

**University of Stuttgart**

Institute of Thermal Turbomachinery and  
Machinery Laboratory

**WP4 - Cryogenics**

# Turbocompressor test facility operating with Helium mixtures and heat transfer effect

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- 1 Introduction
- 2 Helium test rig
- 3 Heat transfer effect
- 4 Conclusion and outlook

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## One of WP4's objective:

- **Efficient and sustainable precooling cycle** for the FCC

## Made possible by:

- A **Closed-loop cryogenic cycle**
- Replacing screw compressor by **turbocompressor**
- Operating with **Nelium** mixtures

## Axis of research:

- **Turbocompressor** operating with **light gases**
- **Test facility** to validate compressor performance

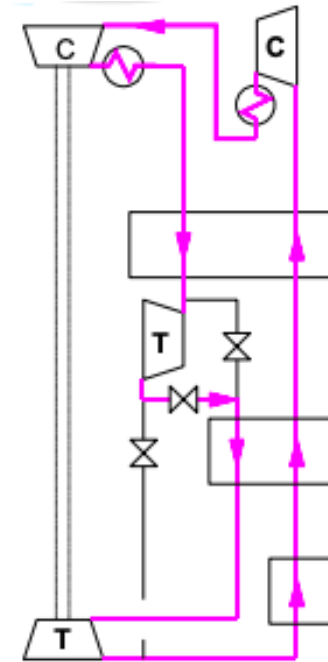
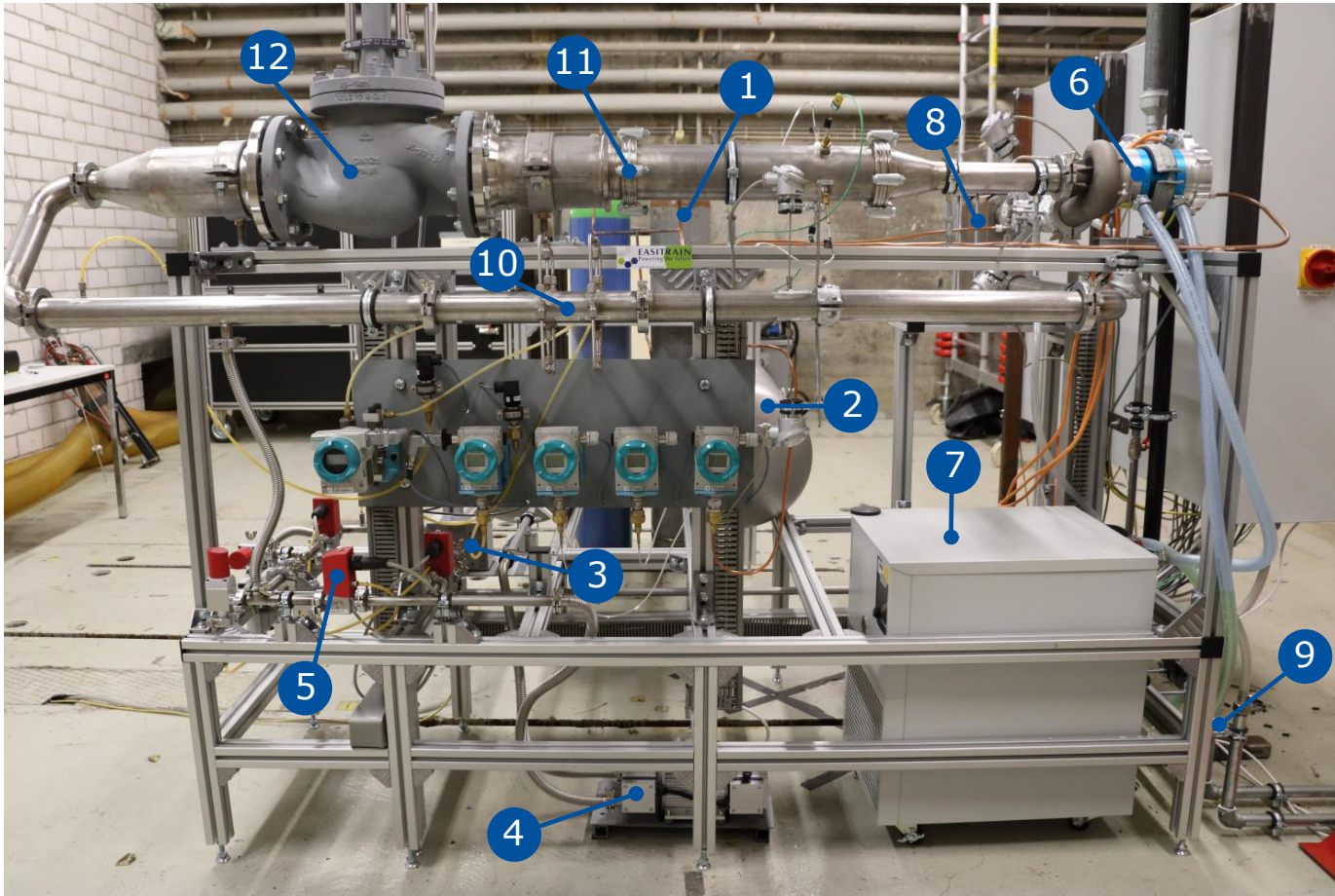


