Design of a Partial Admission Impulse Turbine for an Automotive ORC-Application

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Outline

1. **Motivation**
2. **Thermodynamic analysis**
3. **Design of the impulse turbine**
4. **Conclusion/Outlook**

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Motivation

Thermodynamic analysis

Design of the impulse turbine

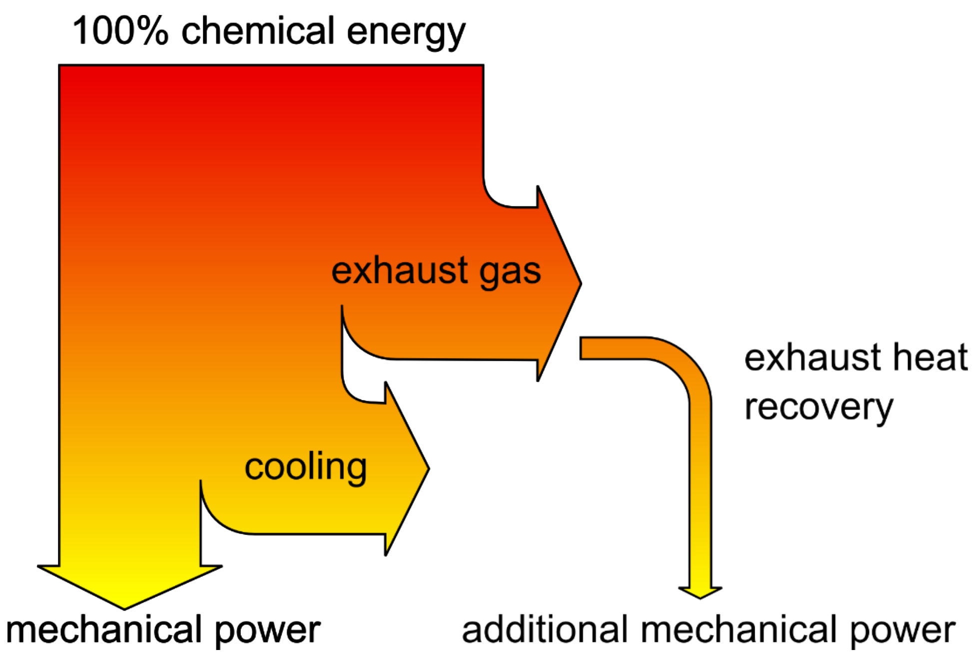
Conclusion

Objectives

Goals of automobile manufacturers:

- Reduction of fuel consumption
- Achieving emission targets

→Increase efficiency of the power-train



Approach:
Energy recovery from the exhaust gas using an Organic Rankine Cycle (high percentage of exergy)
(Span et al. 2011)

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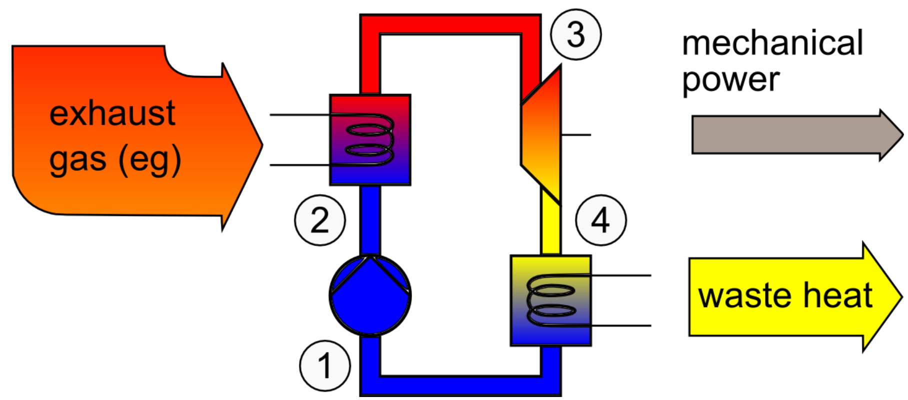
Thermodynamic model and limitations

Truck application; diesel-engine			
	$\dot{m}_{eg}$ [kg/s]	T_{eg} [K]	$\Delta H_{T,eg;343K}$ [kJ/s]
Design point (DP)	0.249	615.15	78.5
Part-load (PL)	0.126	569.15	31.6
Overload (OL)	0.338	630.15	108.4

<u>Model:</u>

- Investigation of the thermodynamic cycle for the design point
- Fluid properties: NIST Database 23 (Lemmon et al.)
- Parameter study (e.g. max. pressure, min. pressure)
- Supposed turbine efficiency: 70%



