Preliminary Design Method For Small Scale Centrifugal ORC Turbines

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Outline

1. 0. Introduction
2. 1. ORC Turbine
3. 2. The *zTurbo* code
4. 3. Preliminary design of a 10 kW_{el} ROT

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Introduction

- ORC systems $\Rightarrow$ important for decentralized power generation.
  - Future development of micro-ORC turbogenerator (10-100 kW_{el})
  - WHR from truck engines, concentrated solar, domestic CHP, ...

The turbine represents the most critical component in terms of efficiency, compactness, cost.

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ORC Turbine (1/2)

Use of ORC fluids:

- simple layout, compact and reliable turbine $N_{\mathrm{stg}} \downarrow$, $U \downarrow$
- complex aerodynamic design $M \uparrow$, $\left(\dot{V}_{\mathrm{out}}/\dot{V}_{\mathrm{in}}\right) \uparrow$
- Large compressibility effect $\rightarrow$ No similarity rules (D_{s}, ω_{s})

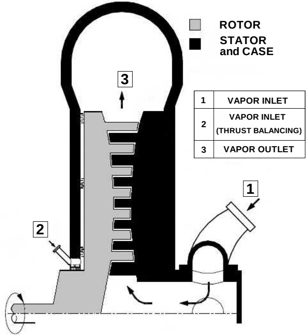
$\Longrightarrow$ non-conventional turbine architectures
$\Longrightarrow$ reliable preliminary design *1D* tool for ORC turbines

ORC Turbine (2/2)

- Centrifugal Architecture
  - $D \uparrow \Rightarrow A_{\text{flow}} \uparrow$
  - "Easy" and compact multi-stage solutions
  - centrifugal term!!

$$L_{\text{eu}} = \frac{V_1^2 - V_2^2}{2} + \frac{W_2^2 - W_1^2}{2} + \frac{U_1^2 - U_2^2}{2}$$

- ORC application Macchi (1977); Casci (1979):
  - stator-rotor solution, not counter-rotating (1 generator)



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zTurbo

- *zTurbo*: 1D design-analysis code `(fortran 90)`
- Turbine preliminary design:
  - selecting basic design parameters ⇒ necessary condition for a good turbine Macchi (1977, 1985)
  - "rigorous" approach ⇒ multi-variable optimization
- Main features:
  - proper treatment of real gases (LUT)
  - multiple turbine architectures
  - different loss models

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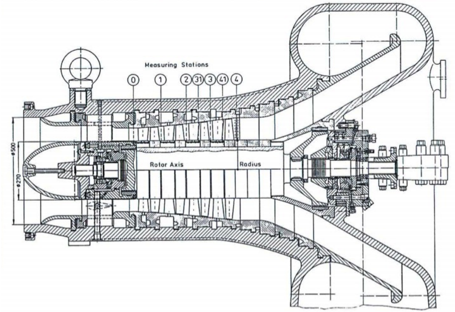
Code Validation (1/3)

- *zTurbo* vs test-case TG 4 stages Fottner (1990)

n_0	7500 rpm
$\dot{m}_{\text{flow}}$	7.8 kg/s
$T_{\text{t,in}}$	413 K
$p_{\text{t,in}}$	2.6 bar
p_{out}	1.022 bar
β_{stg}	1.255
r_{is}	0.5

Operative conditions



Cross section test-case

	α_{out} [°]	S/b_{ax}	cl/b_{ax}	b_{ax} [mm]	tip [mm]	$D_{\text{out}}/D_{\text{in}}$
Stator	68	0.81	0.15	49.4	0	1.01
Rotor	69.1	1.07	0.6	36.9	0.4	1.01

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Code Validation (2/3)

- Measured data and *zTurbo* resultes:

	1^{st}	2^{st}	3^{st}	4^{st}
p_t **[*bar*]**				
Data (meas.)	2.11	1.68	1.335	1.046
zTurbo	2.1	1.66	1.32	1.04
err. [%]	0.47	1.19	1.12	0.57
T_t **[*K*]**				
Data (meas.)	386.2	363.1	340.1	320.2
zTurbo	391.1	366.0	343.2	323.1
err. [%]	1.28	0.82	0.87	0.62
V_{out} **[m/s]**				
Data (meas.)	66.1	66.3	62.5	59.5
zTurbo	65.48	65.47	61.62	58.55
err. [%]	0.93	1.25	1.408	1.59
h_{bld} **[*m*]**				
Data	67.5	77.5	89.2	103
zTurbo	65.7	75	88.5	0,104
err. [%]	2,67	3,23	0,78	0,97

	Data	zTurbo	err. [%]
η_{ts}	0.913	0.894	2.08

- the overall relative error is within the ranges of uncertainty of all the statistics correlations used.
- 3-D turbine $\Rightarrow$ 1-D tool

$\Rightarrow$ reliable procedure.