Fig. 1 FCC precooling cycle  
(Operating with Nelium mixtures)

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- ① Gas bottles
- ② Buffer tanks
- ③ Gas analyser
- ④ Pump
- ⑤ On/off valves
- ⑥ Turbocompressor
- ⑦ Cryostat
- ⑧ Heat exchanger
- ⑨ Water throttle valve
- ⑩ Venturi flow meter
- ⑪ Flow conditioner
- ⑫ Gas throttle valve

Fig. 2 Picture of the Nelium test rig

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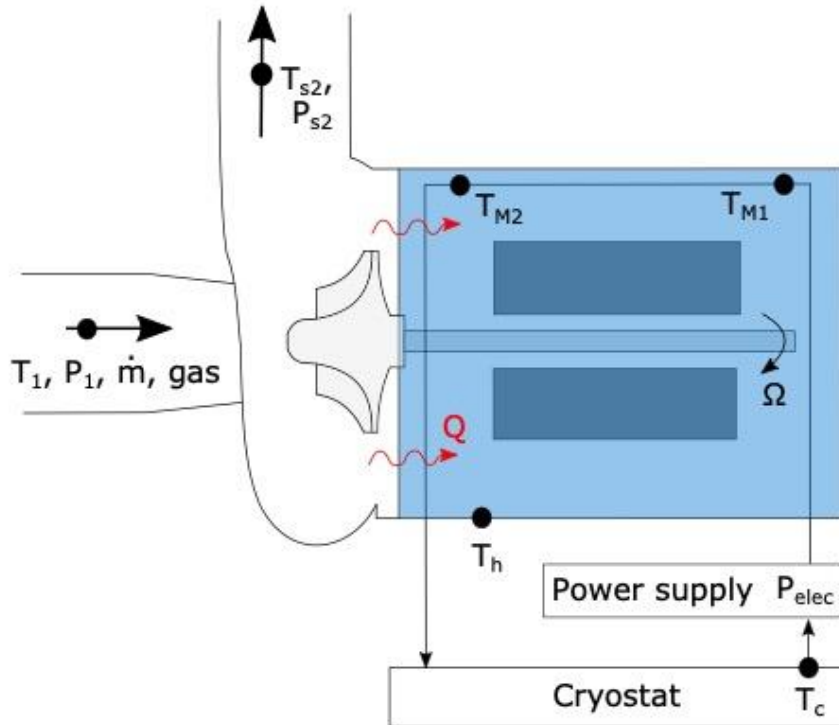


Fig. 3 Compressor stage with occurring heat transfer

- Reduction of outlet stage temperature and increase of stage efficiency
- Efficiency difference decreases with  $M_{U2}$  and  $\dot{m}$

