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Efficiency Correlations for Off-Design Performance Prediction of ORC Axial-Flow Turbines

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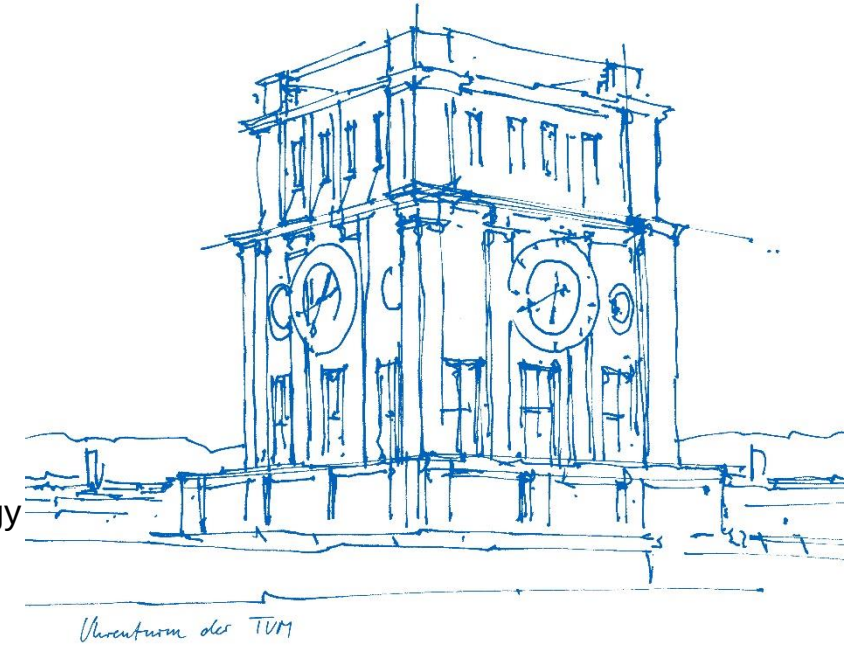

Athens, 9th September 2019

Outline

1. Axial-Flow Turbines for ORC Power Systems
2. Design and Optimization of Axial-Flow Turbines
3. Turbine Design Tool: AxialOpt
4. Turbine Off-design Tool: AxialOff
5. Test cases
6. Results and Correlations
7. Summary and Future Outlook

1. Axial-Flow Turbines for ORC Power Systems

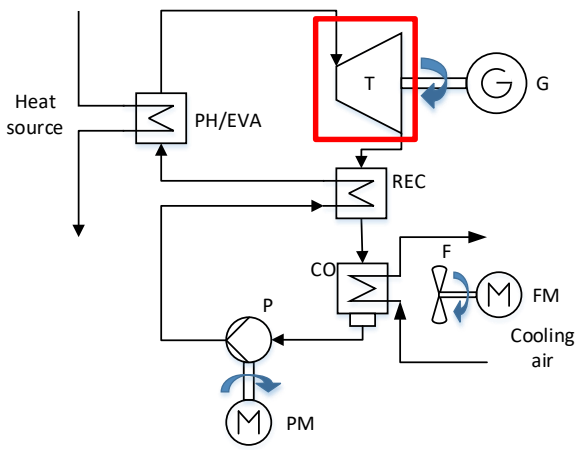

Figure 1: Organic Rankine Cycle Unit with recuperator and direct air cooling

Expander:

- Thermo-mechanical **conversion**
- Crucial component for **high efficiency**

Classical design of ORC power systems:

→ Assumed constant, reasonable isentropic efficiency of turbine

Integrated ORC/expander design:

→ Both ORC and expander design in the **same optimization loop** or

→ Expander design characterized by **correlations**

Off-design prediction

→ **Model-based** or **correlations**

1. Axial-Flow Turbines for ORC Power Systems

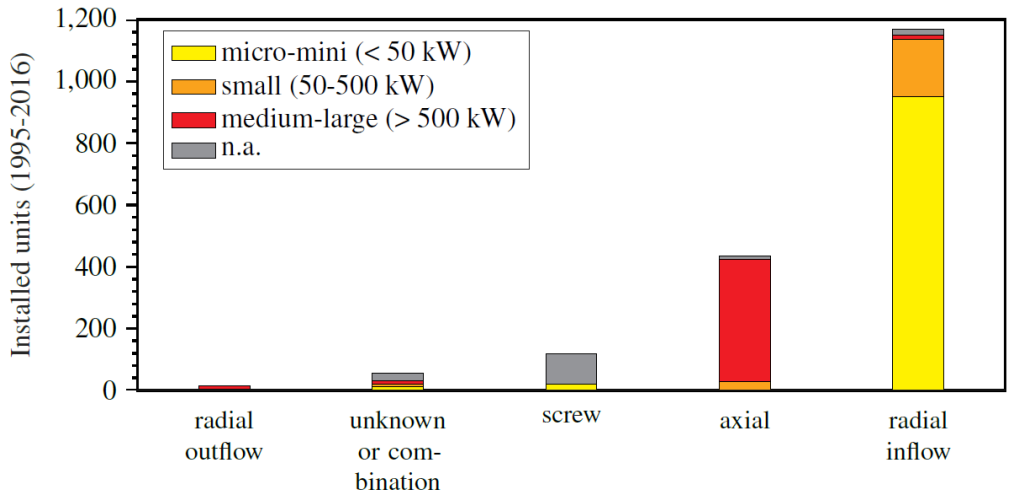

Figure 2: Number of installations in the period 1995-2016 (Meroni, 2018).

Figure 3: Axial-flow turbine in Siemens factory (Wikipedia, 2018).

Axial-flow turbines are the dominant type of expander for large-scale ORC units.

→ Efficient in broad range of application

→ Advantageous for high specific speed (increased number of stage)

2. Design of Axial-Flow Turbines

Integral ORC/turbine design:

→ mean-line models based on flow deviation and loss correlations

→ codes available:

1) Axtur (Macchi and Perdichizzi, 1981)
2) Turax (Meroni et al, 2016a)
3) AxialOpt (Agromayor and Nord, 2019)

To reduce computational effort:

→ efficiency correlations developed by Astolfi and Macchi (2015) for one, two and three-stage turbines

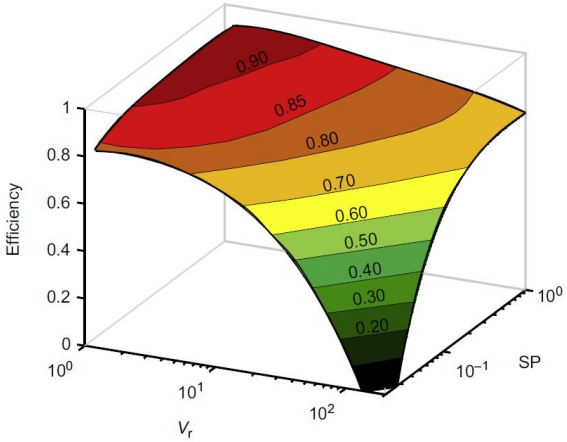

Figure 4: Efficiency map for single-stage axial-flow turbine (Macchi and Astolfi, 2017).

Function of:

$$SP = \frac{\dot{V}_{out,is}^{0.5}}{\Delta h_{is}^{0.25}}$$

$$V_r = \frac{\dot{V}_{out,is}}{\dot{V}_{in}}$$

+ for optimal specific speed

3. AxialOpt – Design of Axial-Flow Turbines

1) Objective function:

$$\eta = \frac{h_{0,in} - h_{out}}{h_{0,in} - h_{out,s} - \phi_E \frac{v_{out,a}^2}{2}}$$

2) Fixed input parameters:
   - → working fluid
   - → mass flow rate
   - → stagnation temperature and pressure at inlet
   - → static pressure at outlet