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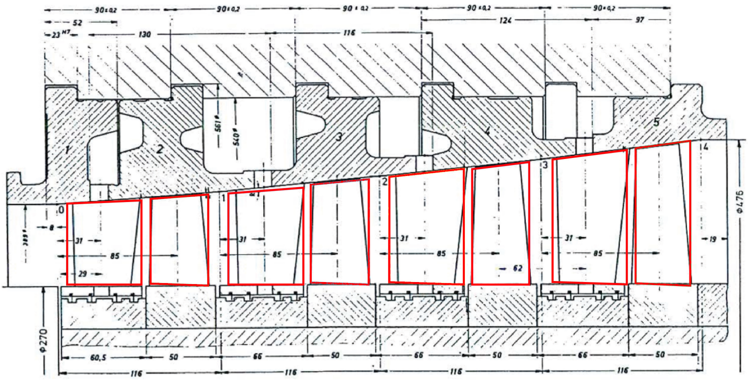
Code Validation (3/3)

- Overlap of real and resulted meridional channel.



Optimization (1/2)

- *zTurbo* doesn't solve an optimization problem

$$\eta = f(\psi, r_{is}, \beta_{stg}, b_{ax}, \left(\frac{S}{b_{ax}}\right), \alpha_{geo}, ...)$$

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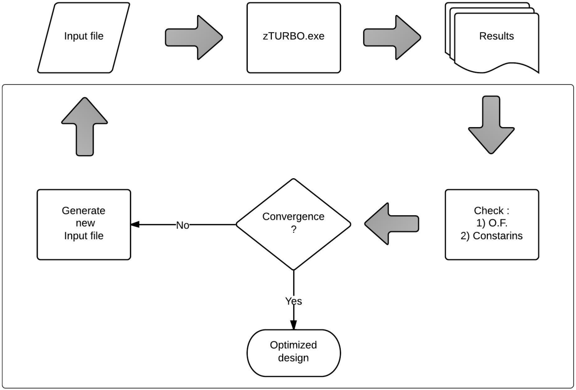
Optimization (1/2)

- *zTurbo* + optimization tool.



Optimization (2/2)

- zTurbo coupled to an external optimization software Sandia National Laboratories (2012)
- Flexibility:
  1. objective function(s)
  2. independent variables
  3. constraints
  4. search algorithms

$\Rightarrow$ different optimization strategies

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Thermodynamic cycle

- Application ⇒ waste heat recovery from a Diesel engine.

- thermodynamic cycle (input) from literature Lang et al. (2013)
- Requirements: efficiency and compactness

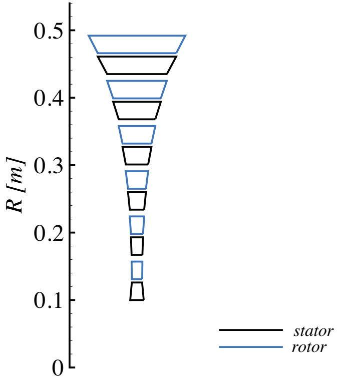
⇒ choice: centrifugal transonic multi-stage turbine

Parameter	Unit	Value
Fluid	-	D_4
$\dot{m}_{\mathrm{flow}}$	kg/s	0.266
$T_{\mathrm{t,in}}$	°C	242.5
$p_{\mathrm{t,in}}$	bar	4.4
p_{out}	bar	0.087
$\Delta h_{\mathrm{turb,is}}$	kJ/kg	48.120
β_{tot}	-	50.57
$\dot{V}_{\mathrm{out}}/\dot{V}_{\mathrm{in}}$	-	53

Design strategy (1/3)

- First approach $\Rightarrow$ "repeating-stage" procedure Coomes et al. (1986); Cerri et al. (2003); Pini et al. (2013)

  * independent variables:
    1. Radial chord $\Rightarrow b_{\text{rad,s}} = b_{\text{rad,r}}$
    2. Outlet geometric angle $\Rightarrow \alpha_{\text{geo}} = -\beta_{\text{geo}}$
    3. Reaction degree $\Rightarrow r_{\text{is}}$
  * Constraint: $\delta \leq 30°$
  * Objective function: η_ϕ ($\phi = 0.5$)



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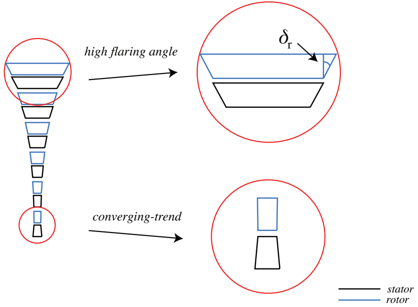
Design Strategy (2/3)

- Assessing "repeating-stages" in the context of micro turbines.

$$C.E. = \frac{D_{\text{in}}}{D_{\text{in}} + b_{\text{rad}}} \qquad (1)$$

$$h_{\text{bld, out}} \propto \frac{1}{\cos \beta_{\text{geo}} D_{\text{out}}} \qquad (2)$$



$\Rightarrow$ the assumption of the repeating-stages can not be extended to micro-ROT

First stages $\Rightarrow b_{\text{rad}} \downarrow \alpha_{\text{geo}}, \beta_{\text{geo}} \uparrow$
Last stages $\Rightarrow b_{\text{rad}} \uparrow \alpha_{\text{geo}}, \beta_{\text{geo}} \downarrow$

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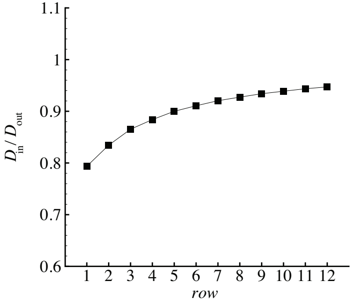

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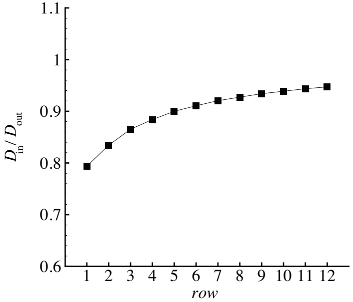

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Design strategy (3/3)

- Novel procedure for micro ROT's

* Independent variables:

- b_{rad} for each stage (x 5)
- α_{geo} for each blade row (x 10)
- D_{in} and n
- $h_{\text{bld,in}}$

* Fixed parameters:

geometric parameter	value
t_{cl} [mm]	0.1
t_{e} [mm]	0.1
$cl\,/\,b_{\text{rad}}$ [-]	0.1

* Assumptions for transonic machine ($M < 1.1$):

1. $N_{\text{stg}} = 5$
2. $\beta_{\text{stg}} = \sqrt[N]{\beta_{\text{tot}}}$
3. $r_{\text{is}} = 0.4$

* Constraints:

constraint	value
Flaring angle $[^\circ]$	$\delta \leq +7.0$
outlet section [mm]	$o \geq 1.0$
aspect-ratio [-]	$h_{\text{bld}}\,/\,b_{\text{rad}} \geq 0.30$

* Objective function: η_ϕ ($\phi = 0.5$)

* Optimization parameters:

Keyword	choice
population size	100
mutation type	*replace_uniform*
convergence type	*best_fitness_tracker*
percent change	0.10
number of generations	200

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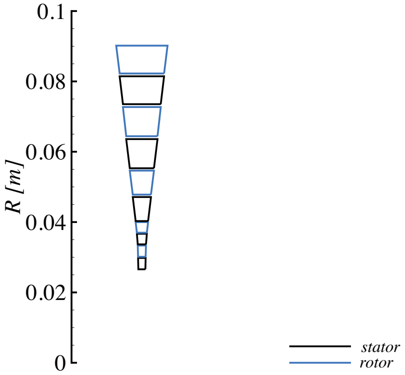
5-stages turbine

- Optimization results.

