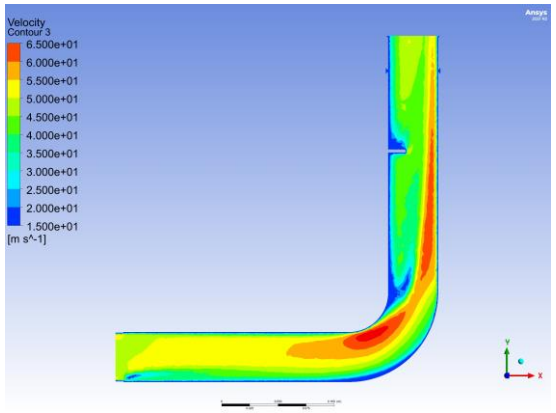
- A preliminary simulations taking into account most of the relevant physical models, i.e. the so-called "proof-of-concept" in terms of the feasibility of the given type of computation in the simulation environment used
- Input values set based on estimation and experience with similar injector simulations (PFI)
- To be refined according to the specific components used and working conditions



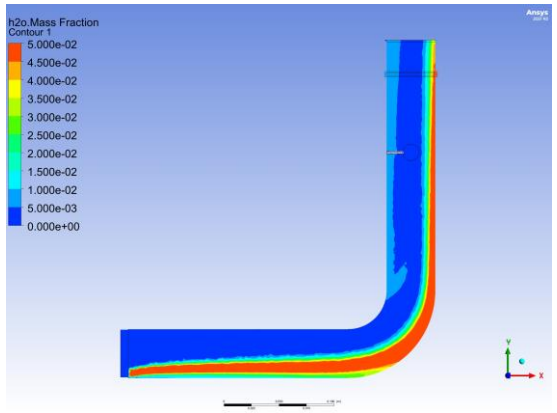
Segment of manifold for CFD simulation



Water vapour concentration



Flow velocity

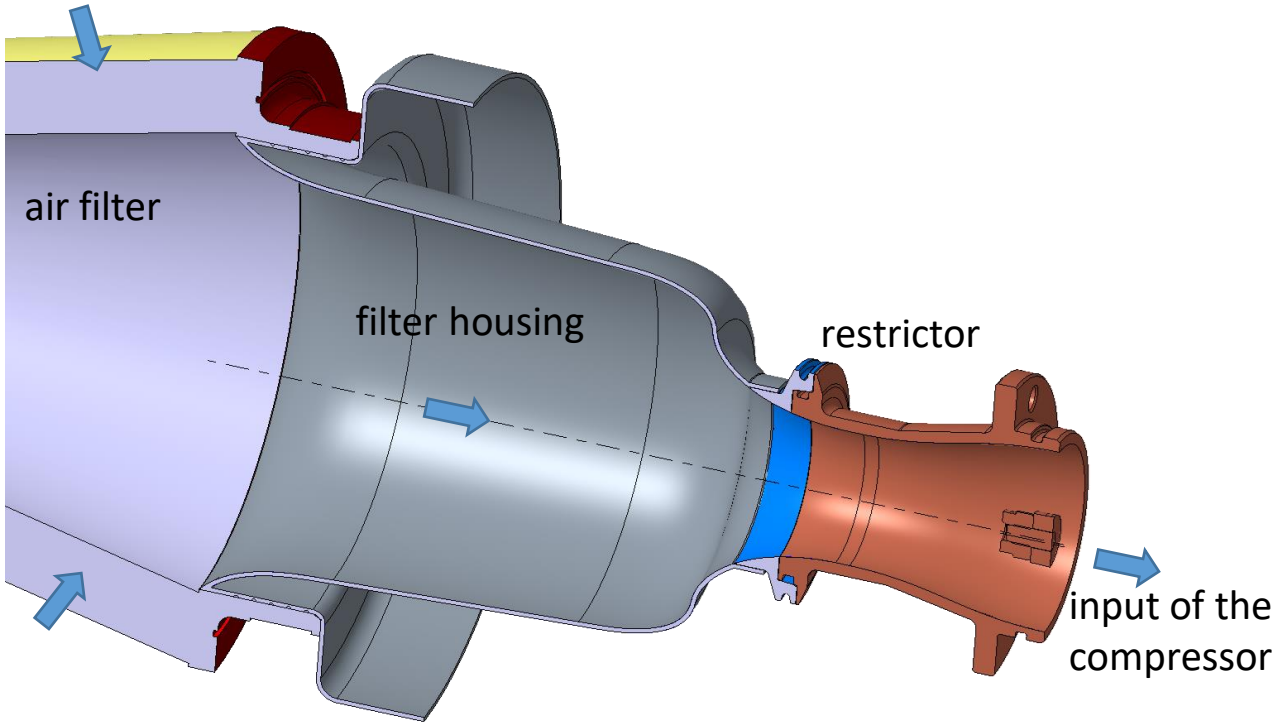


Segment of manifold for CFD simulationH2O mass fraction

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

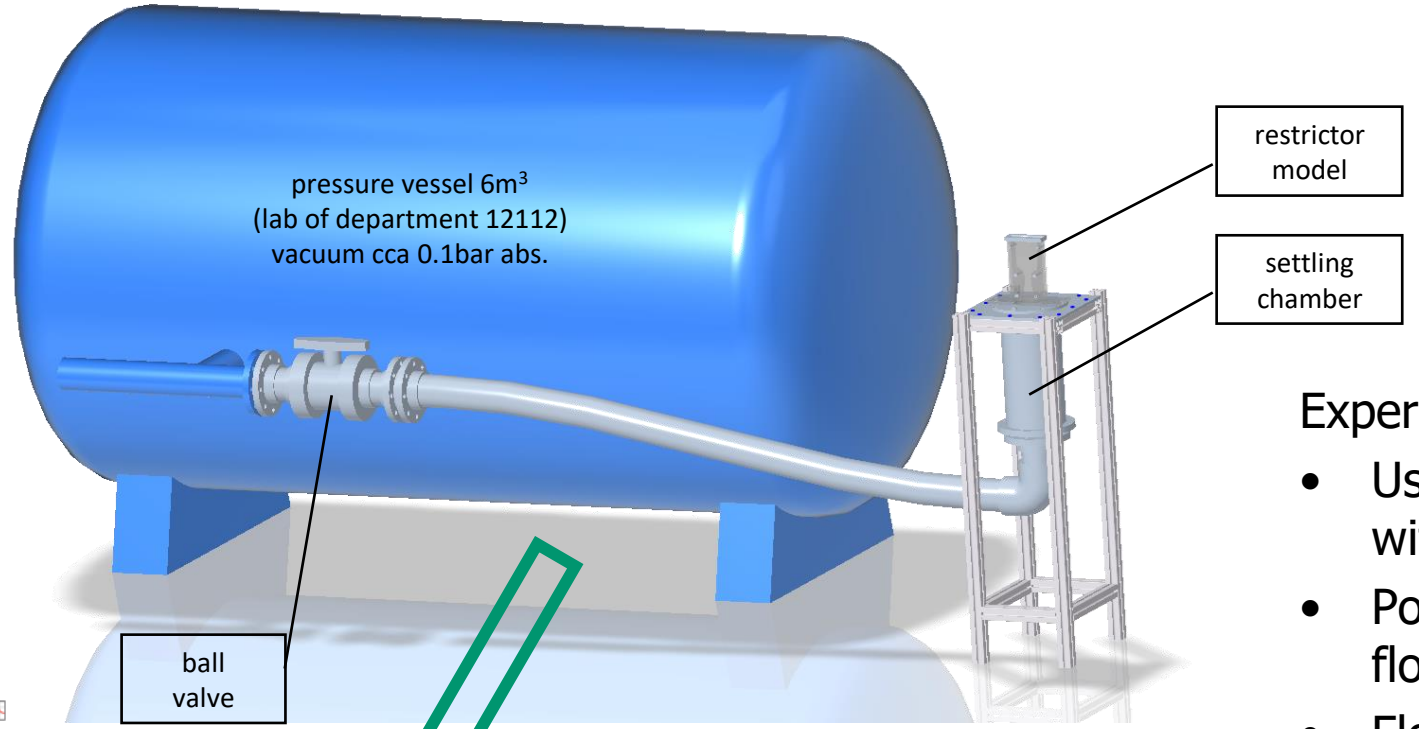
4-WP03-002: Optimized restrictor of the compressor for turbocharged high-power SI ICE