Limitations of the ORC (predefined)		Criterion
Max. pressure	40 bar	Safety
Min. pressure	0.5 bar	
Min. ΔT heat-exchangers	20 K	Size heat-exchanger
Min. T of condensation	343 K	

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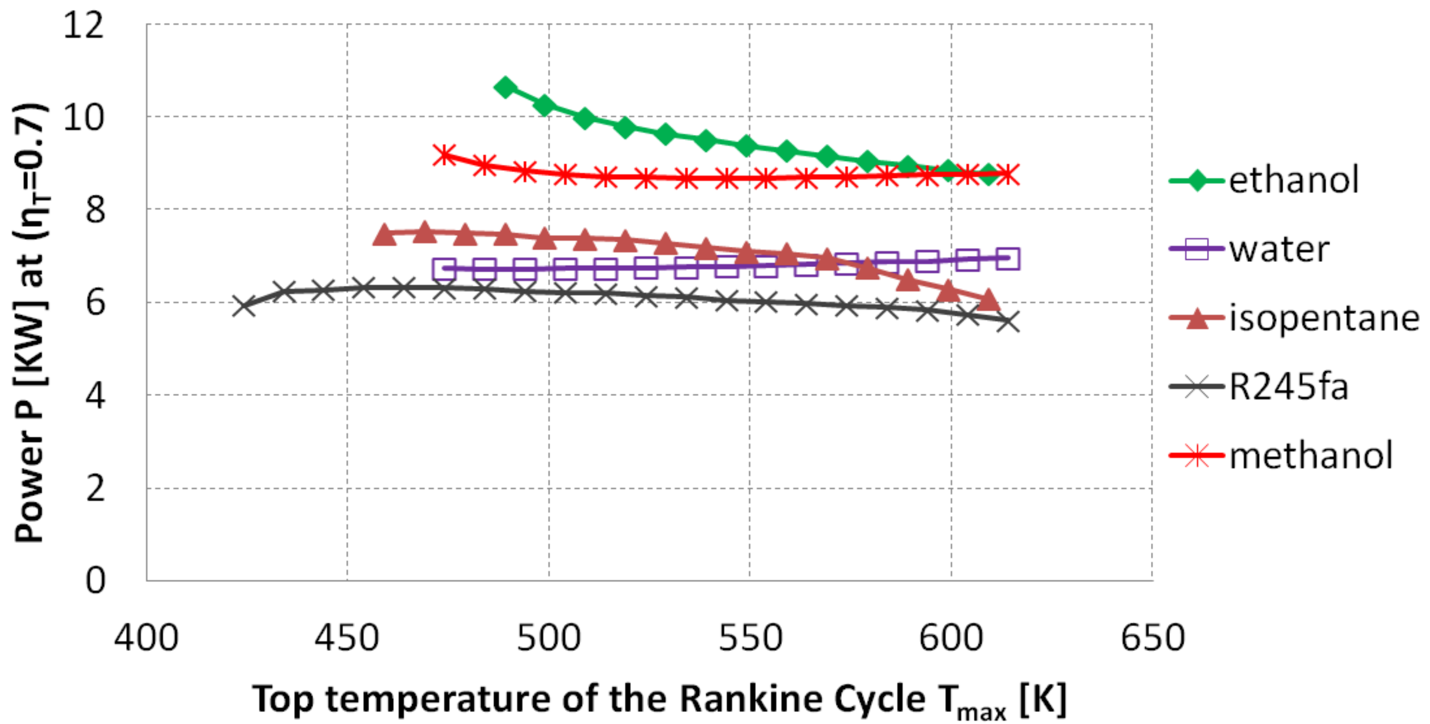
Results of the thermodynamic analysis (DP)



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- Ethanol promises highest power output
- Superheating decreases power output for ethanol

