Brief Dexpand design study of small 1- 50 kW turbo expanders for MM and Isobutane ORC plants

For the p, T- boundary conditions of the **MM ORC plant** at UCEEB/Prague

Inlet pressure 6,5 bar
Outlet pressure 0,55 bar
Inlet Temperature 190 °C

three different turbine turbine architectures i.e. turbines in the power range 1-2-4-8-16-30-50 kW_{el} were investigated .

Applying the in-house 1DTDT, combined with manual adjustments guided by engineering judgement, the following results (Weiß et al. 2020) were achieved for the **axial impulse turbine**:

power	is_effic_ts	mass flow rate	diameter	rotational speed	deg-o-adm	b-height	b-chord
kW	%	kg/s	m	rpm	%	mm	mm
1	63	0,0308	0,05	51000	50	2,6	7,0
2	65	0,0597	0,05	51000	50	4,7	8,0
4	68	0,1148	0,06	46000	95	4,0	10,0
8	68	0,2267	0,09	31000	95	5,2	10,0
16	69	0,4550	0,12	23000	95	7,7	14,0
30	69	0,8370	0,15	18000	95	11,0	14,0
50	70	1,3859	0,20	14000	95	14,0	14,0

As expected, diameter must increase, rotational speed decrease with power rating. Furthermore, efficiency increases also with power rating. This effect is most probably underestimated, because the 1DTDT does not take into account

- Reynolds number dependency of friction losses
- Gaps and the corresponding (tip) leakage losses
- Trailing edge thickness and trailing edge losses

All these issues are getting worse if reducing power rating (= smaller turbine). In particular, if partial admission Is necessary (1 kW, 2 kW). However, generally, efficiencies are rather high. Measurements with 12 kW_{el} MM-axial turbine showed even 73% for quite similar boundary conditions (Weiß et al. 2018).

The same approach was choosen for the investigation of the **quasi-impulse cantilever turbine**:

power	is_effic_ts	mass flow rate	liamete	rotational speed	deg-o-adm	b-height	b-chord
kW	%	kg/s	m	rpm	%	mm	mm
1	73	0,0268	0,05	61000	57	2,3	7,5
2	75	0,0520	0,05	63000	75	3,3	7,5
4	75	0,1039	0,07	45000	95	3,6	10,0
8	75	0,2072	0,10	32000	95	5,0	15,0
16	75	0,4116	0,14	23000	95	7,2	22,5
30	76	0,7685	0,15	21000	95	11,9	22,5
50	76	1,2827	0,20	16000	95	14,7	30,0

Again, as expected, the cantilever turbine performs better. This is also confirmed by experimental investigations. However, the difference between cantilever and axial impulse turbine in experiments was only 3 % p.p. (76 % to 73 %). The advantage of the cantilver turbine is the quasi-impulse principle which is also explained in (Weiß et al. 2018). As an disadvantage of this approach, the higher necessary rotational speed must be mentioned. Finally, an interesting issue is the fact, that effcicieny is obviously less dependent to power rating for the cantilever compared to the axial turbine.

Finally, a velocity staged radial re-entry turbine, called Elektra (Weiss et al. 2020), was considered for the above listed boundary conditions. The rotational speed was fixed to 3000 rpm to enable the application of an out-of-the-shelf generator.Because the available 1DTDT for the Elektra-architecture proofed to be to uncertain, cumbersome and time consuming in use, the following data were derived based on the analytical, numerical and experimental investigation of several two-fold-re-entry air turbines (Stümpfl et al.; Streit et al. 2024) and the four-fold-re-entry **MM-Elektra** which was experimentally investigated with air and MM:

Power	remark	estimated efficiency	mass flow rate	wheel passes	u_opt	D	h	# nozzles	#flows	flow ratio	area ratio
kW					m/s	m	m	-			
4	experimentally determined	0,4	0,1939	4	40,14	0,2556	0,0200	2	1	1,00	1,00
1	assessment, smaller than	0,3	0,0646	4	40,14	0,2556	0,0130	1	1	0,33	0,33
2	experimentally determined	0,4	0,0970	4	40,14	0,2556	0,0200	1	1	0,50	0,50
8	experimentally determined, better than	0,4	0,3878	4	40,14	0,2556	0,0400	2	1	2,00	2,00
16	assessment	0,5	0,6205	2	80,29	0,5111	0,0255	5	1	3,20	3,19
30	+x%	0,5	1,1635	2	80,29	0,5111	0,0400	6	1	6,00	6,00
50	assessment	0,45	2,1546	2	80,29	0,5111	0,0370	6	2	11,11	11,10

