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Design and optimization of a Tesla turbine for ORC applications

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HIGHLIGHTS

- A novel methodology for the complete design of a Tesla turbine was developed.
- The losses were evaluated at component level.
- An innovative model for the solution of rotor flow field was applied.
- The Tesla turbine performance potential for ORC application was assessed.
- The estimation of total to static expander efficiency above 60% was achieved.

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ABSTRACT

In recent years, small-micro power generation was appointed as one of the proper solutions to tackle the increasing energy consumption, while opening the way to distributed energy systems and micro grids. The most interesting solution for small-micro power generation is the ORC technology, however, it still needs further developments especially regarding the design of small and micro expanders. A possible solution for micro-expanders is the Tesla turbine, which is a viscous bladeless turbine. This concept was developed by Nikola Tesla at the beginning of the 20th century, but it went through a long period of indifference due to the run towards large size centralized power plants. Only recently it found a renewed appeal, as its features make it suitable for utilization in small and micro size systems, like ORC applications, where low cost components become very attractive for the exploitation of residual pressure drop.

The present study develops a design procedure of a Tesla turbine for ORC applications. A throughout optimization method was performed by evaluating the losses of each component and by introducing an innovative rotor model.

Three turbine configurations with different expander size were assessed, in order to show the performance potential of the Tesla turbine, which achieved 64% total-to-static efficiency when working with N-hexane fluid.

1. Introduction

1.1. Small power generation

The world scenario recently experienced a strong increase in energy consumption demand, associated with a series of issues related to the exhaustion, environmental impact and cost of the resources, especially for fossil fuels. This framework encourages the search of alternative energy solutions for power generation, as well as the improvement of already existing conversion systems, particularly in the field of small and medium power range, which is also the basis to move towards the direction of distributed energy systems.

The Organic Rankine Cycles (ORC) are an interesting solution in the small to medium power range, in particular when associated to low temperature resources (90 °C < T < 180 °C). This technology utilizes organic fluids in place of steam. The Organic fluids are characterized by lower saturation temperature and pressure, and higher molecular mass when compared to steam. These properties make ORCs suitable for small-medium size power plants (50–5000 kW) and for heat recovery applications by way of gas turbine discharge [1–3], internal combustion engines [4] or industrial waste heat [5,6], as well as for energy conversion from biomass [7], solar [8] or geothermal resources [9,10] and micro-scale CHP units [11–15]. On the other hand, due to the low temperature of the resources, ORCs usually have efficiencies in the range between 8% and 20%. Therefore, the selection and the design of the expander are of paramount importance. Axial turbines are widespread used for plants with power production between 500 kW and few MWs [16], while radial turbines are better suited for the lower power

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Nomenclature

Symbols

$\dot{m}$	mass flow rate [kg/s]
a	laminar coefficient [–]
A	section [m^2]
b	channel height [m]
h	height of plenum chamber [m]
h	enthalpy [kJ/kg]
H	height [m]
I	rothalpy [kJ/kg]
k	loss coefficient [–]
L	length [m]
Ma	Mach number
n	turbulent coefficient [–]
n_{ch}	number of rotor channels [–]
P	pressure [Pa]
r	radius [m]
Re	Reynolds number [–]
s	discs thickness [m]
u	peripheral velocity [m/s]
v	absolute velocity [m/s]
w	width of plenum chamber [m]
w	relative velocity [m/s]
Z	number of nozzles [–]

Subscripts

0, 1, 2, …	reference points of expander sections
all	allowable
ch	channel
cl	camber line
diff	diffuser
e	enlargement
i	inlet
o	outlet
PS	pressure side
r	radial direction
r	rotor
Rod	Rodger
s	stator
t	throat
t	tangential
ts	throat section
z	axial direction
θ	tangential direction

Greeks

ζ_n	loss coefficient [–]
ζ_{Rod}	loss coefficient [–]
ϕ_n	velocity ratio [–]
α	absolute angle [°] in radial direction
η	efficiency [–]
μ	dynamic viscosity, [kg/(m s)]
ν	kinematic viscosity, [m^2/s]
ρ	density [kg/m^3]
σ	material stress [Pa]
ω, Ω	rotational speed [rad/s]

Acronyms

CFD	Computational Fluid Dynamics
CHP	Cogeneration of Heat and Power
EES	Engineering Equation Solver
EoS	Equations of State
ORC	Organic Rankine Cycle
rpm	Revolution par minute
TRL	Technology Readiness Level

ranges (50–500 kW), due to their low degree of reaction and therefore their capability of dealing with large enthalpy drops at low peripheral speeds, allowing the adopting a single stage design [17–19]. Finally, for very small and micro power range applications (hW to about 50 kW), volumetric expanders, like scrolls or screws, are usually utilized, although their efficiency is limited by leakages, friction and heat transfer losses [20–22].

The comparison between various types of micro expanders for ORC applications is resumed in Table 1. As it can be noticed, in the very small power range, radial turbines are not suitable, and actually volumetric type machines are the only alternative. Among volumetric machines, scroll and rotary vane expanders are more suitable for very small scale applications, whereas screw and reciprocating piston expanders belong to a higher power output range. Therefore, in this context, the Tesla turbine may represent a direct competitor to scroll and rotary vane expanders, as, if properly designed, it holds the same characteristics of moderate rotational speed (if relatively high rotor diameter is utilized), low manufacturing cost and suitability to very different fluids and applications. Furthermore, conversely to most of volumetric expanders, it does not require lubrication, which may be very important in several applications.

Table 1
Comparison of micro expanders for ORC applications [13,16,19–21,23]

Type	Power range [kW]	Rotational speed [rpm]	Cost	Characteristics
Scroll expander	1–10	< 10,000	Low	+ High efficiency, low cost − Lubrication requirement
Screw expander	10–200	< 10,000	Medium	+ Flat efficiency curve at off-design − Difficult to manufacture, lubrication
Reciprocating piston expander	20–100	< 12000	Medium	+ Mature technology, high pressure ratio − Heavy weight, complex
Rotary vane expander	1–5	< 10,000	Low	+ Low cost and low noise − Small power range, lubrication
Radial Inflow turbine	50–500	5,000–80,000	High	+ Light weight, mature technology − High cost, low efficiency in off-design
Tesla turbine	0.5–10	< 10,000	Low	+ Low cost, low noise, moderate efficiency, reliable − Few prototype tested (very low TRL)