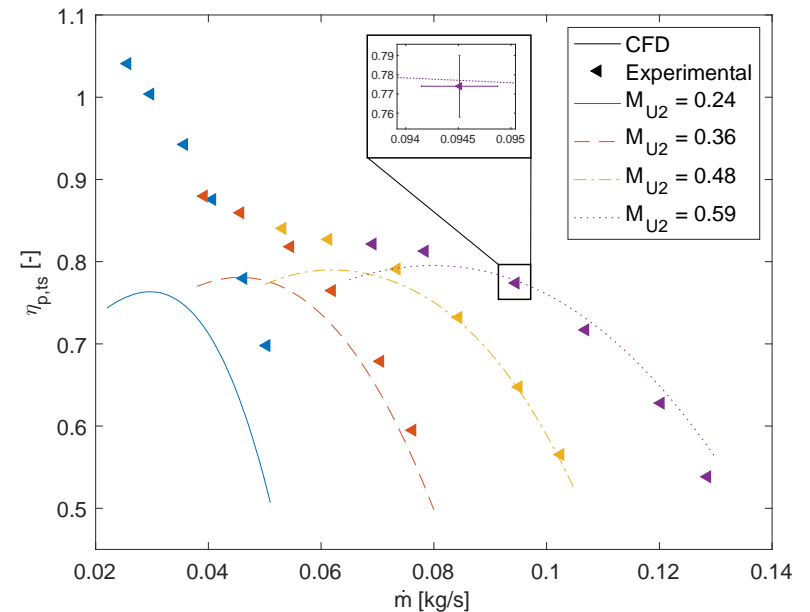


Fig. 4 Experimental and numerical efficiency for air operation

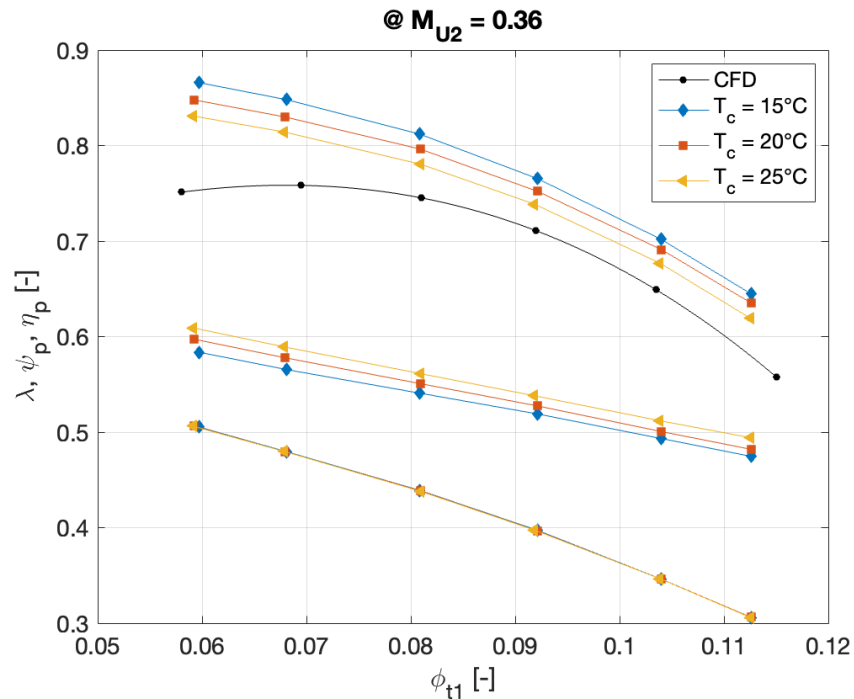


Fig. 5 Effect of cryostat temperature on measured efficiency, work input and pressure rise

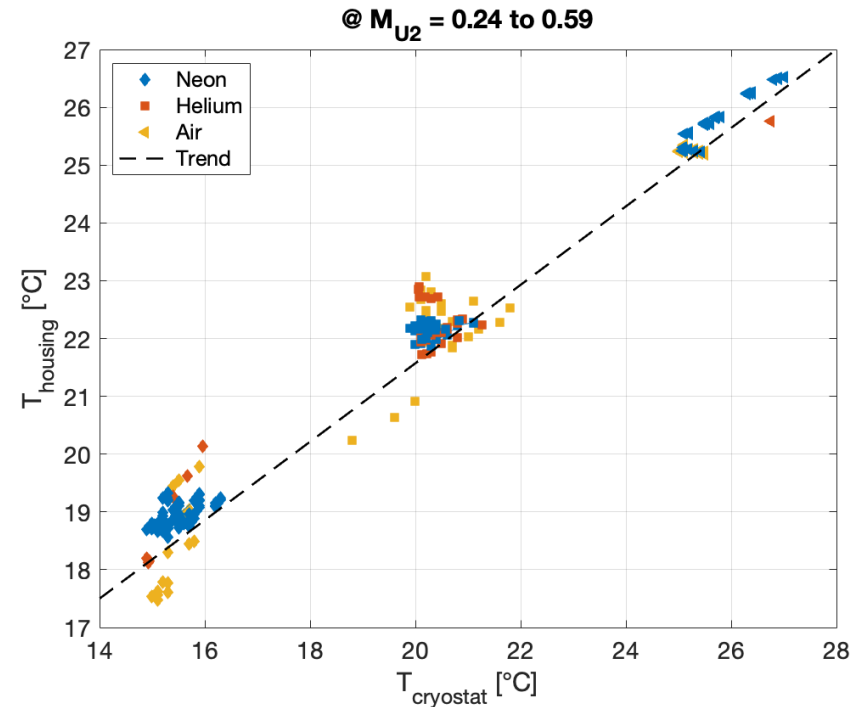
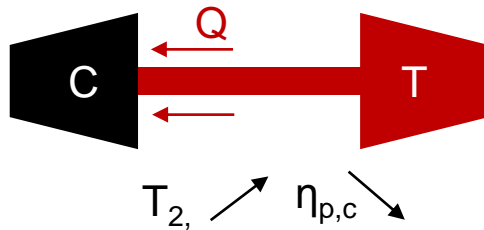