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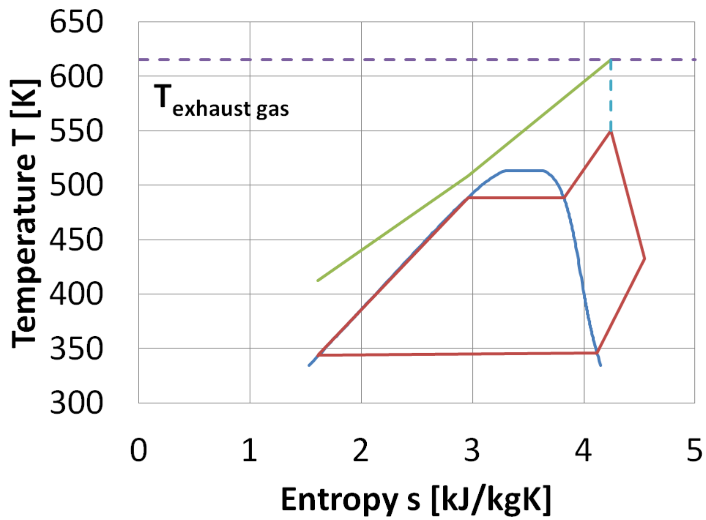
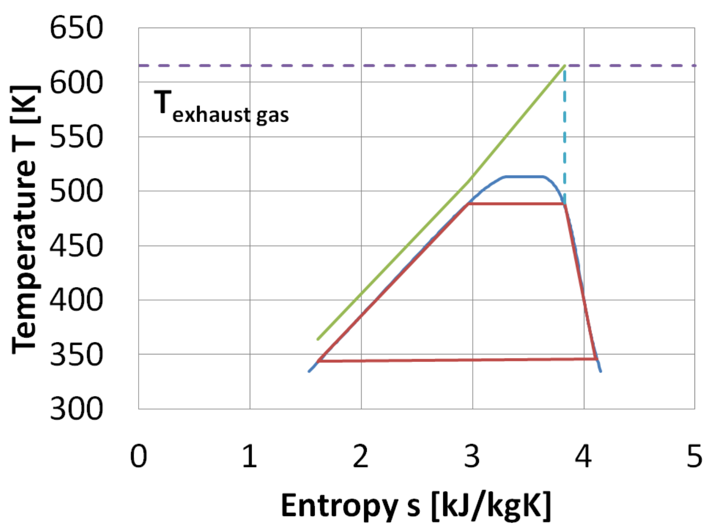
Reason for negative effect of superheating (DP)

Superheated fluid



Fluid without superheating



ORC-Cycle
Condensation line
Exhaust gas temperature

High efficiency of the stator causes an almost isentropic expansion in the nozzles:

In Case of thermal equilibrium

→ Risk of erosion due to droplets

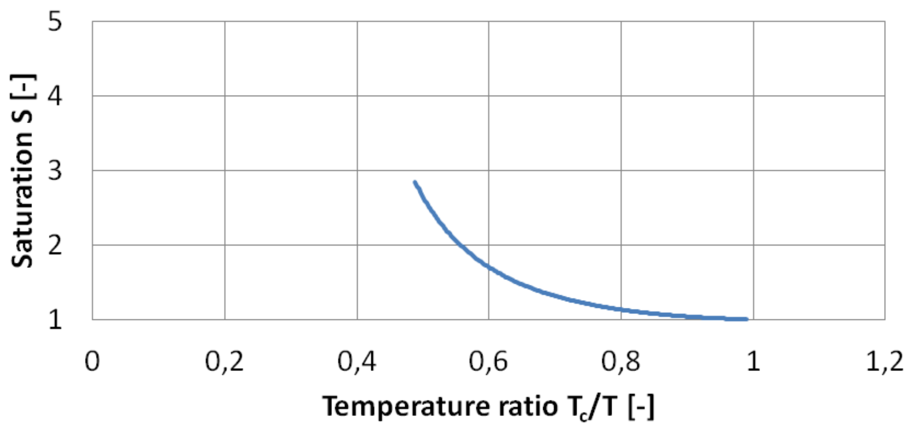
→ Temperature must be raised to avoid erosion