3) Constraints

4) Craig and Cox method, 1970

5) Optimization in MATLAB® with fmincon (SQP algorithm) and MultiStart

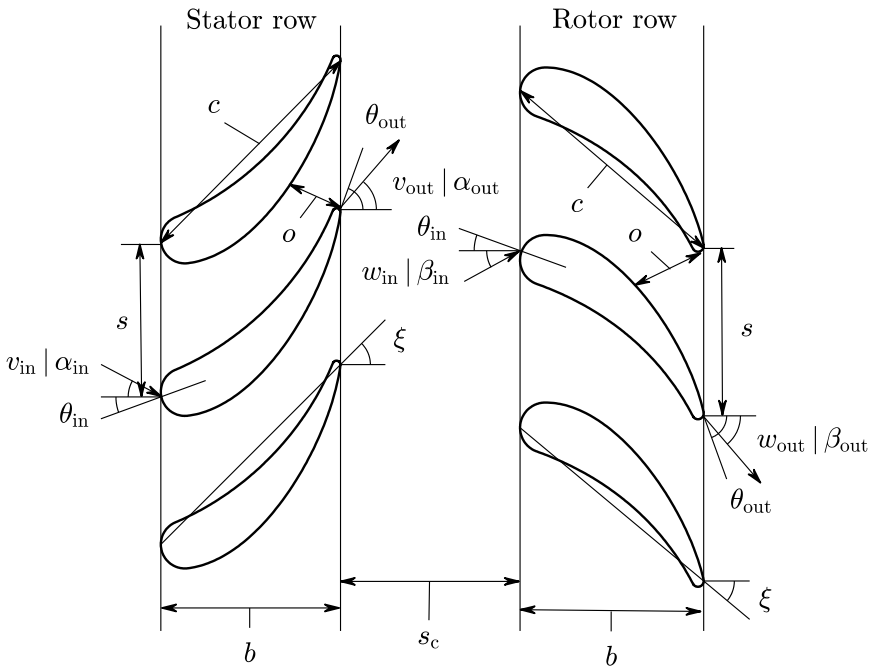

Figure 5: Axial-radial view of stator and rotor blades (Agromayor, 2019).

3. AxialOpt – Validation

Comparison with Axtur (Astolfi and Macchi, 2015)

Working fluid →	R125			Hexane		
Quantity ↓	Axtur	AxialOpt	Difference, %	Axtur	AxialOpt	Difference, %
Inlet stag. temperature, °C	155.0	155.0	-	155.1	155.1	-
Inlet stag. pressure, bar	36.200	36.200	-	8.29	8.29	-
Outlet static pressure, kPa	15.685	15.685	-	0.250	0.250	-
Mass flow rate, kg/s	11.89	11.89	-	2.04	2.04	-
Volumetric ratio, -	2.293	2.312	0.8	34.39	35.31	2.7
Size parameter, m	0.036	0.036	0.8	0.089	0.090	1.1
Rotational speed, rpm	31 000	29 660	-4.3	28 000	24 044	-14.1
Mean diameter, m	0.086	0.086	0.5	0.180	0.233	29.4
Isentropic efficiency, %	87.2	87.1	-0.1	79.5	81.5	2.5

4. AxialOff – Part-load Behaviour

1) Based on AxialOpt

2) Input parameters:
   - → working fluid
   - → stagnation temperature and pressure at inlet
   - → static pressure at outlet
   - → rotational speed

3) Geometry fixed

4) Constraint: mass flow rate <= critical mass flow rate (choking)

5) Solution in MATLAB® with fmincon (target zero, SQP algorithm)

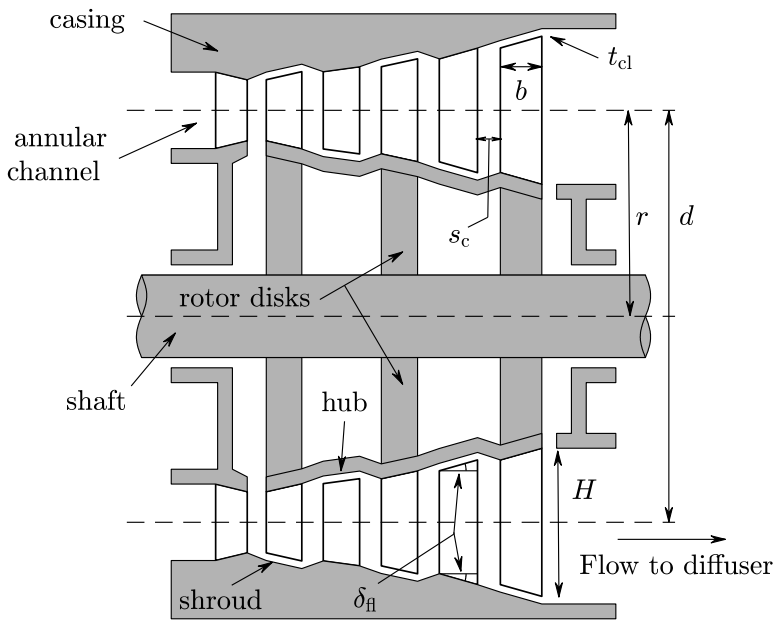

Figure 6: Axial view of stator and rotor blades (Agromayor, 2019).