Fig. 6 Measured housing temperature with respect to cryostat temperature

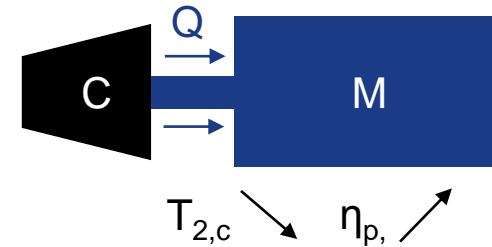


- Heat transfer does not affect the stage pressure rise
- Motor housing temperature varies linearly with cryostat temperature

## Parallel with turbocharger application



$Q$  highly dependent on hot gas temperature



$Q$  highly dependent on coolant temperature

## Literature review on heat transfer correction applied to turbocharger

- 1 Based on standard heat transfer equation dominated by force convection  
Heat transfer coefficient (Nusselt number) calibrated with reference performance map
- 2 Assume constant heat transfer for fixed geometry and hot gas temperature  
Uses fundamentals of compressor performance

## Model (Sirakov and Casey (2013))

- Apparent work input (diabatic) can be related to the adiabatic work input as follow:

$$\lambda_{ad} - \lambda_{ap} = \frac{q_{12}}{u_2^2} = \frac{\dot{Q}}{\rho_{t1} a_{t1}^3 D_2^2} \frac{1}{\phi_{t1} M_{u2}^3} \quad (1)$$

$$\lambda_{ad} - \lambda_{ap} = \frac{k_c}{\phi_{t1} M_{u2}^3} \quad (2)$$

Where  $k_c$  is assumed to be constant for a specific geometry, gas and coolant temperature

- Based on observation, pressure coefficient remains constant leading to:

$$\eta_{p,ad} = \eta_{p,ap} \frac{\lambda_{ap}}{\lambda_{ad}} \quad (3)$$

**Objective:** determine  $k_c$  so that  $\lambda(\phi_2)$  and  $\sigma(\phi_2)$  remain in two separate narrow bands for all  $M_{u2}$

