A PRELIMINARY STUDY OF TWO-PHASE VOLUMETRIC EXPANDERS AND THEIR APPLICATION IN ORC SYSTEMS

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ABSTRACT

Organic Rankine Cycle (ORC) is considered one of the promising solutions for generating power using organic working fluid instead of water. Practically, the efficiency of ORC depends on the applied working fluid and its thermophysical properties. Also, it is significantly influenced by the temperature and the flow rate of the heat source. Some heat sources (e.g., waste heat or heat obtained from biomass combustion) may feature floating thermal and output characteristics. The ORC system may be designed in a way enabling its operation in two-phase conditions (i.e., for the vapour quality of $0 < x < 1$) to efficiently utilize such heat sources. The applicability of turbines is in this operating condition significantly limited as they tend to operate in dry vapour conditions. The literature review shows that different volumetric machines (i.e., rotary and reciprocating positive-displacement (PD) machines, such as piston, gerotor, screw, scroll and vane) can work with liquids and wet gases. Nowadays, these machines are applied mainly as pumps and compressors, but several researchers have been investigating and modifying them into expanders that could be applied in ORC systems. The operating principle of PD pumps and compressors differ from the centrifugal one. The PD pumps are applicable to a broader range of liquids, slurries, and foams that could be pumped without product degradation. Furthermore, the PD compressors are operating at a relatively low-pressure range and are commonly used in pneumatic and refrigeration systems. The PD machines could use gases and liquids as working fluids and therefore have the potential to be modified into two-phase expanders. The application of two-phase expanders in the ORC system gives the possibility to enhance the range of operating conditions in the system. This paper presents the results of a literature review on the mathematical models and experimental results related to the application of volumetric expanders in steam and ORC power systems operating in two-phase conditions. The most important features and characteristics of the two-phase expanders are discussed. Moreover, a preliminary experimental study concerning the possibility of applying a multi-vane expander for a two-phase expansion in a micro-power ORC system is reported.

1 INTRODUCTION

Organic Rankine Cycle (ORC) is one of the possible ways of thermal power generations that has a wide potential to be implemented to harvest energy from different heat sources (i.e., geothermal, industrial waste heat, biomass, ocean thermal, solar thermal, etc.). Compared to steam power plants operating according to Rankine Cycle (RC), thanks to the application of low-boiling working fluids, the ORC has a more comprehensive operating temperature range (even in extremely cold temperatures, i.e. cryogenic temperature) (Daniarta and Imre, 2020). In the ORC system, the expansion process is essential as expanding working fluid drives the shaft of the expander connected with a generator to produce electricity. In a conventional scheme, the expansion is often taking place in the dry vapour region (superheated vapour region); the reason behind it is to avoid droplets that may cause erosion or damage the turbine blades (Staniša and Ivušić, 1995). Superheating however might lead to decreased efficiency because adding considerable heating power is necessary to evaporate the working fluid and superheat the obtained vapour (i.e., it seems that the input heat increases and the efficiency of the cycle could be lower, depending on the characteristic of the working fluids). Another cycle, the so-called Trilateral Flash Cycle (TFC) that starts expanding the saturated liquid, has been studied to recover the heat from heat carriers below 200 °C. This system uses a two-phase screw expander being a type of volumetric machine. This expander is working under wet conditions, and it was found that the net power output is between 10–80% greater than in the case of classical RC (Smith, 1993). In a further study, Smith *et al.* (1996) also reported that a twin-screw machine might be a promising technology to be implemented in TFC if the working fluid and operating conditions are appropriately selected. It was also proved that TFC could produce 14–20 % more power than ORC (Fischer, 2011).

Since the layout of ORC consists of two heat exchangers (an evaporator and a condenser), pump and expander, the typical design of the ORC system is in some way similar to the design of reversed refrigeration system. Both in ORC and refrigeration systems, compression and expansion processes are proceeded in specially designed machines, which are essential to increase the pressure and expand the working fluid. Small-scale applications often choose rotary and reciprocating positive-displacement (PD) volumetric machines because of their low rotational speeds, compact and simple design, low level of noises and vibrations, etc. (Badr *et al.*, 1984; Kolasiński, 2019; Kolasiński, 2021a; Kolasiński *et al.*, 2016; Tassou and Qureshi, 1998). Some researchers have been investigating the application of selected types of volumetric expanders like piston, gerotor, screw and vane in ORC systems. Some volumetric expanders, applied in the experimental ORCs, are often modified reversed compressors used in refrigeration or pneumatic systems (Badr *et al.*, 1984; Kolasiński *et al.*, 2016). The application of a reversed compressor as the expander in many cases causes the operating efficiency of machines to be lowered.

Some selected types of volumetric machines are manufactured as pumps applied to pump the liquids (Bala *et al.*, 1985; Parker, 1994). Besides in the refrigeration systems, the volumetric compressors are operating not only in dry and saturated vapour conditions (Cengel and Boles, 2007) but also in the two-phase region (Verpe *et al.*, 2019). Since volumetric machines could operate both with liquids and gases, there is a possibility to modify their construction into two-phase volumetric expanders. This article will discuss the literature reports on the mathematical models and experimental results related to applying two-phase volumetric expanders in ORCs.

2 VOLUMETRIC MACHINES AND GENERAL MATHEMATICAL MODEL

Two types of mechanical machines (i.e., the PD and the rotodynamic) could be implemented as a pump, a compressor, and an expander. Nevertheless, only selected types of volumetric machines could be designed and used as expanders in ORC systems. Table 1 reports the operating pressure range of volumetric expanders that were applied and tested in ORC systems.

Table 1: An operating pressure range of the selected types of volumetric expanders that were applied and tested in ORC systems expanders.

Volumetric types	p_{in} (MPa)	p_{out} (MPa)	$\delta_{\text{pr,max}}$ (-)	Refs
Piston	20	0.1	200	(Kolasiński, 2020)
Gerotor	1.8 – 3.28	0.1	32.8	(Park *et al*., 2016; Saghlatoun *et al.,* 2014)
Screw	1.5 – 1.6	0.1	16	(Dumont *et al*., 2018; Kolasiński, 2020)
Scroll	1.0	0.1	10	(Kolasiński, 2020)
Multi-vane	0.7	0.1	10	(Kolasiński, 2020)

Practically, volumetric machines are characterized by essential parameters, i.e., pressure and volumetric expansion/compression ratio (Kolasiński, 2020) that could be described by Equations (1) and (2).

$$\delta_{\mathrm{pr}} = \frac{p_{\mathrm{in}}}{p_{\mathrm{out}}} \tag{1}$$

$$\delta_{\mathrm{V}} = \frac{V_{\mathrm{in}}}{V_{\mathrm{out}}} \tag{2}$$

There is a typical range of pressure expansion ratio applicable to different types of volumetric expanders, as shown in Table 1. Each type of expanders has its specific design defining its applicability to expand the dry and wet vapour. The thermodynamic modelling and simulation of machine operation may be described using the similar approach, in which the model could be defined based on the conservation of mass and energy considering the phase change. Vasuthevan and Brümmer (2016) have developed a mathematical model valid for a screw expander operating in TFC by involving simple conservation of mass and energy. Kanno and Shikazono (2017) have carried out an experiment and thermodynamic modelling to investigate the two-phase expansion process in a cylinder. Wang *et al*. (2019) have proposed a model of a two-phase expansion using a piston-type expander that no leakages was considered in the conservation of mass. In this article, the mathematical models will be generally described to give the possibility to be implemented in all kinds of volumetric expanders operating under two-phase conditions.
Equations (3) and (4) describe the conservation of mass of a two-phase expansion for the liquid and the vapour. The input and the output of mass flow rate may be well defined as the suction, discharge, and leakage through the shaft. The leakage may occur during the machine operation, which could be caused, for example, by the wear of sealing or improper selection of sealant materials for the low boiling working fluid. Since the quality of working fluid in ORC is changing from 0 up to 1, the mass flow rate of liquid decreases with the increasing mass flow rate of vapour. This condition could be well described as the negative and positive sign on the parameter of the mass flow rate of each phase ($\dot{m}_{phase}$).

$$\frac{dm_{\mathrm{l}}}{dt} = \sum \dot{m}_{\mathrm{i/o}} + \sum \dot{m}_{\mathrm{p/c}} = \dot{m}_{\mathrm{in,l}} - \dot{m}_{\mathrm{out,l}} - \dot{m}_{\mathrm{leak,l}} - \dot{m}_{\mathrm{phase}} \tag{3}$$

$$\frac{dm_{\mathrm{v}}}{dt} = \sum \dot{m}_{\mathrm{i/o}} + \sum \dot{m}_{\mathrm{p/c}} = \dot{m}_{\mathrm{in,v}} - \dot{m}_{\mathrm{out,v}} - \dot{m}_{\mathrm{leak,v}} + \dot{m}_{\mathrm{phase}} \tag{4}$$