Based on the experimentally determined efficiency (first line) for the four-fould radial-re-entry Elektra in the MM ORC plant at UCEEB/Prague, efficiencies were assessed in 5 p.p.-steps. The 2 kW-turbine can easily be implemented just by closing one of the two nozzles of the 4 kW-turbine. Efficiency is retained (proofed by air measurements). The 8 kW can be realized by doubling blade height (h) – efficiency unchanged.

Thanks to the doubled mass flow rate, the diameter for the 16 kW turbine can be doubled. Thus, two velocity stages i.e. two (re-)entries are sufficient which should result in an efficiency increase by 10 p.p. Again, 30 kW can be implemented just by increasing blade heigt (h) – efficiency unchanged.

However, for the 50 kW Elektra, single flow, the blade height would achieve 74 mm. Although, the cantilever blades are supported by a shroud, the author did not dare to consider this. Therefore, 50 kW are achieved by adding a second flow, back-to-back to the first one. Regarding two flows, more wetted area, flow separators etc., a efficiency penalty of 5 p.p. was assumed.

At the lower end, 1 kW turbine can be easily derived from the existing 2 kW turbine by reducing balde height to 13 mm on a 255 mm wheel – looks surely strange.

By carrying out these assessments, the phyisics behind the "Specific Speed n_s Concept" become once more clear: Rotational speed was fixed to 3000 rpm. Total enthalpy drop was given/fixed by the thermodynamics. Varying power rating means varying volume flow rate and thereby n_s.To sum up, for the given thermodynamic boundary conditions, the Elektra architecture fits obviously for power ratings between 2-4 kW and 30 kW. Above, one should use a simple impulse (cantilever) turbine, below a volumetric expander…

For the p, T- boundary conditions of the **Isobutane Expand Rig**

Inlet pressure 4,0 bar
Outlet pressure 1,6 bar
Inlet Temperature 125 °C

two different turbine turbine architectures in the power range 1-2-4-8-16-30-50 kW_{el} were investigated .

Applying the in-house 1DTDT, combined with manual adjustments guided by engineering judgement, the following results (Weiß et al. 2020) were achieved for the **axial impulse turbine**:

power	is_effic_ts	mass flow rate	diameter	rotational speed	deg-o-adm	b-height	b-chord
kW	%	kg/s	m	rpm	%	mm	mm
1	68	0,0304	0,05	54000	67	1,7	7,5
2	71	0,0571	0,05	56000	95	2,1	7,5
4	72	0,1141	0,07	40000	95	2,9	10,0
8	73	0,2240	0,10	28000	95	3,9	10,0
16	74	0,4025	0,11	25000	95	6,2	14,0
30	75	0,8139	0,14	20000	95	9,6	14,0
50	76	1,3536	0,15	18000	95	14,6	14,0

Efficiencies are aboviously higher than for MM. This is mainly due to the smaller required pressure ratios. The smallest turbines with 2 kW and 1 kW are technically feasible but it is questionable wether they are reasonable. Efficiency of the smallest one suffers from partial admission.

The same approach was choosen for the investigation of the **quasi-impulse cantilever turbine**:

power	is_effic_ts	mass flow rate	diameter	rotational speed	deg-o-adm	b-height	b-chord
kW	%	kg/s	m	rpm	%	mm	mm
1	77	0,0268	0,05	62000	56	2,1	7,5
2	80	0,0511	0,05	64000	95	2,3	7,5
4	80	0,1025	0,07	46000	95	3,2	10,0
8	80	0,2044	0,10	32000	95	4,5	15,0
16	81	0,4116	0,11	29000	95	7,8	17,5
30	81	0,7523	0,14	23000	95	11,3	22,5
50	82	1,2514	0,15	21000	95	16,8	22,5

As for MM, efficiencies and required rotational speed are higher for the cantilver turbine compared to the axial impulse turbine. Furthermore, efficiency speed dependency is again smaller for the cantilever turbine.

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