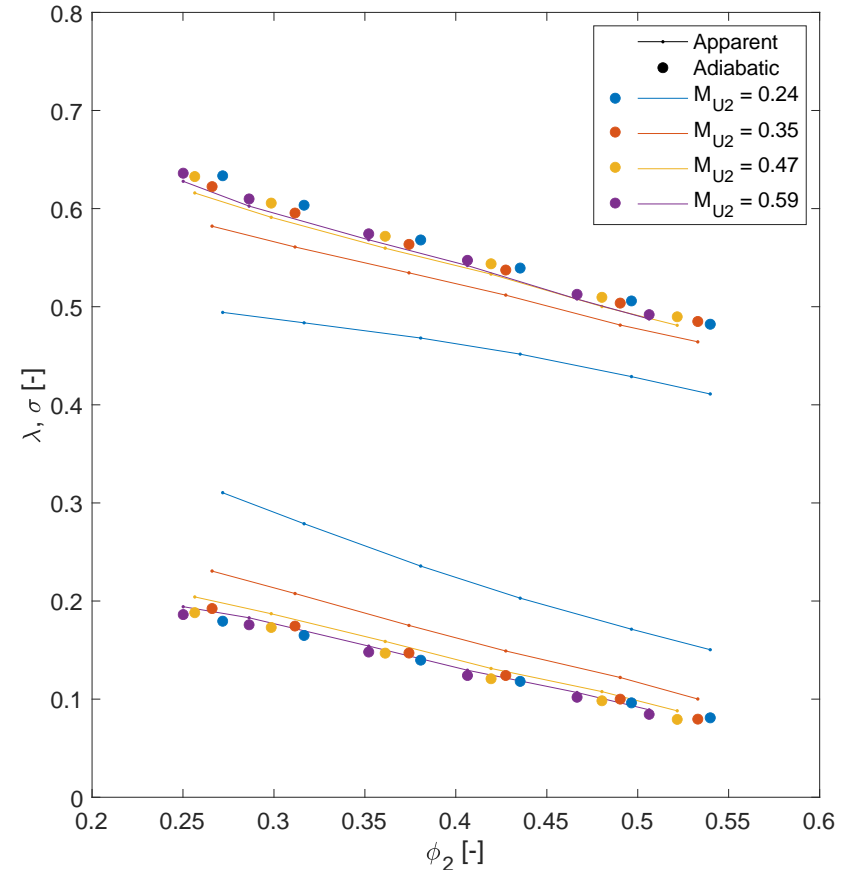


Fig. 7 Apparent and adiabatic work input and slip factor for air operation

## Different gases and coolant temperature

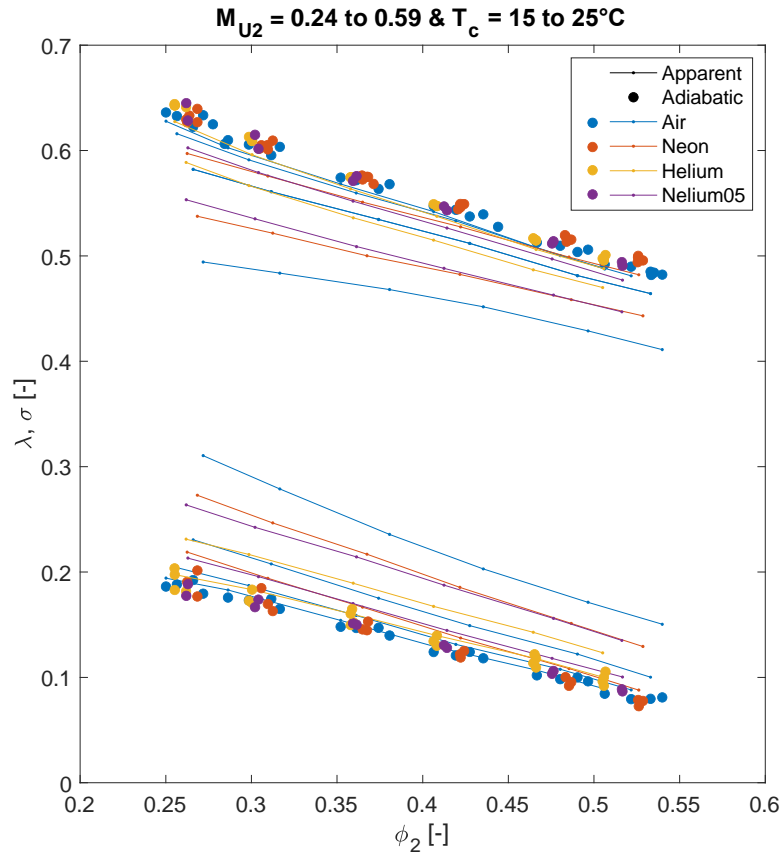


Fig. 8 Apparent and adiabatic work input and slipp factor

	$T_c$	Gas			
		He	Nelium05	Ne	Air
$k_c * 1e-5 [-]$	15°C	5	-	11	15
	20°C	3	5.5	7	10
	25°C	1	-	3	-

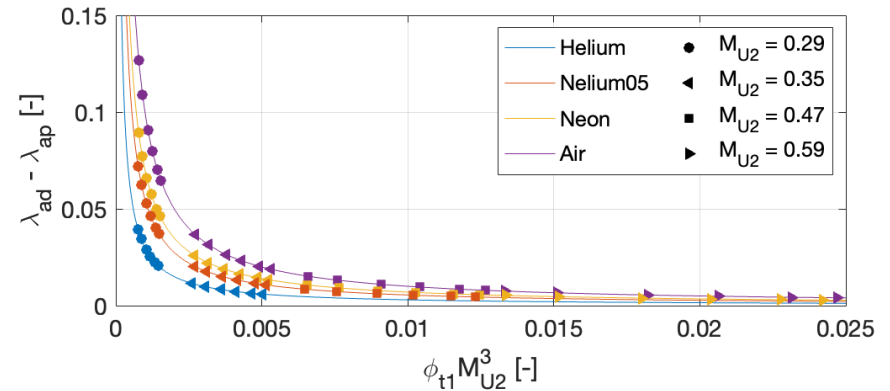


Fig. 9 Work input model correction for various gases (@ $T_c=20^\circ\text{C}$ )