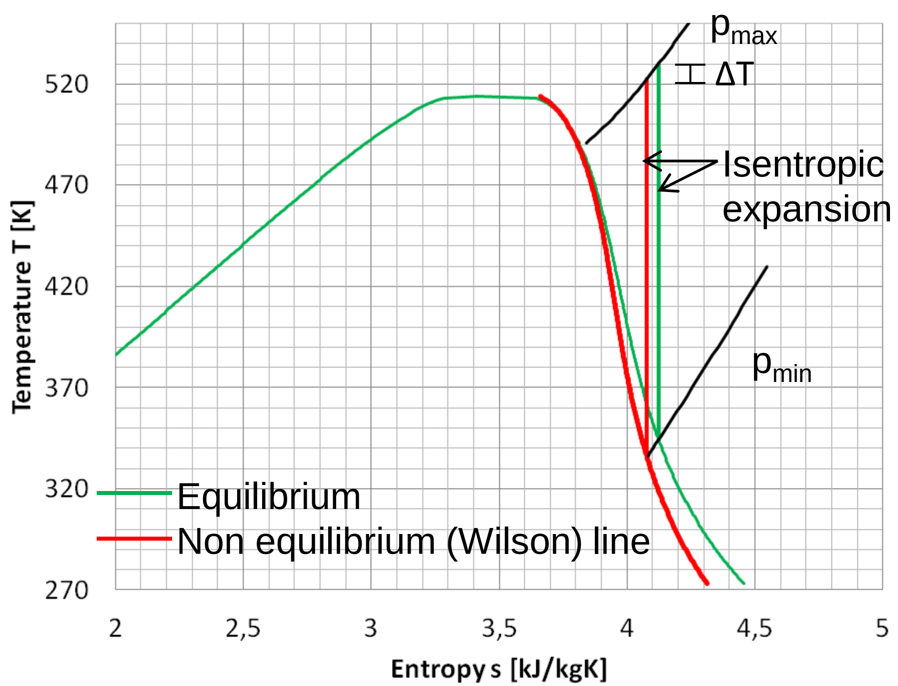
→ Decreased power output

In reality:

Homogeneous nucleation effects delay droplet formation

Supersaturation of the vapour phase according to Hale (1988)





<u>Definition of saturation (WA (2005)):</u>

$$S = \frac{p_{VAP}}{p_{VAP,s}(T)}$$

S=1: saturated
S>1: supersaturated

<u>Approach by Hale (1988):</u>

$$\frac{\ln S}{\Omega^{3/2}} = \frac{(36\pi)^{1/2} x_o \delta_0}{\sqrt{\ln(J_c / J)}} \left(\frac{T_c}{T} - 1 \right)^{3/2}$$

Effect of supersaturation according to Hale (1988)

Benefits of supersaturation vs. equilibrium condensation (η_T=0.7):

	ΔP [%]	ΔP [W]	P_{Wilson} [kW]	Π [-]	T_{in} [K]
DP	+1.18	+118	10.20	49.1	522.2
PL	+0.62	+19	3.09	32.5	496.6
OL	+0.84	+127	15.13	39.2	508.0

Potential and uncertainties:

+ The expansion rate is no factor in this model.
  High expansion rates, like in laval-nozzles, promises considerably higher supersaturation (choosen model is very conservative) (Treffinger (1994))

+ The possible supersaturation for ethanol is higher than predicted by the model (vapour phase is stabilized by molecular associations) (WA (2005))

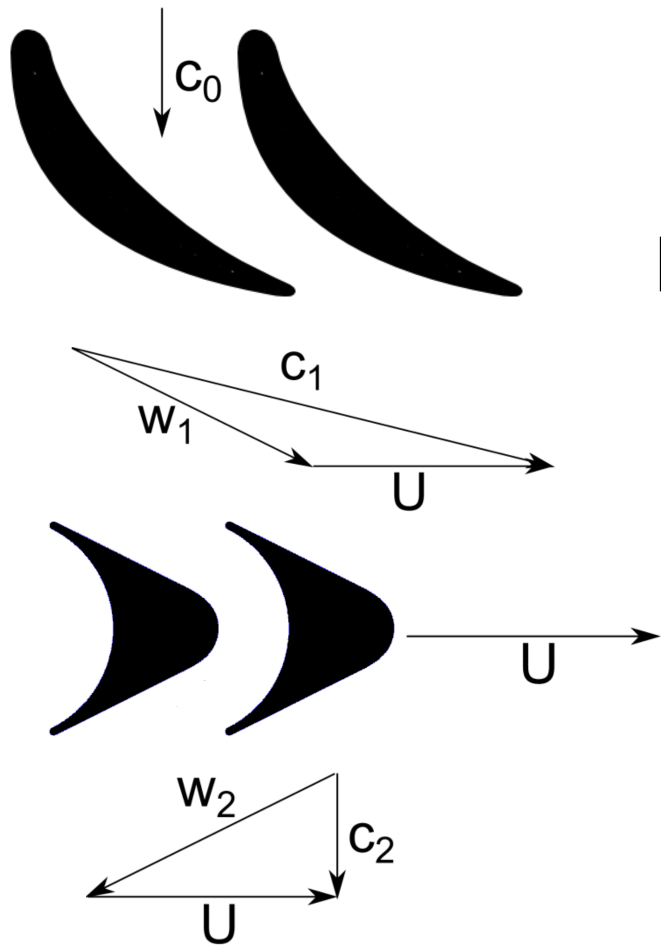
− Homogeneous nucleation requires very clean fluids (Bier et al. (1995))

− Uncertainties by the model itself (Treffinger (1994))

Impulse turbine

<u>Benefits of the axial impulse turbine:</u>

- High efficiency at high pressure ratios (Verneau (1987))
- Acceptable rotational speed (compared to other turbine designs)
- Single stage→compact
- Wide operating range due to variable partial admission



<u>Stator:</u>

Degree of reaction $R = \frac{\Delta h_{static,Rotor}}{\Delta h_{static,stage}} = 0$