4. AxialOff – Validation

Single-stage

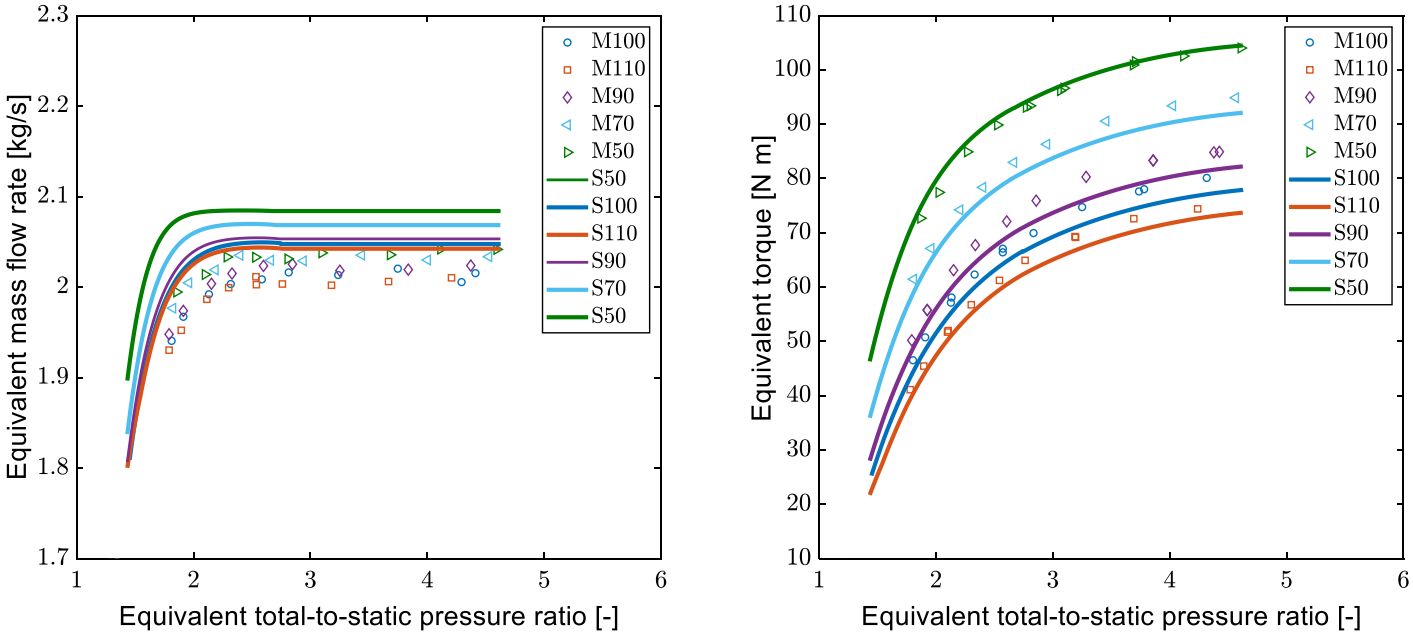

Figure 7: Validation against experimental data (single-stage) from Kofskey and Nusbaum (1972).