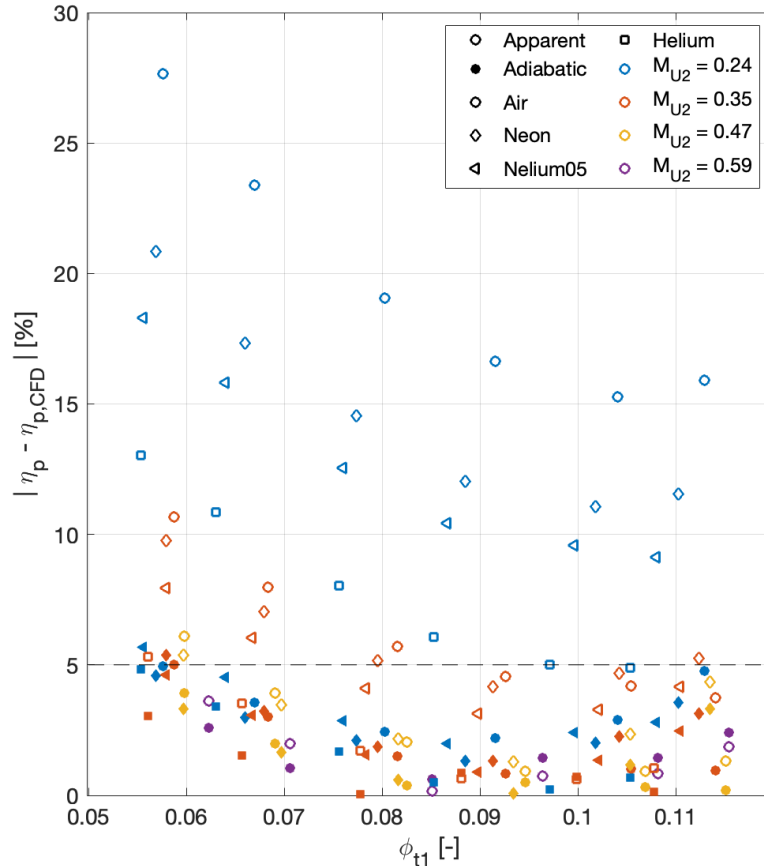


Fig. 10 Difference between experimentally corrected and CFD obtained efficiency

## Conclusion

- Simple approach enabling an error reduction from 27% to below 5% for all operating points and gases
- No need for a reference performance map
- Still discrepantcies near surge and choke

## Strategy to reduce error even further:

- Consider non-constant  $k_c(\phi_{t1}, M_{U2})$
- Dependency on  $M_{U2}$  near surge and choke solved using  $\lambda$  and  $\sigma$  criteria
- Need of a new approach to determine 2  $k_c$  values:

$$k_c(\phi_{t1,surge}) @ M_{U2,d} \text{ \& } k_c(\phi_{t1,choke}) @ M_{U2,d}$$

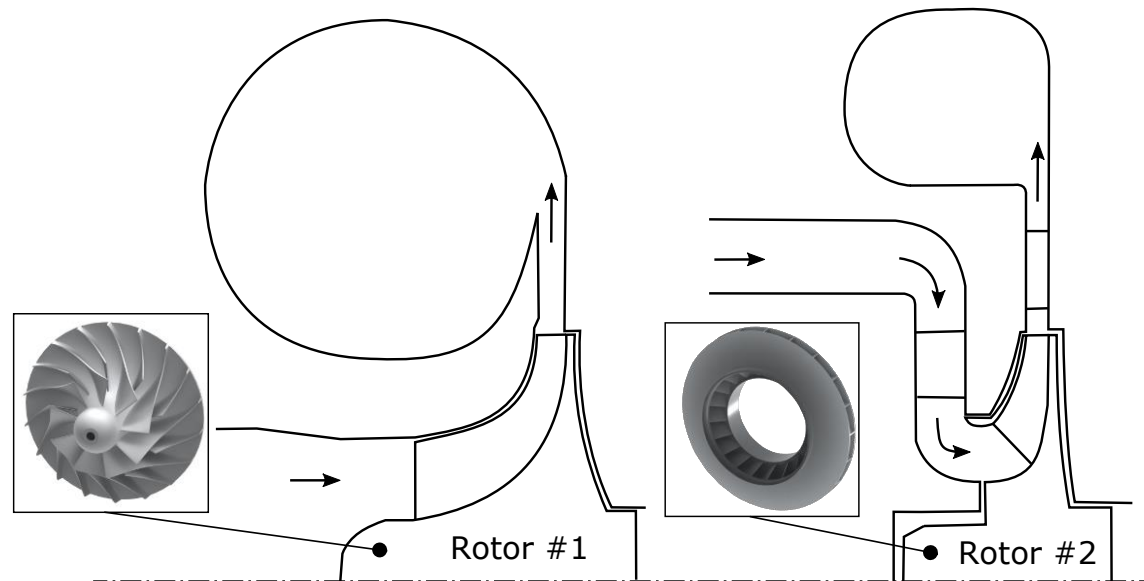
- Efficiency error can be reduced below 2.5%

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## Key results

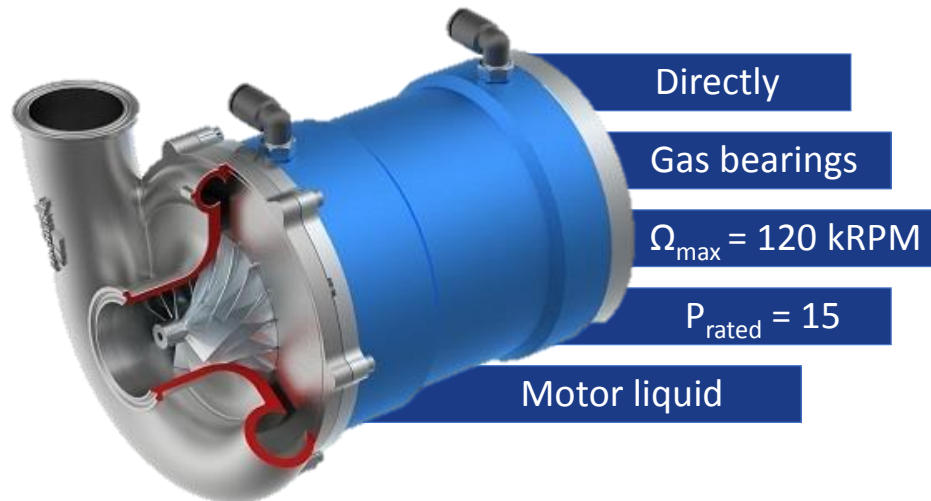
- **Novel experimental test rig** operating with **Nelium** mixtures
- **Model** derived to account for **heat transfer** originating from motor coolant