The complete expansion takes place in the stator

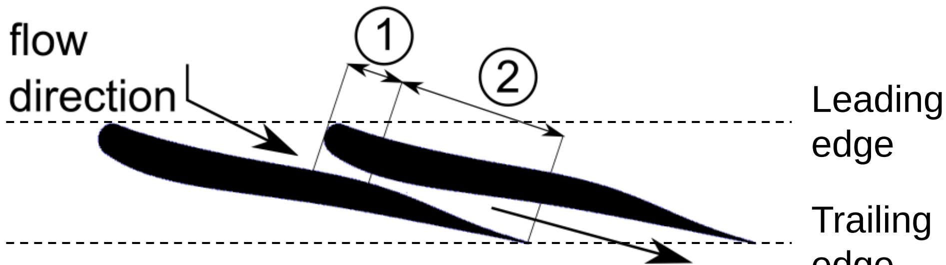
<u>Rotor:</u>

The rotor redirects the flow without a change of static pressure or the relative velocity ($|w_1|=|w_2|$)

Supersonic blade design

<u>Stator; Laval-nozzles:</u>

- Subsonic flow up to the throat ①
- Sonic velocity at the throat
- Supersonic flow in the divergent nozzle part ②



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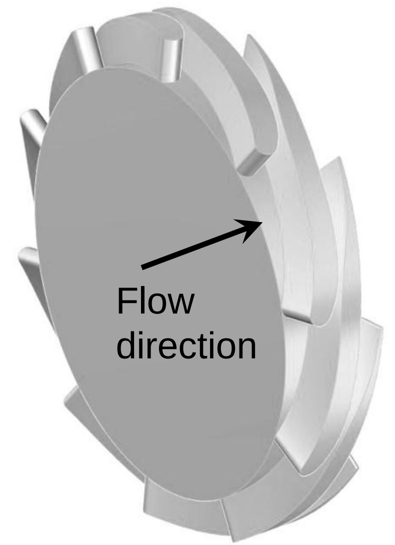
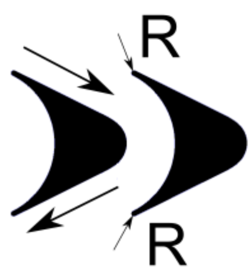


<u>Rotor; Impulse blades:</u>

Sharp leading and trailing edges minimize supersonic shock losses



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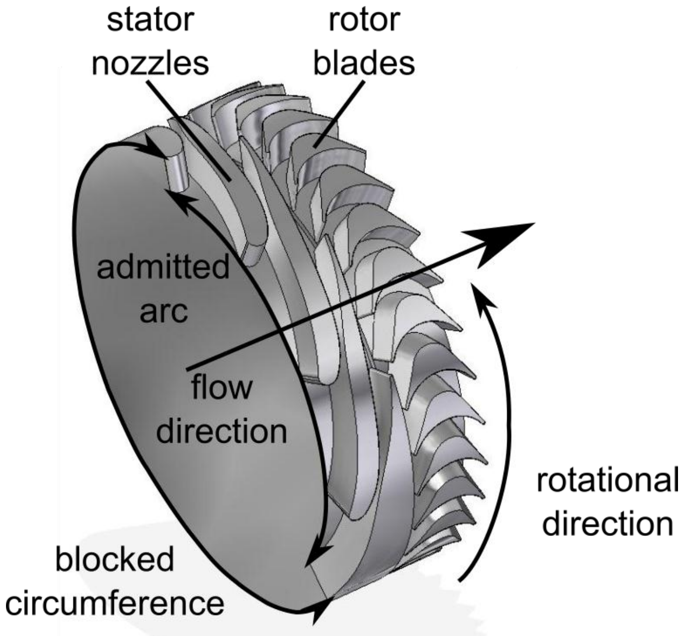
Flow control



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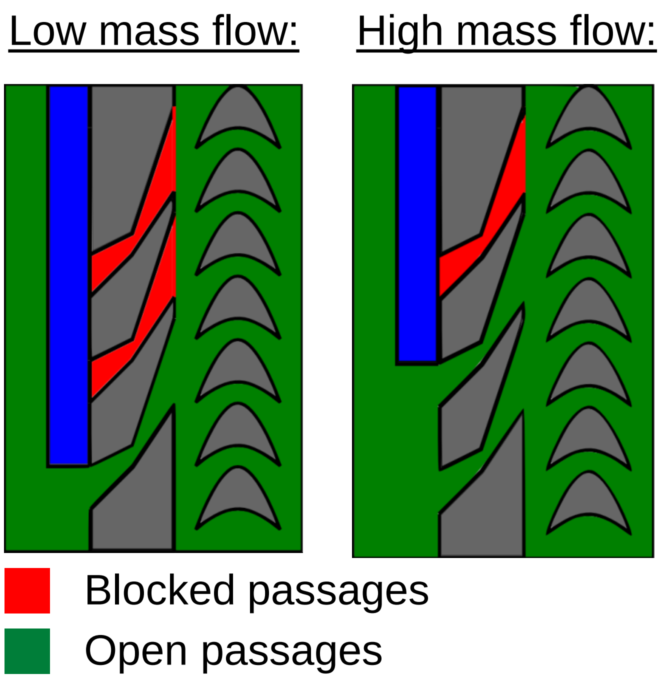