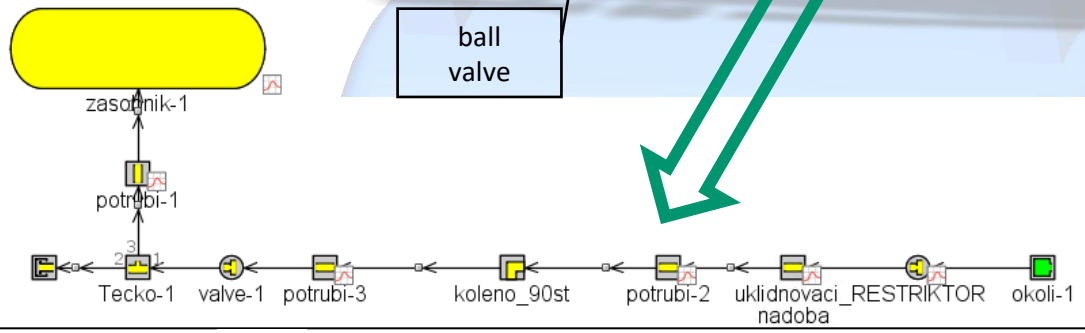
- Finding the causes of flow separation and possible ways to eliminate or minimize it and reduce the input losses in the restrictor.
- Flow mapping on the restrictor model
- New simple experimental test bench with the possibility of achieving a choked flow
- Design of restrictor with shape modifications based on the results of numerical simulations and experiments.
- Experimental verification on the real turbocharged engine with unsteady pressure measurement.



Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-002: Optimized restrictor of the compressor for turbocharged high-power SI ICE



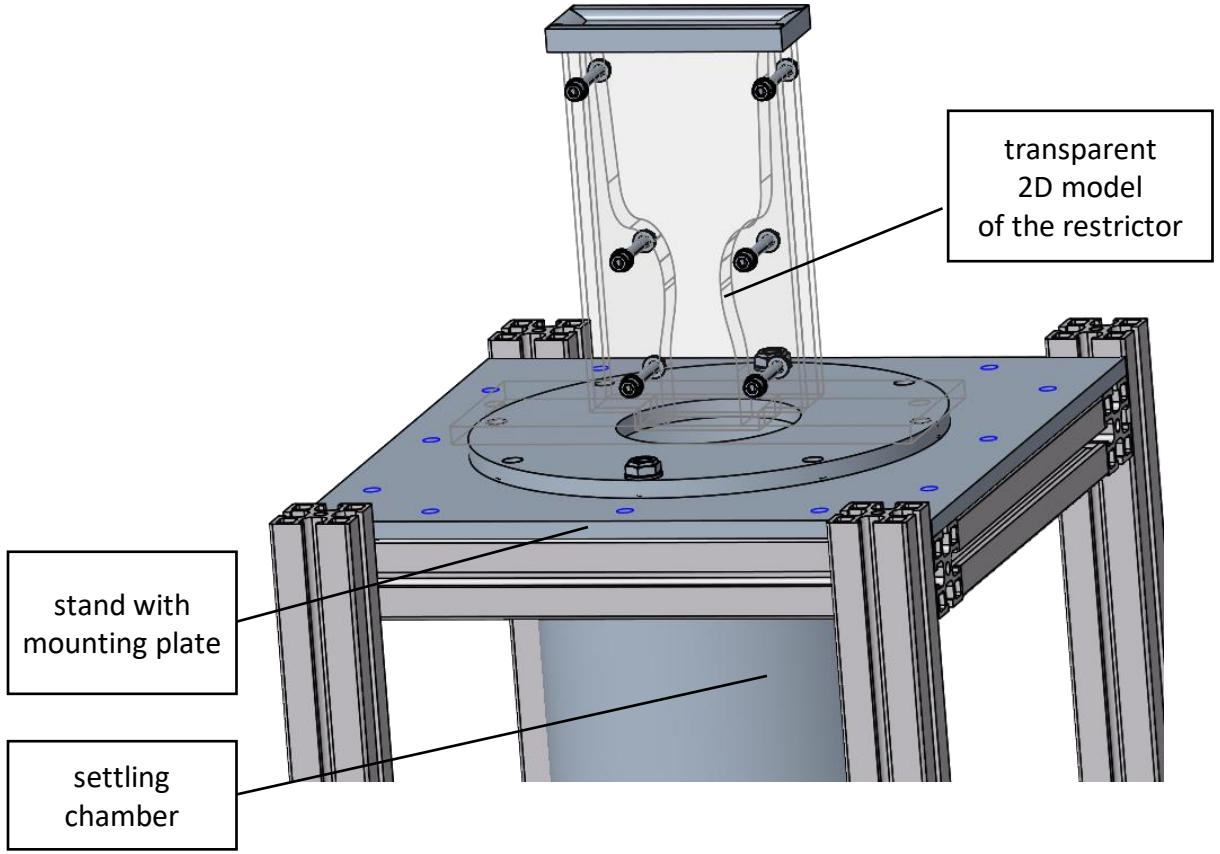


Experimental test bench:

- Use of existing pressure vessel with the vacuum pump
- Possibility of achieving a choked flow
- Flow model in GT-Power
- Estimated operating time in critical condition approx. 20 s

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-002: Optimized restrictor of the compressor for turbocharged high-power SI ICE



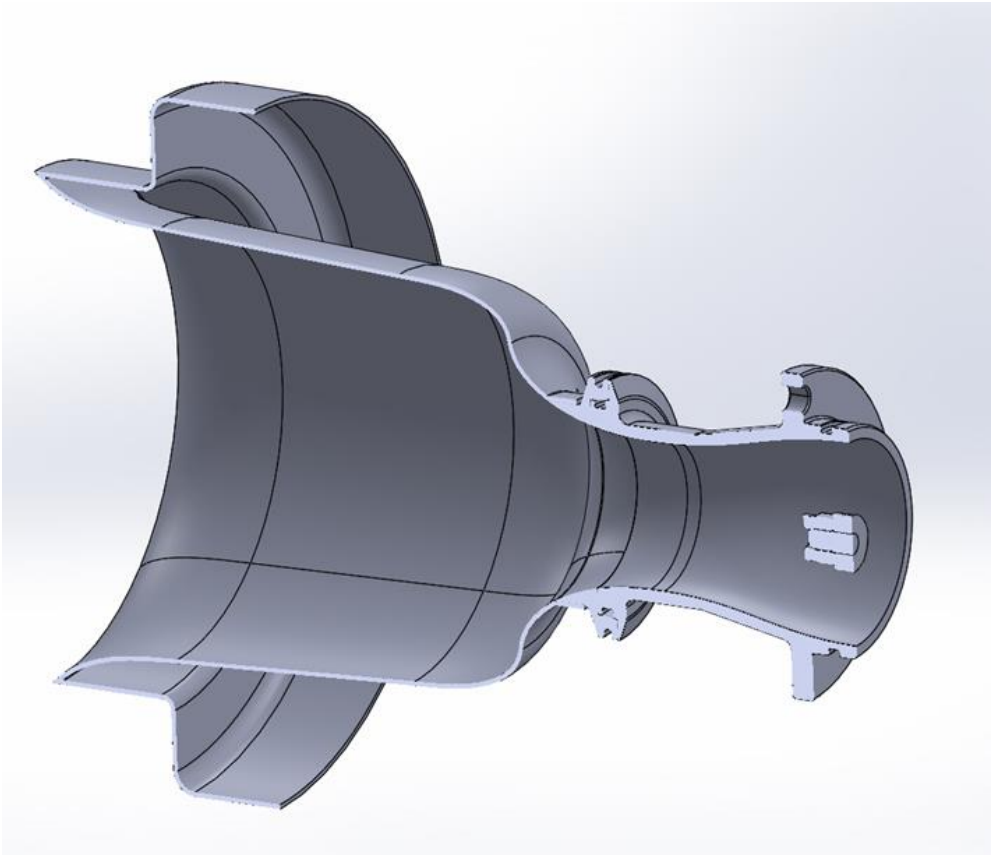
Experimental test bench:

- Stand with mounting plate and settling chamber allows mounting of variant models of the restrictor (2D i 3D)
- 2D model advantages – possibilities of flow visualisation:
  - Shadow or Schlieren method - changes in density of fluid - detect shock waves.
  - Pressure sensitive paint – wall pressure measurement
- 2D model disadvantage – 2D flow measurements cannot be directly converted to the 3D case

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-003: Database of subsonic flow simulations

- Two own numerical method developed in last years:
  - Method of J. Fürst implemented in the OpenFOAM software
  - Method developed by group of employee on own platform Orion for finite volume method
- Finite volume method on hybrid unstructured grids
- Averaged Navier-Stokes equations with different turbulent models (SST)
- Possibility to include laminar and transition part of boundary layer (transition and turbulence model)

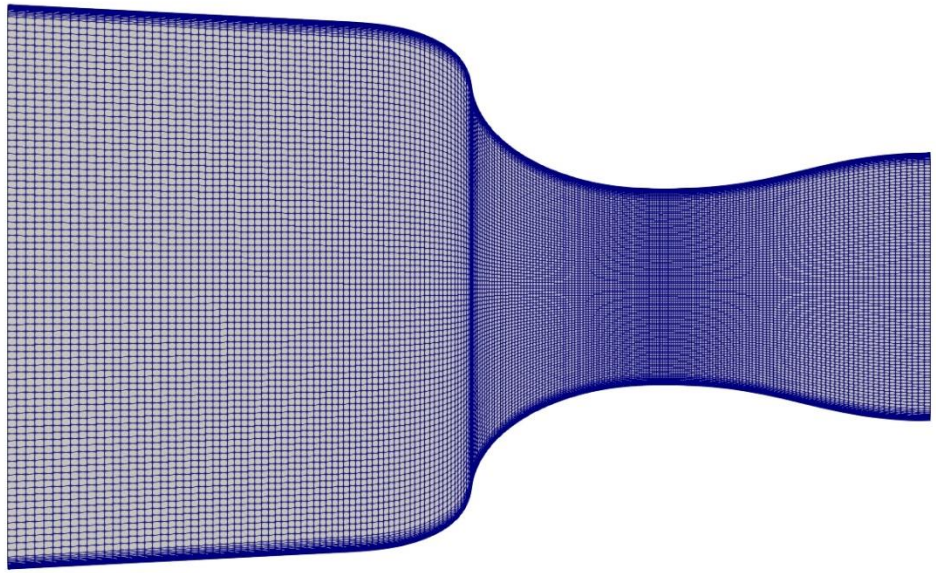


- The restrictor geometry and the upstream calming chamber obtained in cooperation with Škoda Motorsport
- Related to preparing experiment of fast non-stationary pressure measurement – 2D cut
- Transonic flow regime

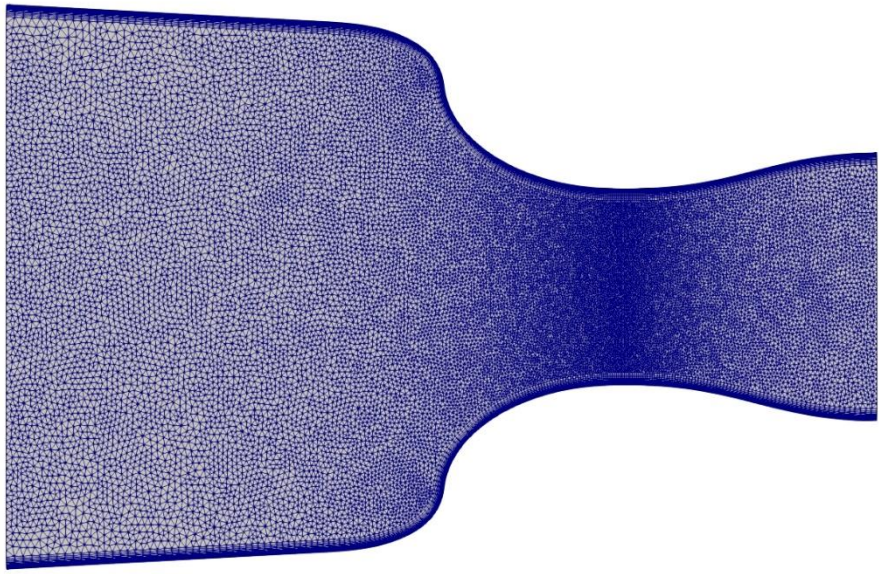
Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-003: Database of subsonic flow simulations

Computational grids



(A) Quadrilateral grid

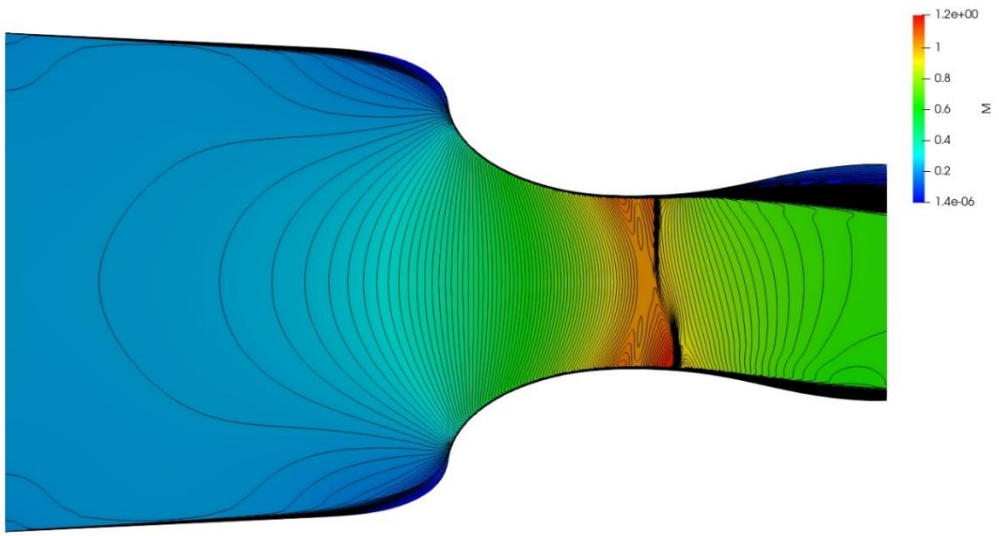


(B) Hybrid grid

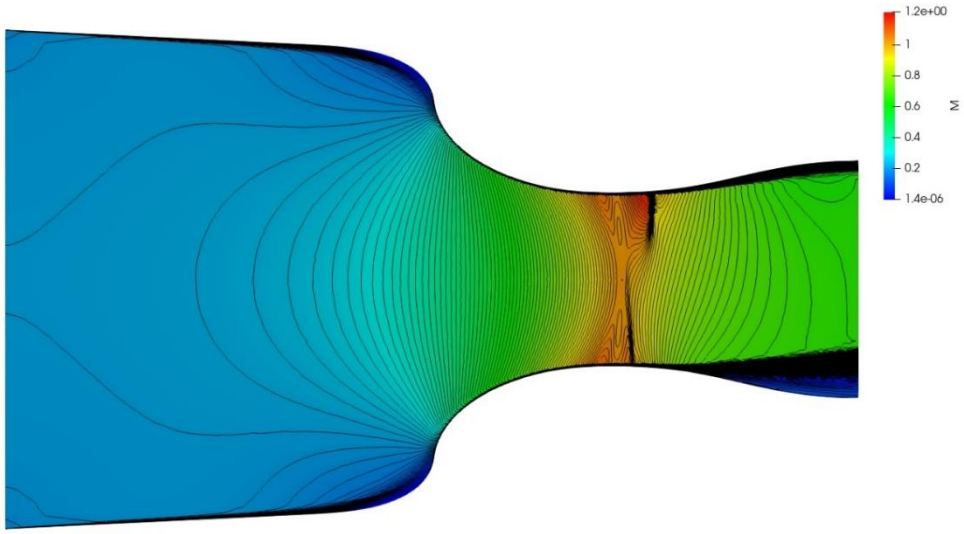
Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-003: Database of subsonic flow simulations

SST turbulence model



(A) Isolines of Mach number – grid A



(B) Isolines of Mach number – grid B

- Asymmetric flow with separation
- Unstable position of flow separation upper-lower boundary
- Simulation **converges** to the stationary state

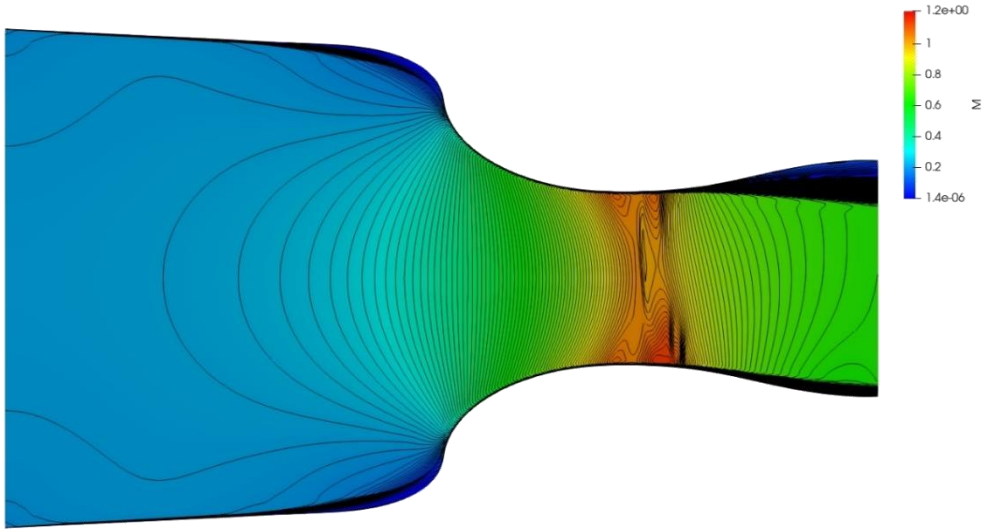
Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-003: Database of subsonic flow simulations

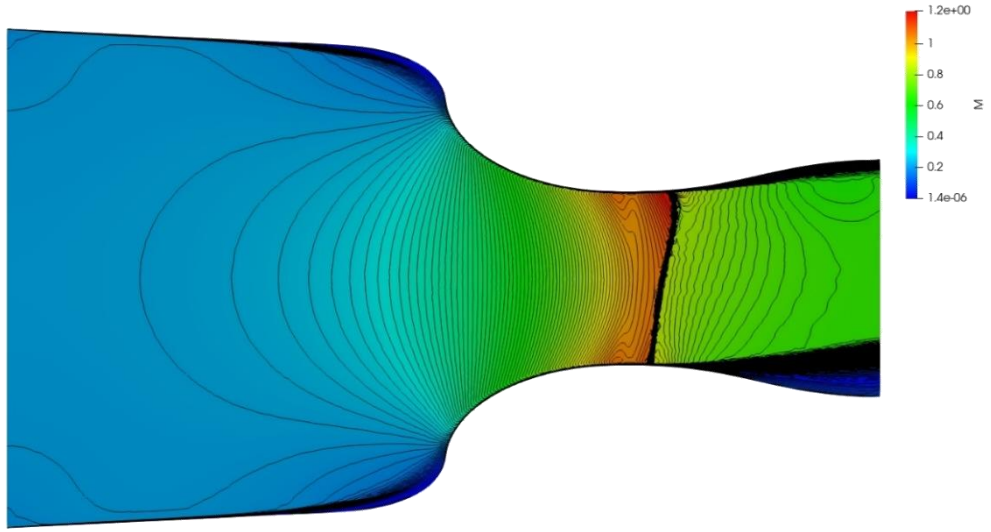
y-SST turbulence model

Three equations model - intermittency coefficient γ:

- γ = 1 ... fully turbulent flow
- γ = 0 ... fully laminar flow (boundary layer)



(A) Isolines of Mach number – grid A



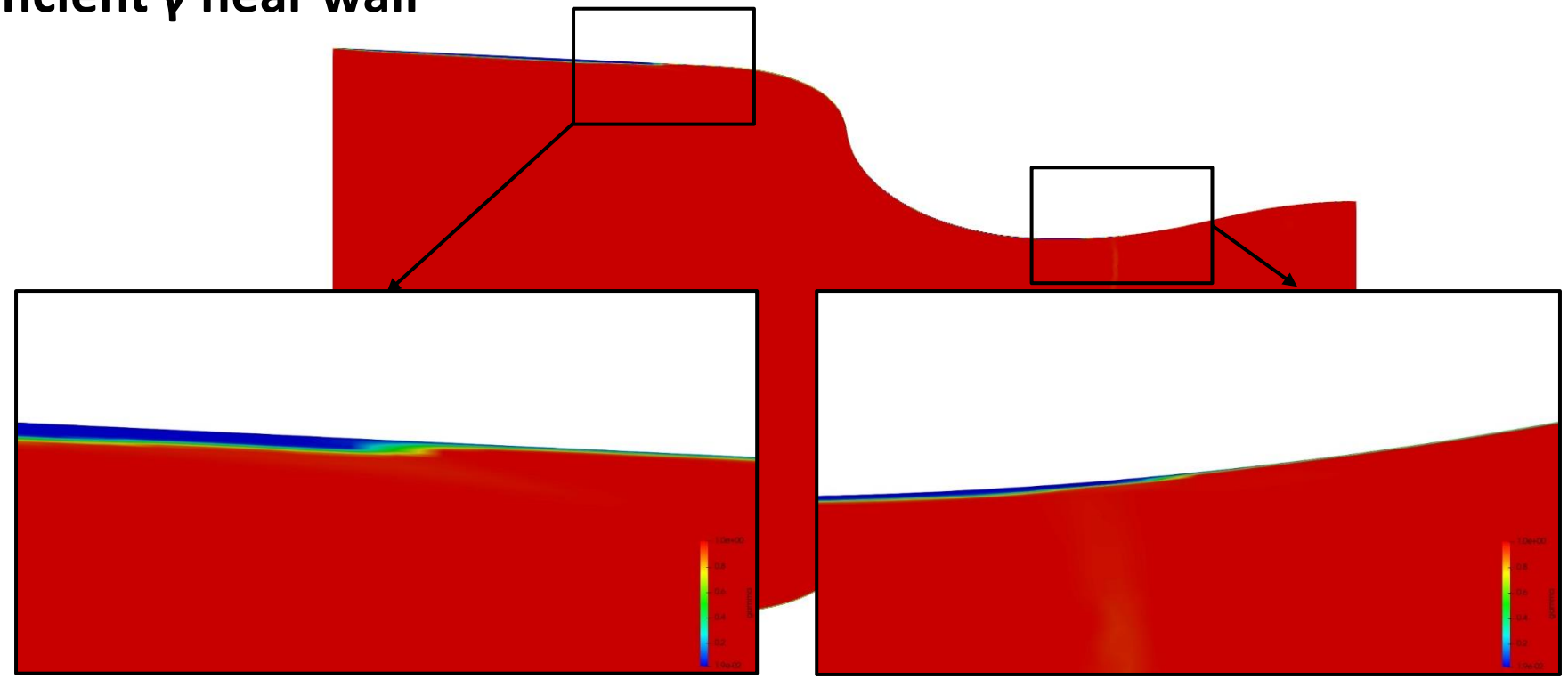
(B) Isolines of Mach number – grid B

- Asymmetric flow with separation
- Unstable position of flow separation upper-lower boundary
- Simulation **does not converge** to the stationary state

Activities in 4-WP03 Solutions for Flow Component/System Testing and Analysis

4-WP03-003: Database of subsonic flow simulations

Detail of coefficient γ near wall



- Possible re-laminarization of boundary layer
- Unstable interaction of shock wave with boundary layer

Fulfillment of goals and deliverables of 4-WP03 Solutions for Flow Component/System Testing and Analysis

Current State of Deliverables and Fulfillment of Goals

- 4-WP03-001 | Test bench for hydrogen fuel cell system components,
  G-funk, XII./2025, CTU 0.5; EATON 0.5 – **in progress & no major delays:**
  - P&ID design, specific components quotations,
  - 1-D thermodynamics simulations (virtual test bench), working conditions assessment (physical limits specifications)
  - Preparation of the 3-D CFD model of the humidification
  - Preliminary 3D CAD design

- 4-WP03-002 | Optimized restrictor of the compressor for turbocharged high-power SI ICE,
  G-funk, XII./2025, CTU 0.5; SKODA AUTO 0.5 – **in progress & no major delays:**
  - Design of experimental equipment for measurements on models and real restrictors at real pressure drop and real velocities - assembly is in progress
  - 2D model of the restrictor - designed and manufactured
  - preparation for verification measurements

Fulfillment of goals and deliverables of 4-WP03 Solutions for Flow Component/System Testing and Analysis

Current State of Deliverables and Fulfillment of Goals

- 4-WP03-003 | Database of subsonic flow simulations,
  O, XII./2025, CTU 0.95; SKODA AUTO 0.05 – **in progress & no major delays:**
  - Simulation of flow fields in restrictor with respect to considered experimental verification
  - Creation of the simulation results database

List of Due Deliverables and Their Added Value

Current contribution of 4-WP03 Solutions for Flow Component/System Testing and Analysis

Assessment of the Contribution of Deliverables

- Fuel Cells and Energy Management for Future Vehicles: 4-WP06
- New ICE Combustion Concepts: 3-WP07
- ICE turbocharging: 3-WP05 a 3-WP06

Current contribution of 4-WP03 Solutions for Flow Component/System Testing and Analysis

Assessment of the Formal/Administrative Goals of the Work Package

	CTU	EATON	SKODA AUTO
Finances (reporting/spending)	OK	OK	OK
Commercialization (the whole organization)	OK	OK	OK
Deliverables	OK	OK	OK

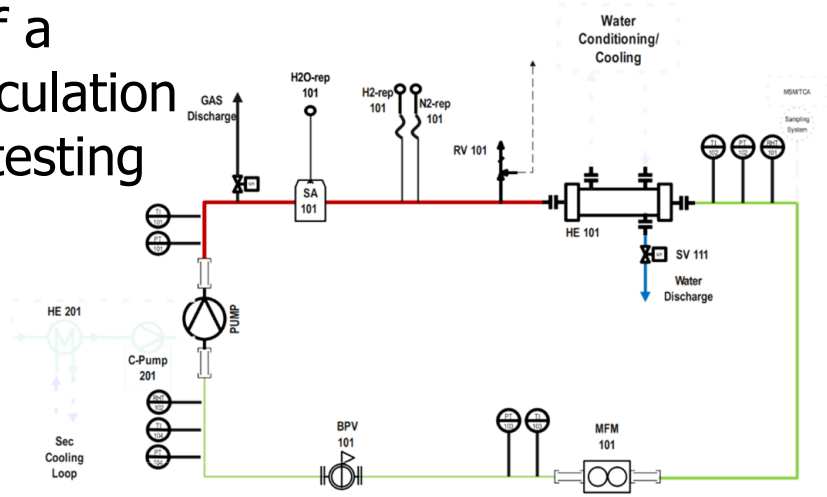
Current contribution of 4-WP03 Solutions for Flow Component/System Testing and Analysis

Acknowledgment

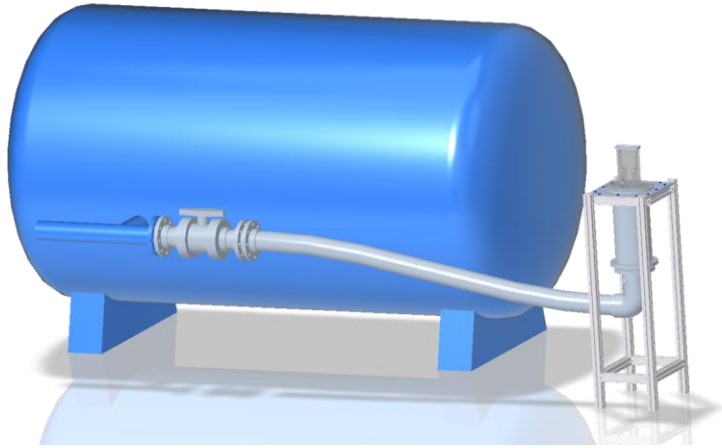
This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

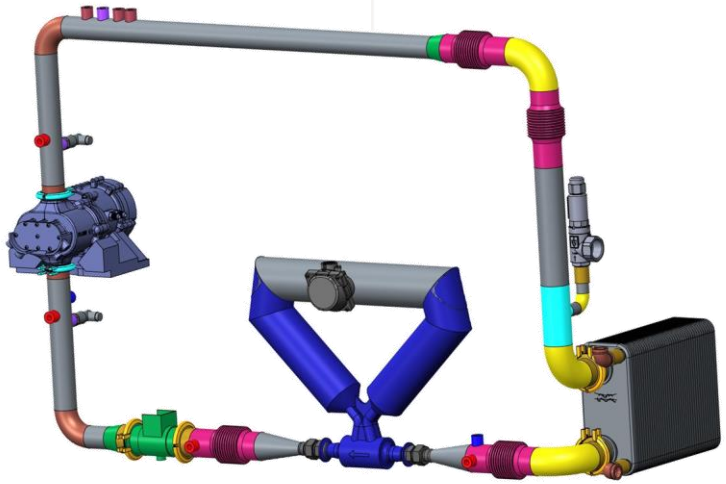
Výtah z prací 2023 na 4-WP03 Řešení pro testování a analýzu komponent průtokových systémů

P&ID design of a hydrogen recirculation blower (HRB) testing loop



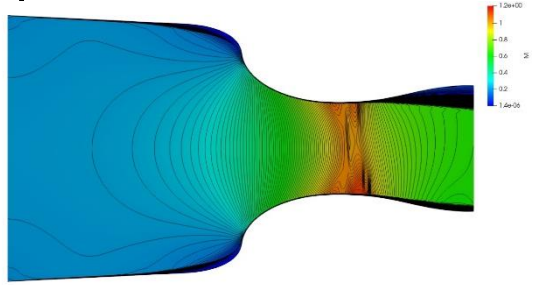
Zkušební trať pro exp. optimalizaci restriktoru

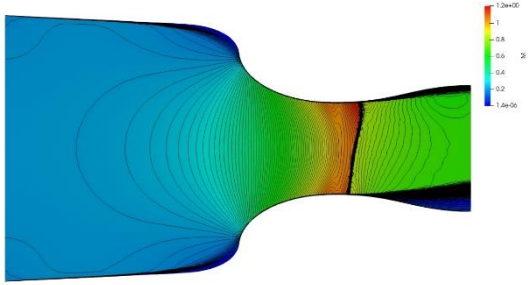




Preliminary 3D CAD Design of a HRB testing loop

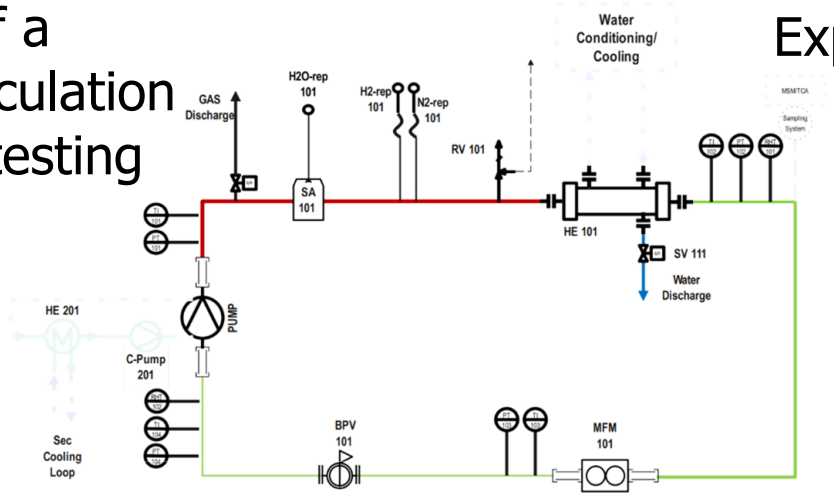
Simulace proudění v restriktoru s ohledem na experimentální ověření



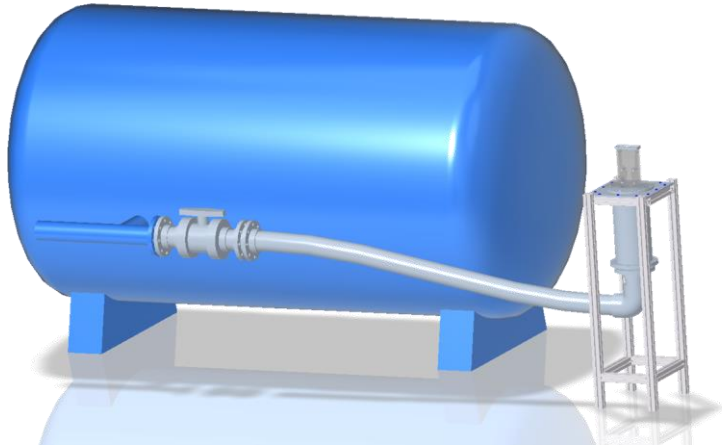


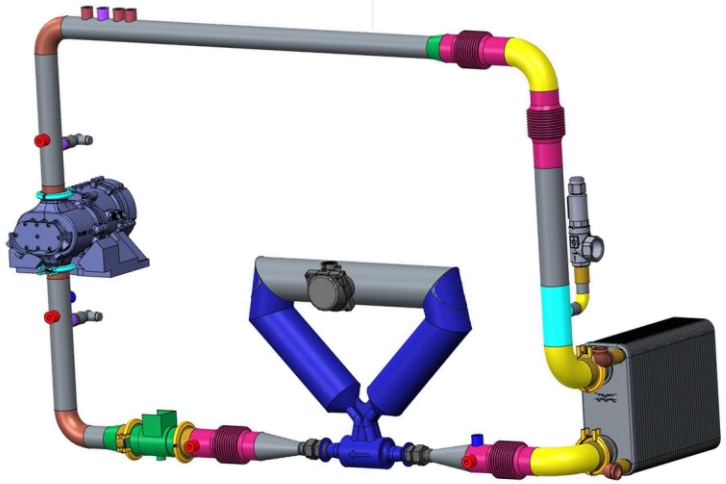
Results of 4-WP03 Solutions for Flow Component/System Testing and Analysis – achieved 2023

P&ID design of a hydrogen recirculation blower (HRB) testing loop



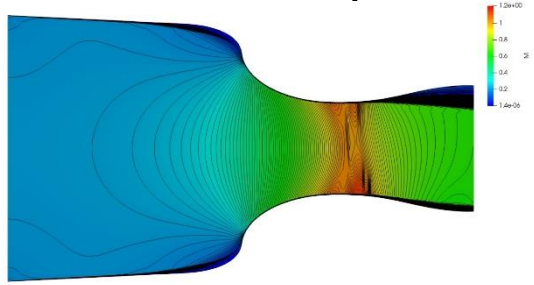
Experimental test bench for restrictor optimisation

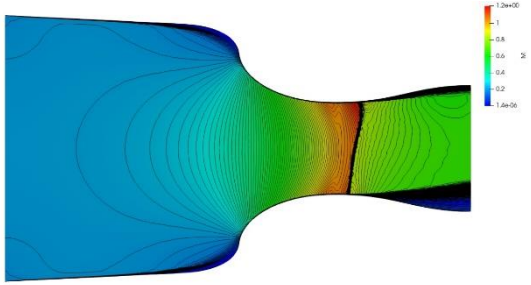




Preliminary 3D CAD Design of a HRB testing loop

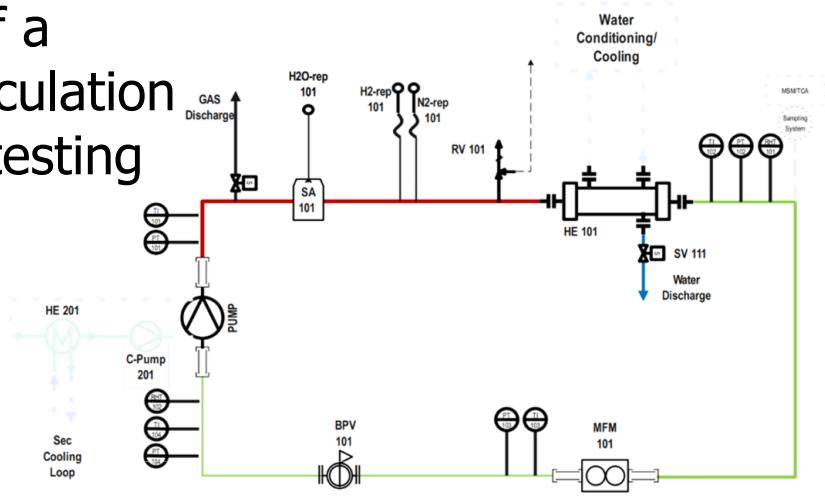
Simulation of flow fields in restrictor with respect to considered experimental verification