4. AxialOff – Validation

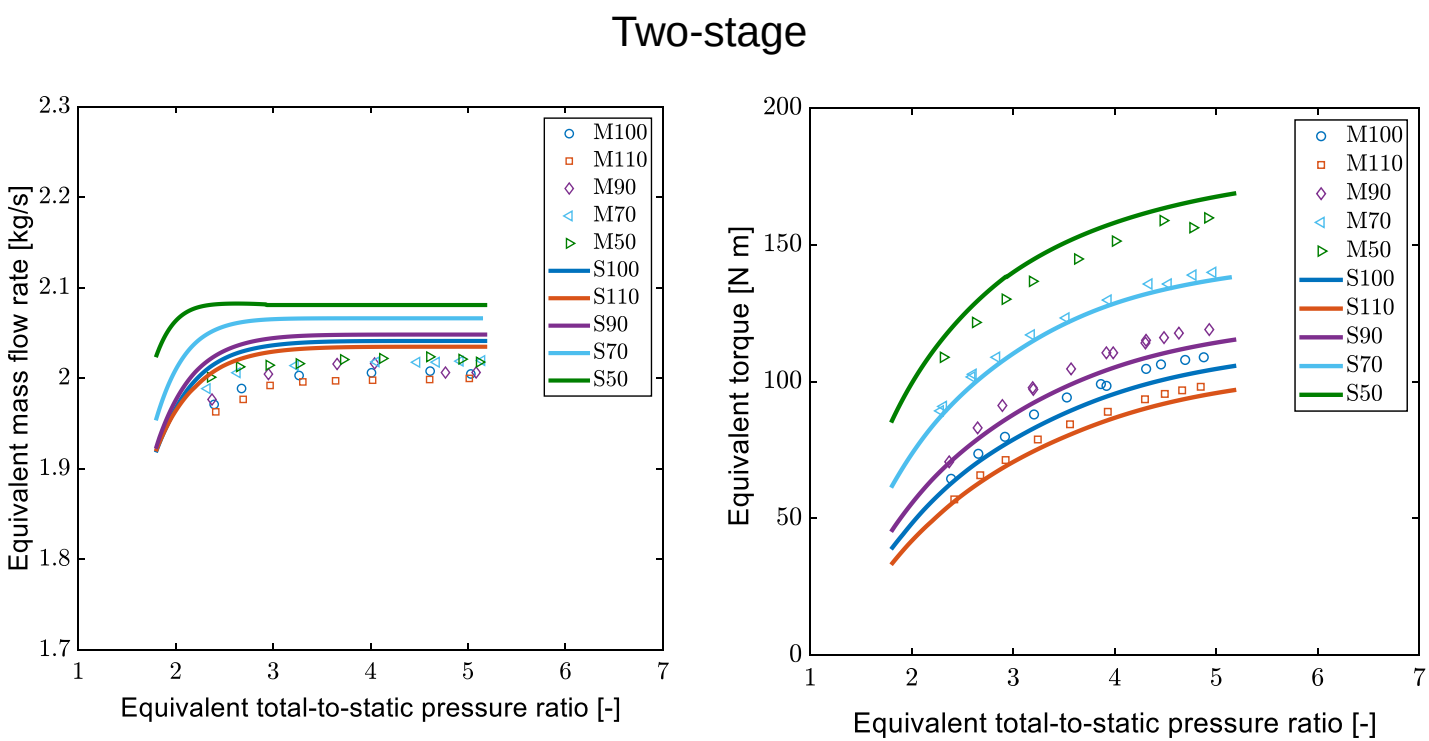

Figure 8: Validation against experimental data (two-stages) from Kofskey and Nusbaum (1972).

5. Test cases

No.	Application	Working fluid	Stagnation inlet temperature, °C	Stagnation inlet pressure, bar	Static outlet pressure, bar	Mass flow rate, kg/s
1	Biomass	MDM	305.00	7.92	0.22	5.46
2	Biomass	Toluene	292.02	21.90	0.41	13.69
3	Geothermal	R1234yf	128.50	42.57	8.44	190.73
4	WHR Cement	Pentane	162.00	19.40	1.03	16.67
5	WHR Ship	Benzene	225.34	19.66	0.16	3.06
6	WHR Steel	Toluene	290.85	5.21	0.15	11.74
7	n/a	R125	155.00	36.20	15.69	11.89
8	n/a	Hexane	155.10	8.29	0.25	2.04

Pressure ratios: 2-124
Isentropic power output: 250 kW-2.5 MW
Molecular mass: 72-237 kg/kmol

6. Results - Turbine Design

No.	Working fluid	Isentr. volume ratio, -	Isentr. size parameter, m	Isentropic efficiency, %								
				AxialOpt			Axtur (diff, %)			AxialOff (diff, %)		
				stages			stages			stages		
				1	2	3	1	2	3	1	2	3
1	MDM	41.91	0.13	82.3	85.6	86.9	-1.8	-0.8	0.1	-1.3	0.0	0.0
2	Toluene	58.74	0.18	84.7	86.3	87.5	-5.2	-1.9	-1.0	-0.6	0.0	0.0
3	R1234yf	6.14	0.16	88.4	78.4	79.1	-1.3	-0.2	0.6	0.0	0.0	0.0
4	Pentane	23.17	0.14	82.4	87.1	88.7	1.1	-2.0	-0.8	0.9	0.0	0.0
5	Benzene	112.15	0.12	76.3	87.7	88.3	-5.5	3.4	5.1	-1.6	-0.6	-0.4
6	Toluene	31.82	0.29	82.7	85.5	86.6	0.7	-0.2	0.2	-1.1	0.0	0.0
7	R125	2.29	0.04	87.1	87.7	88.3	0.7	0.9	1.0	0.0	0.0	0.0
8	Hexane	34.35	0.09	81.5	85.0	86.0	-2.0	-1.5	-0.4	-2.0	0.0	0.0

Pressure ratios: 2-124
Isentropic power output: 250 kW-2.5 MW
Molecular mass: 72-237 kg/kmol

6. Results - Part-load Correlations

Geometry designed with AxialOpt and part-load simulated with AxialOff

Coefficients	Number of stages, -		
	1	2	3
a	0.245	0.418	0.548
b	1.632	1.066	0.937
c	-1.940	-0.568	-0.609
d	0.033	0.057	-0.056
e	-1.085	0.000	-0.043
f	2.112	0.035	0.228
R^2	0.994	0.993	0.992

$$\frac{\eta}{\eta_D} = a + b\left(\frac{\Delta h}{\Delta h_D}\right) + c\left(\frac{\Delta h}{\Delta h_D}\right)^2 + d\left(\frac{\dot{V}_{out}}{\dot{V}_{out_D}}\right) + e\left(\frac{\dot{V}_{out}}{\dot{V}_{out_D}}\right)^2 + f\left(\frac{\Delta h}{\Delta h_D}\right)\left(\frac{\dot{V}_{out}}{\dot{V}_{out_D}}\right)$$

6. Results - Comparison

Comparison with turbine out of pool for correlation development

Turbine (Meroni, 2016)
Working fluid R245fa
Pressure ratio: 2.83
Size parameter: 0.082 m

Turbine stages	Coefficient of determination, R^2 [%]
1	96.6
2	90.0
3	94.9

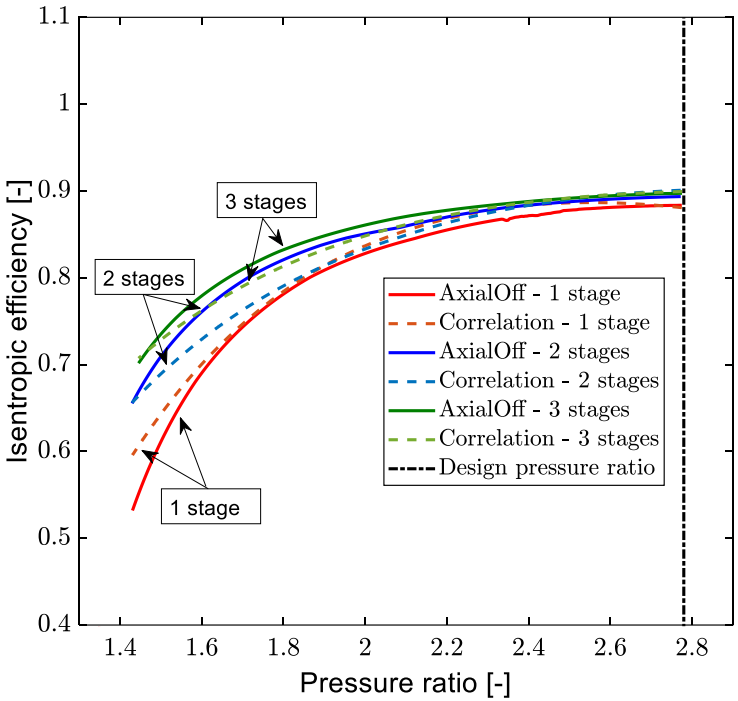

Figure 9: Validation against additional turbine from Meroni (2016b).

7. Summary and Future Outlook

<u>Summary</u>

Two tools for **design optimization (AxialOpt)** and **part-load prediction (AxialOff)** of **ORC axial-flow turbines** based on **mean-line method** are presented.

The tools have been applied to design and study the part-load of turbines from several applications (**broad range**).

Correlations for the **performance prediction of axial-flow turbines** in part-load have been developed.

<u>Future outlook</u>

Further comparison with **operational data**.

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Thank you very much for the attention.

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