## Outlook

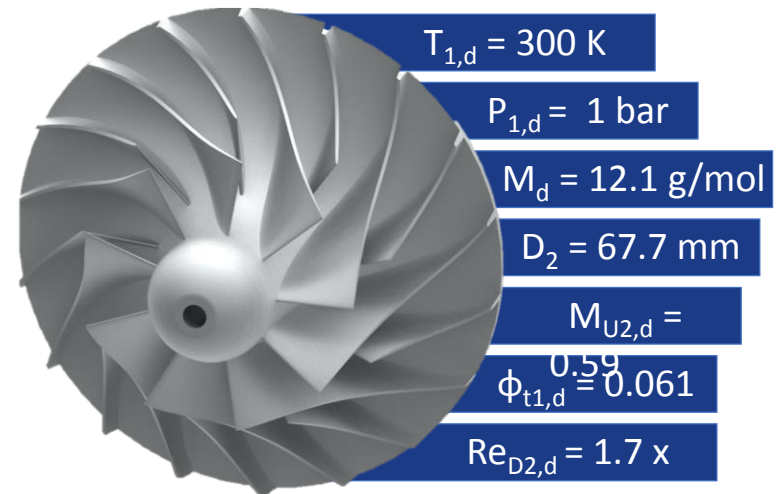




# Compressor design

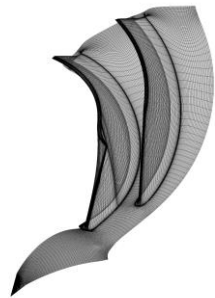


Compressor motor, housing and impeller



Impeller design and geometrical parameters

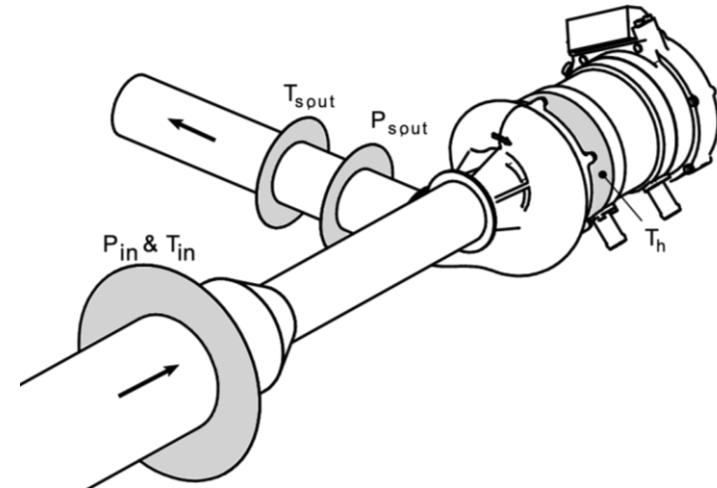
# Numerical set up



Impeller mesh (Structured)



Volute mesh (Unstructured)



Test rig and numerical set up and measuring planes

Equation solved	Reynolds Averaged Navier Stokes
Turbulence model	Spallart Allmaras
Number of cells	5 millions (one sector)
Inlet BC	Total pressure and temperature
Outlet BC	Static pressure

CFD and mesh parameters

# Experimental results with air: pressure ratio

**Why with air?**

$$PR, \eta_p \approx f(\underbrace{MU_2}_{\text{New rotational speed}}, \underbrace{\phi_{t1}}_{\text{New mass flow}}, \lambda, \gamma)$$

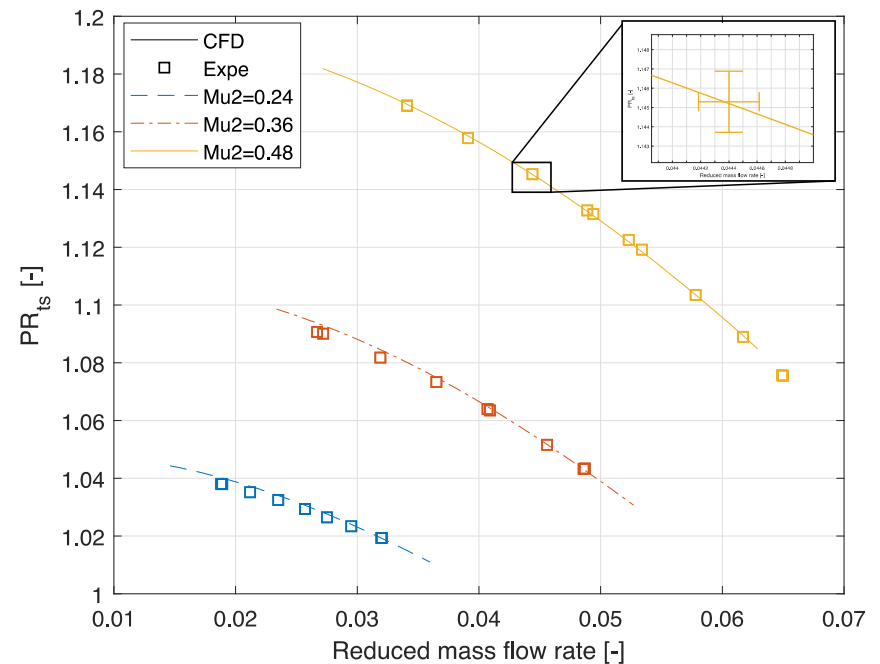
By similitude: can cover all operating points with air

**Example for  $PR_{ts} \approx 1.1$  (@  $M_{U2} = 0.36$ )**

**Air:**  $m = 40.0 \text{ g/s}, \Omega = 35.1 \text{ kRPM}$

**Neon:**  $m = 36.5 \text{ g/s}, \Omega = 45.9 \text{ kRPM}$

**Helium:**  $m = 16.2 \text{ g/s}, \Omega = 103 \text{ kRPM}$



Compressor map with air – Pressure ratio

# Experimental results with all gases:

