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Research Paper

Development of a thermodynamic low order model for a twin screw expander with emphasis on pulsations in the inlet pipe

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HIGHLIGHTS

- A multi-chamber model is developed from the mass and energy conservation laws.
- To better predict inlet pipe pulsations a 3D inlet pipe model is coupled to it.
- Flow coefficients are derived from 3D CFD calculations.
- Maximal deviation between the full CFD and the presented model is around 5%.
- This model is a good compromise between accuracy and computational resources.

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ABSTRACT

A twin screw expander is a positive displacement machine used in various applications of waste heat recovery. The performance of this machine is influenced by internal leakages, gas pulsations formed in the inlet pipe and the properties of the refrigerant. In this paper a multi-chamber mathematical model of a twin screw expander is presented to predict its performance. From the mass and energy conservation laws, differential equations are derived which are then solved together with the appropriate Equation of State (EoS) in the instantaneous control volumes. In order to calculate the mass flow rates through leakage paths more accurately, flow coefficients used in the converging nozzle model were derived from 3D Computational Fluid Dynamic (CFD) calculation. Due to high gas pulsation levels at the inlet port, a coupling with a 3D CFD inlet pipe model is introduced in order to better predict throttling losses. The maximal deviation between predictions by the developed model and 3D CFD calculations of the complete machine is around 5% for the mass flow rate and the power output.

1. Introduction

In recent years, one of the leading technologies for waste heat recovery is the Organic Rankine Cycle (ORC). The expander's performance is the crucial factor for achieving a sufficient thermal efficiency in the ORC. For a small scale ORC system, positive displacement machines are highly suitable [1,2]. In particular, screw expanders show a promising energy conversion [3].

Modelling of a twin screw expander is a complex process and the performance may be calculated using either zero or multidimensional mathematical models. Both models can represent one or more chambers existing within the machine. Zero-dimensional models for twin screw compressors are in use for decades already [4–6]. In 2007, Janicki developed a simulation program for screw machines which made a distinction between the different working chambers and the connections between them [7] and gave a detailed description how the model is developed. In 2011, Bell presented a mathematical model for a liquid flooded scroll compressor [8]. Despite their speed and relatively accurate results, these models neglect some important transient behaviour inside the suction and discharge ports.

Stosic et al. [9] and Huster [10] developed one-dimensional models for the suction and discharge port coupled with a zero-dimensional model of the working chambers. These models can predict the pressure pulsations in the suction or discharge ports well. However, they do not take into account the shape of the ports but only the change in the cross sectional area and this may change the flow losses in the ports.

A three-dimensional simulation of both suction and discharge ports and working chambers presents the most precise but also computational costly model. One of the additional challenges in three-dimensional calculations is grid generation and grid motion. Until now, only few grid generators have been presented that are

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Nomenclature

Symbols

$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (W)
ρ	density (kg/m^3)
A	area of the leakage path/inlet area (m^2)
C	flow coefficient (–)
E	energy (J/kg)
h	specific enthalpy (J/kg)
k	specific heat ratio (–)
m	mass (kg)
n	rotational speed (rpm)
P	power (W)
T	temperature (K)
u	specific internal energy (J/kg)
V	volume (m^3)
W	work (J)
z	number of lobes (–)

Subscripts

ch	chamber
down	downstream
i	index of the boundary of the working chamber
in	indicated
up	upstream

Abbreviation

ARK	Aungier Redlich–Kwong
CFD	Computational Fluid Dynamics
EoS	Equation of State
ORC	Organic Rankine Cycle

able to deliver high quality (block-structured) grids [11,12]. Consequently, low order models are very valuable for performance prediction of screw machines.

The first analytical model for dry screw expanders was presented in [13]. More recently, the numerical and experimental study of an oil injected twin screw expander for both air and R113 has been presented in [14]. The mathematical model was verified with experiments. The flow coefficients used in the leakage models were constant and were obtained from the experimental results. However, a limitation of the experiments is that they cannot accurately measure flow properties in the clearance area or during the filling.

A typical leakage model used when modelling scroll or screw types of positive displacement machines, is the isentropic converging nozzle [13,15,16]. The drawback of this model is that it does not take friction into account. Therefore empirical correction factors are used to compensate for losses due to frictional effects. Another leakage model presented in [17] is kind of Fanno flow. This model includes the viscous effects and it assumes that the leakage passage is a constant area channel. In [18] a hybrid leakage model is presented where an empirical frictional correction factor for the isentropic nozzle model is derived by calculating the mass flow through variable area leakage paths with real gas properties and then it is correlated to the prediction of an isentropic nozzle model. This hybrid model can only be used when the flow is not choked.

The aim of this paper is to present how to model the inlet pulsation and how to derive leakage coefficients using CFD calculations. For this the authors use the results of 3D CFD analysis of the twin screw expander presented in [19]. A similar attempt was presented in [20] where a simplification has been made using the representative geometry of the tip clearance but the comparison with full 3D CFD results is missing. A multi-chamber mathematical model of the same geometry used in CFD calculations is presented and validated by comparing different parameters depending on the rotational angle of the male rotor. The drawback of the multi-chamber model is that it does not include dynamics and losses in the inlet port. Recently the authors presented [21] a multi-chamber model with the results of 3D analysis in the inlet pipe applied as boundary condition. By contrast, the 3D analysis in the inlet pipe and the multi-chamber model are truly coupled in this work, taking into account the mutual interaction. The results of the coupled low order model were compared to the full 3D CFD result. The comparison of the coupled model and the full 3D CFD calculations of the complete machine were introduced for the first time in the literature.

2. Geometric characteristics

Screw expanders are positive displacement machines with a defined expansion volume ratio. The geometry of the twin screw expander analysed in this paper is shown in Fig. 1. The configuration of the rotor lobes is 4/6 (male/female). The outer diameter of the male and female rotors is approximately 70 mm with an L/D ratio of 1.9. In order to simulate the expansion process of a twin screw expander, the volume curve and the areas of the leakage paths must be known.

The volume of a working chamber as a function of the rotation angle is presented in Fig. 2a. The formation of the chamber starts at $\theta = 0^\circ$ in Fig. 2a. Between $\theta = 7^\circ$ and $\theta = 126^\circ$, the chamber is in connection with the inlet port. At the beginning the volume of the chamber is rising together with the increase in the inlet surface area, and the chamber is filled with the working fluid. After that the inlet area will start to decrease and the volume of the chamber will continue to increase which results in pre-expansion. Once the inlet port is closed, the working fluid starts to expand with increasing volume of the chamber. At $\theta = 387^\circ$, the working chamber is connected to the outlet and the working fluid is discharged through the outlet port.

Mass flow rates through the clearances that are forming leakage paths have a significant effect on the performance of screw machines. Three different clearance gaps were evaluated in the CFD analysis performed by the authors in [19] namely the tip, the sealing and the blowhole leakage. These leakage paths are included in the developed mathematical model and are shown in Fig. 1. Leakages are characterized by the area of the clearance as shown in Fig. 2b. Additionally, the leakage flows are distinguished based on the direction of the flow. The gain leakage flow is associated with the flow coming in the chamber from the neighbouring chamber on a higher pressure. Contrary, the loss leakage flow is going from the chamber with higher pressure to the chamber with a lower pressure. Both gain and loss leakage flows are accounted for in the developed mathematical model.

3. Thermodynamic multi-chamber model

For this model it is assumed that spatial gradients in the important state variables are negligibly small within the working chamber (zero-dimensional model) and thus the fluid is considered to be homogeneous in each chamber. In comparison to the one-chamber model, the multi-chamber model used in this study increases the quality of the simulation results because it introduces the leakage flows between the chambers.