Main parameters	value
P [kW]	11.19
η_{ϕ} [-]	0.835
n [rpm]	12400
D_{in} [m]	0.053
D_{out} [m]	0.18
h_{in} [m]	0.002
δ_{max} $[^{\circ}]$	7.00
M_{max} [-]	1.02
$(h_{bld}/b_{out})_{max}$ [-]	1.84



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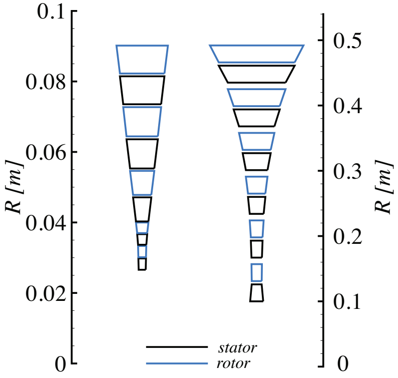

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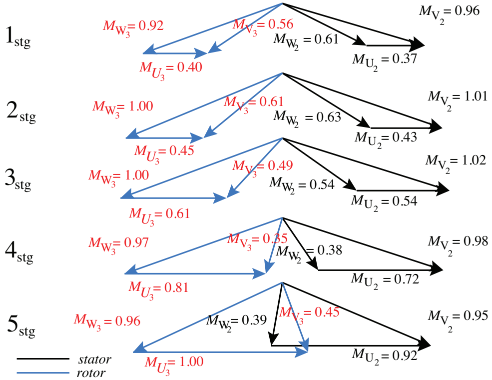
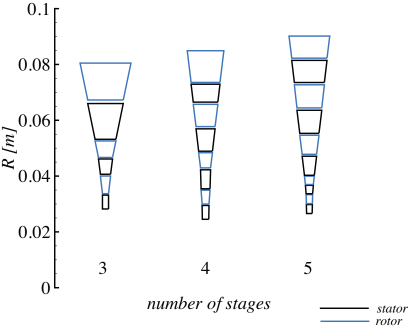


Summary

- Comparing the 3 machines...

Results	5-stages	4-stages	3-stages
P [kW]	11.19	10.9	10.51
η_{ϕ} [-]	0.835	0.818	0.799
η_{ts} [-]	0.823	0.802	0.773
$\Delta\eta$ [%]	1.43	1.95	3.25
M_{max} [-]	1.02	1.2	1.33
n [rpm]	12400	14300	15400
D_{in} [m]	0.053	0.048	0.057
D_{out} [m]	0.18	0.169	0.162
h_{in} [m]	0.002	0.0023	0.0021
δ_{max} [°]	7.05	7.15	11.75
h_{out} [m]	0.0146	0.0131	0.0182
$(h_{bld}/b_{out})_{max}$ [-]	1.84	1.67	1.38



$$D_{out} = \frac{1}{\pi h_{bld,out}} \left(\frac{\dot{V}_{out}}{\dot{V}_{in}} \right) \left(\frac{V_{rad,in} A_{in}}{V_{rad,out}} \right) \quad (3)$$

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ROTs vs RIT

- Comparison with a radial-inflow single-stage turbine.

1. higher efficiency
2. similar dimension
3. half rotational speed

	5-st	4-st	3-st	1-st (RIT)
P [kW]	11.19	10.9	10.51	10.3
η_{is} [-]	0.835	0.818	0.799	0.78 (?)
M_{max} [-]	1.02	1.2	1.33	N.A.
n [rpm]	12400	14300	15400	26000
D_{out} [m]	0.18	0.169	0.162	0.16

4. lower disk friction losses ($\sim \frac{1}{5}$)

$$P_{\mathrm{loss,df}} = \omega c_{\mathrm{m}} \rho D_{\mathrm{out}}^3 U_{\mathrm{out}}^2 \qquad (4)$$

	5-st	4-st	3-st	1-st (RIT)
$P_{\mathrm{loss,df}}$ [W]	37.36	41.80	42.26	191.32
$P_{\mathrm{loss,df}}/P$ [%]	0.33	0.38	0.40	1.86
$P_{\mathrm{loss,df}}/P_{\mathrm{loss,RIT}}$ [%]	19.0	21.8	22.1	-

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$P_{\mathrm{loss,df}} / P$ [%]	0.33	0.38	0.40	1.86
$P_{\mathrm{loss,df}} / P_{\mathrm{loss,RIT}}$ [%]	19.0	21.8	22.1	-

Conclusions

- *zTurbo* + optimizer $\Rightarrow$ reliable and flexible design tool
- Novel design strategy for micro centrifugal turbines presented
- centrifugal architecture promising for (micro)ORC systems

THANK YOU FOR YOUR ATTENTION

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