$$\dot{m}_{\mathrm{l}} = (1-x)\dot{m}_{\mathrm{total}} \tag{5}$$

$$\dot{m}_{\mathrm{v}} = x\dot{m}_{\mathrm{total}} \tag{6}$$

In this article, Equations (5) and (6) introduce the total mass flow rate, the vapour quality, and the void fraction to determine the mass flow rate of liquid and vapour in two-phase operating conditions. Furthermore, from Equations (5) and (6), the area of liquid and vapour could be defined regarding the total area of the two-phase flow.
Equations (7) and (8) describe energy conservation for liquid and vapour, where the heat transfer rate in these equations is the sum of heat losses from a machine into the environment due to friction, phase changing, etc. The conservation of energy could be described as,

$$m_{\mathrm{l}} \frac{du}{dt} = \sum \dot{m}_{\mathrm{i/o,l}} (h_{\mathrm{i/o,l}} - u) + \sum \dot{Q}_{\mathrm{l}} - \dot{E}_{\mathrm{phase}} + P_{\mathrm{s}} - p\frac{dV_{\mathrm{ch}}}{dt} \tag{7}$$

$$m_{\mathrm{v}} \frac{du}{dt} = \sum \dot{m}_{\mathrm{i/o,v}} (h_{\mathrm{i/o,v}} - u) + \sum \dot{Q}_{\mathrm{v}} + \dot{E}_{\mathrm{phase}} + P_{\mathrm{s}} - p\frac{dV_{\mathrm{ch}}}{dt} \tag{8}$$

The efficiency of ORC and the output power could be easily determined using enthalpy change and the mass flow rate, described by Equations (9) – (14).

$$\dot{Q}_{\text{pre}} = m_{\text{total}}(h_{\text{out,pre}} - h_{\text{in,pre}}) \tag{9}$$

$$\dot{Q}_{\text{ev}} = m_{\text{total}}(h_{\text{out,ev}} - h_{\text{in,ev}}) \tag{10}$$

$$\dot{W}_{\text{ex}} = m_{\text{total}}(h_{\text{in,ex}} - h_{\text{out,is,ex}})\eta_{\text{is,ex}} \tag{11}$$

$$\dot{Q}_{\text{cd}} = m_{\text{total}}(h_{\text{in,cd}} - h_{\text{out,cd}}) \tag{12}$$

$$\dot{W}_{\text{pm}} = m_{\text{total}}(h_{\text{out,is,pm}} - h_{\text{in,pm}}) / \eta_{\text{is,pm}} \tag{13}$$

$$\eta_{\text{cycle}} = \frac{\dot{W}_{\text{ex}} - \dot{W}_{\text{pm}}}{\dot{Q}_{\text{ev}} + \dot{Q}_{\text{pre}}} = \frac{P_{\text{net}}}{\dot{Q}_{\text{in}}} \tag{14}$$

Since the volume of the working chamber is essential in volumetric expanders and has an influence on the machine operation and performance, the volumetric efficiency and filling factor are important design parameters and could be defined by Equations (15) and (16),

$$\eta_{\text{V,ex}} = \eta_{\text{V}}\eta_{\text{is}} = \frac{N\rho V_{\text{ch}}(h_{\text{in,ex}} - h_{\text{out,ex}})}{60 \cdot \dot{m}_{\text{total,in}}(h_{\text{in,ex}} - h_{\text{out,is,ex}})} \tag{15}$$

$$F_{\text{f}} = \frac{\dot{m}_{\text{m}}}{\dot{m}_{\text{th}}} = \frac{\dot{m}_{\text{m}}}{\rho \dot{V}_{\text{ch,th}}} \tag{16}$$

The total and measured mass flow rate in Equations 15 and 16 might be the same. Since the two-phase volumetric machines are working with wet vapour, the wet isentropic efficiency could be introduced to assess the machine operation. Based on dry isentropic efficiency, Baumann (1921) proposed an empirical method for correction efficiency by dryness (x) or wetness (y) that these following Equations (17) and (18) could define the wet efficiency.

$$\eta_{\text{is,wet}} = \eta_{\text{is,dry}}(1 - \beta_B y) \tag{17}$$

$$y = 1 - x \tag{18}$$

Baumann's rule is a good approach to design the expansion machine in the early stages for predicting the wet energy loss, but the wetness impurity effects and some energy losses have to be taken into account for further calculation (Petr and Kolovratnik, 2013). It is also reported that for low values of y an increase of the Baumann factor is predicted. What is more, during the wet steam expansion the adverse aerodynamics induced by the condensation process can occur and the effect of deposition of fine droplets on machine subassemblies generates the additional enthalpy losses which can be dominating losses limiting the wet efficiency.