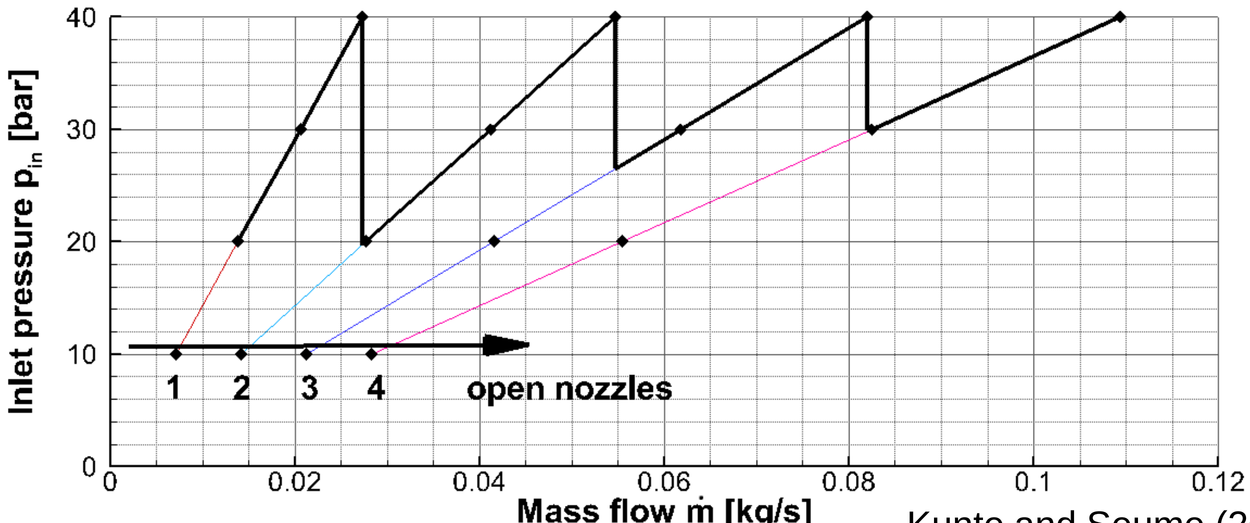

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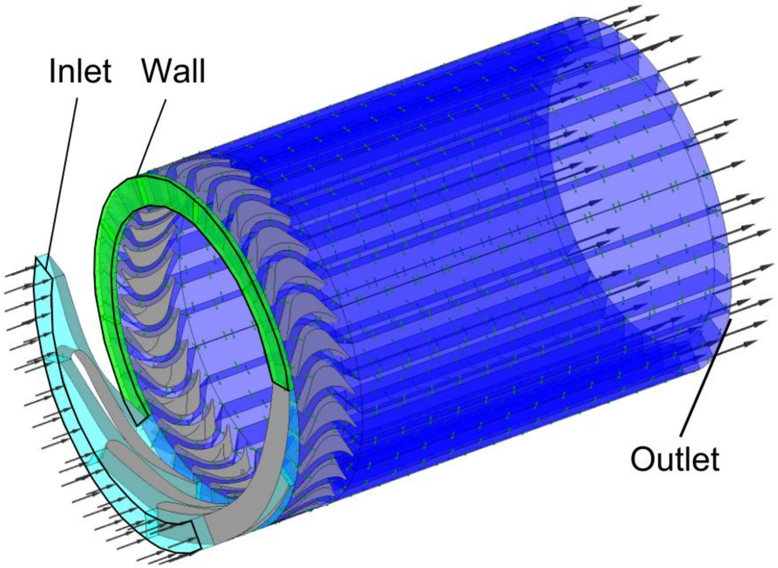
Turbine design parameters and CFD