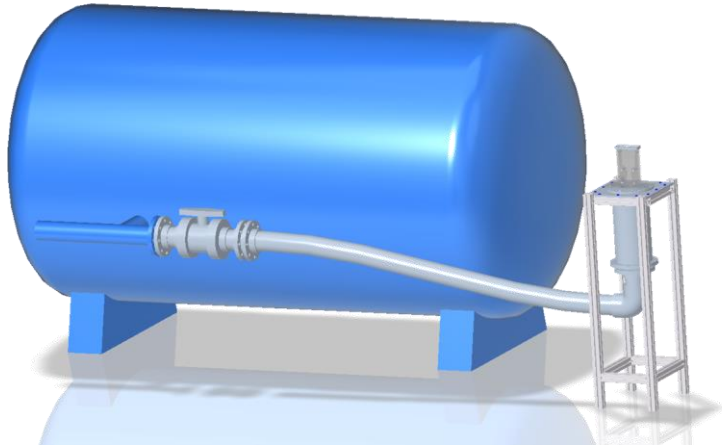


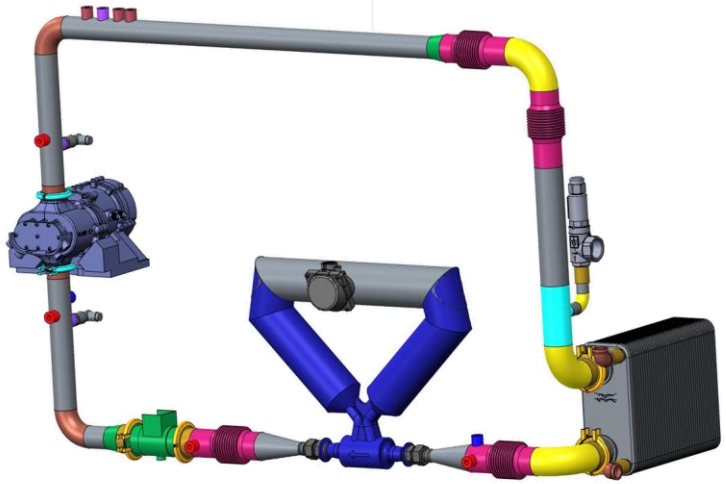
Výtah z prací 2023-2025 na 4-WP03 Řešení pro testování a analýzu komponent průtokových systémů

P&ID design of a hydrogen recirculation blower (HRB) testing loop



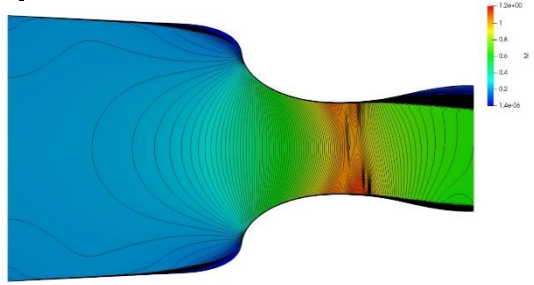
Zkušební trať pro exp. optimalizaci restriktoru

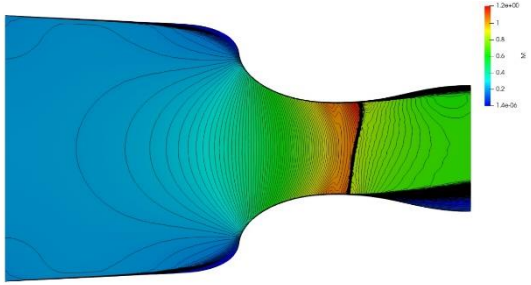




Preliminary 3D CAD Design of a HRB testing loop

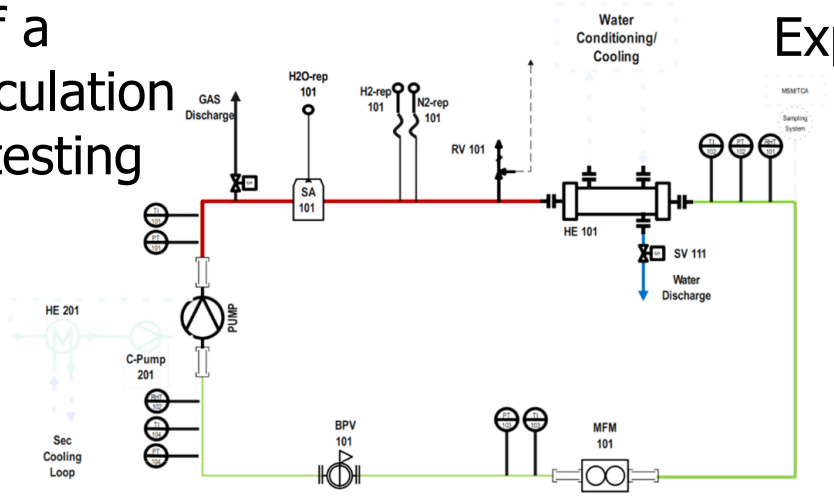
Simulace proudění v restriktoru s ohledem na experimentální ověření



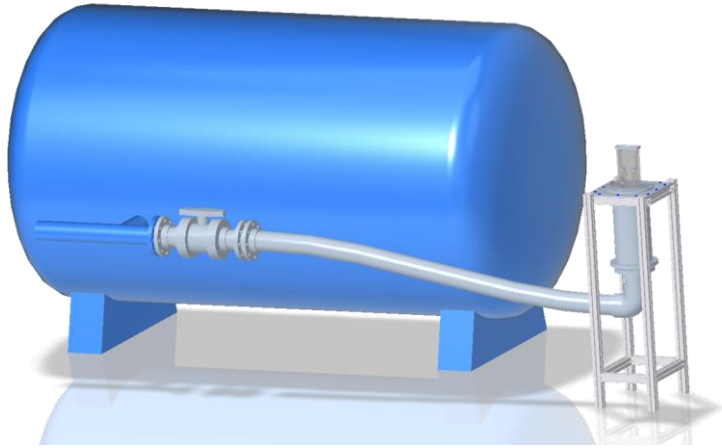


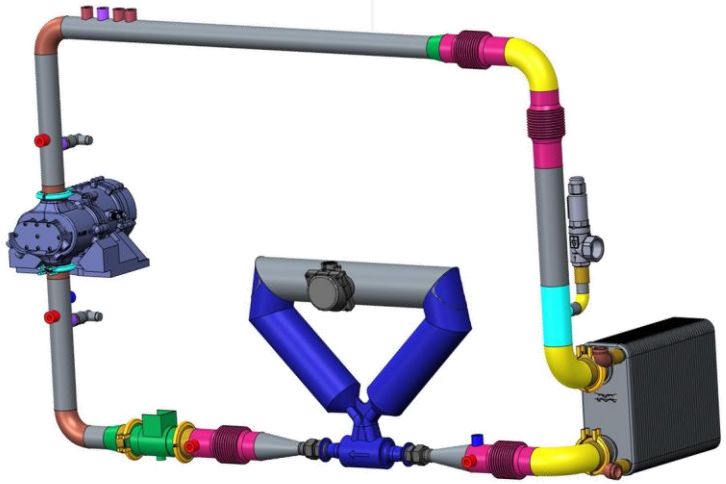
Results of 4-WP03 Solutions for Flow Component/System Testing and Analysis – achieved 2023-2025

P&ID design of a hydrogen recirculation blower (HRB) testing loop



Experimental test bench for restrictor optimisation





Preliminary 3D CAD Design of a HRB testing loop

Simulation of flow fields in restrictor with respect to considered experimental verification