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Impact of major leakages on characteristics of a rotary vane expander for ORC

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Abstract

Volumetric expanders are used for low to medium power output ORC applications. For low power output ORCs (< 10 kW), rotary vane expanders represent a suitable choice. Their isentropic efficiency is often reported as the most important or even the only metrics for comparison. Such approach however neglects the effect of leakages within the expander on the rest of the cycle, especially on the evaporator pressure. Filling factor of rotary vane expanders may be affected, among other leakages, by delayed closure of working chamber.

This work describes a semi-empirical model with two different leakages – lumped leakage area between inlet and outlet and leakage between working chambers due to delayed contact of vane and stator. Primary purpose of the model is to demonstrate the effect of the delayed chamber closure. This is identified as a necessary parameter for modeling of the rotary vane expanders, compared to only single lumped leakage area for the other expander types. Results of the model for several case scenarios are presented, showing an impact of these leakages on an overall cycle performance, isentropic efficiency and filling factor. It is demonstrated that isentropic efficiency of the rotary vane expander might not be always sufficient to compare vane expanders or their modifications even within a same ORC. Lastly the model conclusions are preliminarily checked with our experimental data.

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Keywords: ORC; rotary; vane; expander; filling factor; leakages

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1. Introduction

Low power applications are one of the directions in current energy research [1]. Particularly there is also a demand for units with power output of less than 10 kW. For these applications in a field of heat to electricity conversion, thermodynamic cycles based typically on an ORC are considered as the most perspective and therefore most of the research is focused on them.

A crucial component of the ORC is an expander, for given small power outputs typically realized by volumetric expansion machines [2]. Rotary vane expanders (RVE) could be a suitable option for simple and low cost ORCs because of their simple design and low manufacturing costs. On the other hand, they exhibit lower isentropic efficiency compared to other volumetric expanders due to leakages and higher friction losses [3]. Leakages have significant impact not only on isentropic efficiency of the expander but also on a whole cycle due to possible reduction of evaporator pressure. Volumetric performance of the expander is often expressed by a filling factor. Rotary vane expanders can suffer by vane chatter [4]. It means that the vanes are not in a permanent contact with the stator surface. This can affect a filling phase and cause leakages across the vanes between adjacent chambers. The effect can rapidly influence the filling factor and the volumetric ratio of the expander but the impact on isentropic efficiency and power output may be much smaller.

In this work we present a simple semi-empirical model of RVE with two different leakages – lumped leakage area between the inlet and the outlet and a leakage between working chambers due to delayed contact of a vane and the stator during the filling phase of the RVE. Primary purpose of the model is to demonstrate the effect of these two leakages and their strong impact on specific characteristics of the expander. Finally, several model results are presented including a case demonstrating the same ORC unit operating with two different expanders both with the same isentropic efficiency and having different power production.

Nomenclature

c	number of chambers (-)
h	specific enthalpy ($J \cdot kg^{-1}$)
p	pressure (Pa)
r	ratio (-)
v	specific volume ($m^3 \cdot kg^{-1}$)
A	area (mm^2)
F	force (N)
FF	filling factor (-)
$\dot{M}$	mass flow rate ($kg \cdot s^{-1}$)
N	speed (rpm)
P	mechanical power (W)
$\dot{Q}$	heat flux (W)
V	volume (m^3)
η	efficiency (-)

Subscripts

c	chamber
ev	evaporator
exp	expander
in	inlet
init	initial
is	isentropic
leak	leakages
out	outlet / output
rot	rotational
su	supply
theor	theoretical
v	volumetric
wf	working fluid

2. Leakages within a rotary vane expander

The problem of leaks within the rotary vane expander is very complex. Leakages are influenced by a variety of parameters such as pressure ratio, number, size and shape of the leakage paths, thermodynamic properties of a working fluid, proportion of lubricating oil in the working fluid, etc. The vane expander is a periodically working machine, so many of these parameters change during the working cycle. The flow through different leakage paths will therefore also change. In simple models of volumetric expanders, the leakage description is simplified. In the scroll expander model described by Lemort et al. [5], all the leaks are replaced by one main flow area through which the working substance flows continuously. Although this is a significant simplification, Lemort et al. has shown that