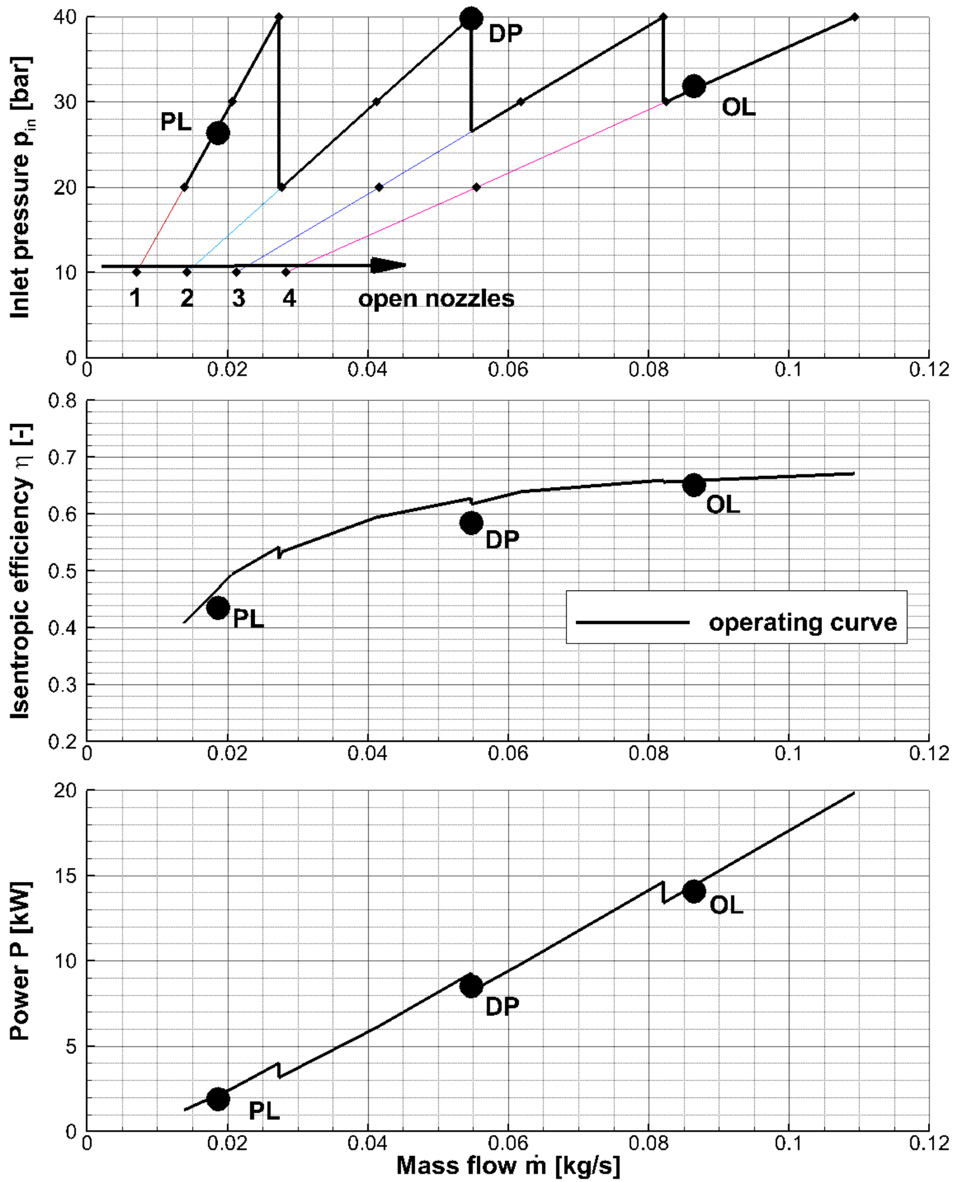
Preliminary design based on a model by Aungier (2006)

Outer Diameter	65.2 mm
Rotational speed at DP	105,000 rpm
Partial Admission at DP(OL)	20 % (40 %)



<u>CFD-Modell:</u>
- Ansys CFX 13.0
- Steady-state calculation
- Frozen rotor interface
- 18 million cells (with full radial resolution)
- Q3D-calculations for the calculation of the operating curve (reduced radial resolution)

Performance prediction for the truck application



	DP	PL	OL
$\dot{m}$ [kg/s]	0.055	0.019	0.087
p_{in} [bar]	39.8	26.3	31.8
P_{aero} [kW]	8.5	1.9	14.1
η_{is} [-]	0.58	0.44	0.65

DP: Design point
PL: Part-load
OL: Overload

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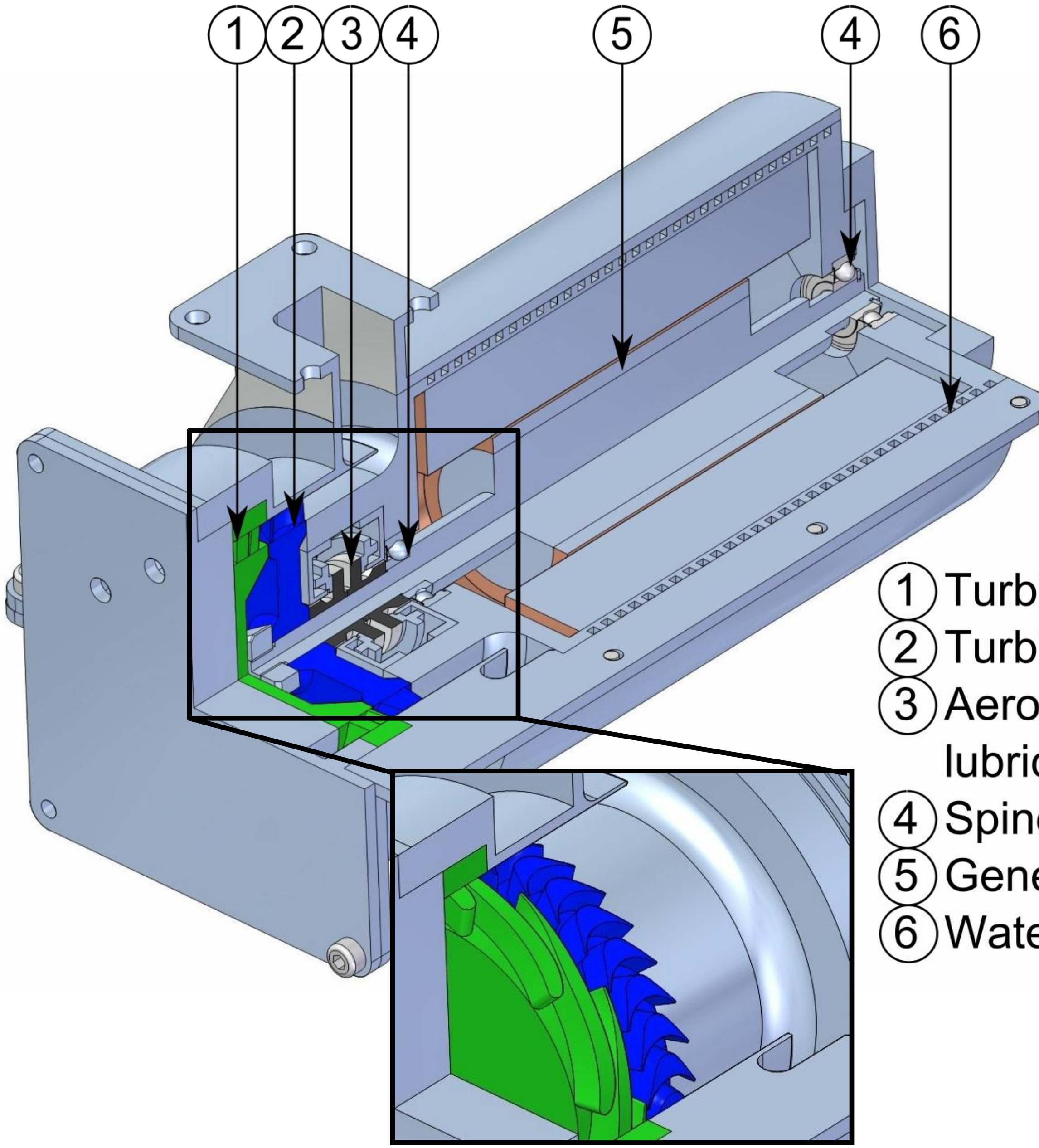
Design of the prototype



1. Turbine stator
2. Turbine rotor
3. Aerodynamically lubricated seals
4. Spindle ball bearing
5. Generator
6. Water cooling jacket

Conclusions

- Working fluid: Ethanol promises the highest power output for the considered application.
- An increase in power compared to thermal equilibrium is possible due to supersaturation in the preliminary performance prediction (Wilson line).
- The axial impulse turbine is suitable for the utilization as an expansion turbine for an automotive ORC (predicted efficiencies):

Design point:	58%
Part-load:	44%
overload:	65%

- Coverage of the performance range requires variable partial admission
- Predicted rotational speeds allow direct coupling of turbine with the generator for compact design.

Outlook

- Detailed aerodynamic investigation with design improvement
- Prototyping for truck application
- Experimental verification
- Investigation of homogeneous nucleation with consideration of the expansion rate (e.g. Treffinger 1994) might further improve performance

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Thank you for your attention!

Thanks to:

Forschungsvereinigung Antriebstechnik e.V.

FVV

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