3 FEATURES AND CHARACTERISTIC IN WETNESS

Some volumetric expanders have promising potential to be applied in modern ORCs thanks to their advantages, i.e., the expansion offers high efficiency, operating speed is moderate, two-phase expansion is possible, machines are characterized by the low investment cost and compact designs. Volumetric expanders are an especially excellent option to be implemented in ORCs applied for heat harvesting from low-grade heat sources (Badr *et al*., 1984; Kolasiński, 2020). Balje´ (1962) reported that a performance map of a different turbine describes as a function of specific speed and diameter, and using a similar concept, this method could be used to compare the performance of different types of expanders. The characteristic of volumetric expanders depends on the way of their expanding the working fluid in the working chamber. Also, it has to be noted here that the pressure ratio is the most important assessment parameter for volumetric expanders because these machines operate at relatively low pressure compared to turbines, as shown in Table 1. The pressure and the volume are essential parameters for designing volumetric expanders. Their operating conditions could be analyzed using $p-V$ diagram and obtained technical work could be computed using the relation $W_{ex} = \int V dp$.

Table 2: Comparison of selected volumetric expanders operating under wet conditions.

Volumetric types	Displacer movements	Operating in wet conditions	Performance in details (Kolasiński, 2021b)
Piston	Reciprocating	This type of expander enables handling wet vapour in a limited range that liquid phase agitation significantly influences efficiency (Kanno and Shikazono, 2015, 2016). The liquid form could cause damage to the cylinder and flow oscillations during the operation requiring to be balanced (Dumont *et al*., 2017, 2018; Kanno and Shikazono, 2016)	Operating pressure range: 11 – 34 bar Operating temperature range: 65 – 340 °C Power output range: 0.25 – 3 kW Rotational speed range: 320 – 4,000 rpm Efficiency range: 55 – 70%
Gerotor	Rotary and reciprocating (i.e., pistonless rotary machine)	It seems that gerotor machine could also handle wet vapour in a limited range, and it could perform multi-phase in a pump-type (Ejim *et al*., 2020), its performance with the liquid fraction is better than piston one.	Operating pressure range: 27.6 – 65 bar Operating temperature range: 80 – 160 °C Power output range: 0.2 – 2.07 kW Rotational speed range: 3,000 rpm Efficiency range: 35 – 85%
Screw	Rotary	This screw-type machine could handle wet vapour, and many researchers believe that this type is an excellent option as a two-phase volumetric expander with a range of power higher than scroll or piston (Badr *et al*., 1984; Dumont *et al*., 2018; Smith *et al*., 2001)	Operating pressure range: 3 – 25 bar Operating temperature range: 90 – 540 °C Power output range: 2 – 630 kW Efficiency range: 27 – 56%
Scroll	Rotary	This scroll-type machine could handle droplets (Weiß, 2015) with the mass fraction of liquid (x > 0.9) (Dumont *et al*., 2018), also could handle two-phase steam developed for a liquid injected cogeneration/LIC (Mayer, 2010)	Operating pressure range: 1.6 – 8.8 bar Operating temperature range: 90 – 250 °C Power output range: 0.187 – 10 kW Rotational speed range: 250 – 6,000 rpm Efficiency range: 10 – 77.5%

Table 2 - continued: Comparison of selected volumetric expanders operating under wet condition

Volumetric types	Displacer movements	Operating in wet conditions	Performance in details (Kolasiński, 2021b)
Multi-vane	Rotary	This type of machine is a good option for low-temperature applications and could handle liquid fractions (Badr *et al*., 1984). Using a multi-vane machine from this setup (Kolasiński *et al*., 2017), the preliminary experimental in two-phase conditions has been conducted. The result showed that this expander could handle wet vapour. Nevertheless, efficient sealing has to be implemented to reduce leakage.	Operating pressure range: 1.5 – 6.39 bar Operating temperature range: 45 – 150 °C Power output range: 0.065 – 8 kW Rotational speed range: 1,200 – 4,100 rpm Efficiency range: 17.2 – 55.8%

There are two types of volumetric machines (i.e., reciprocating and rotary volumetric expanders). The operating cycle of both types consists of the successive processes of filling, expansion, evacuation, and compression, which is influenced by the machine design features. The features of the machine design generally are described as the working chamber, geometry, the rotor and the stator (for rotary types), and cylinder (for reciprocating type), internal leakage, internal friction, lubrication system, noise, and vibration, etc., that is used to classify the operational range of the machine. Several researchers have been conducting the research using reciprocating devices, single-piston, and multi-piston because it is already mature enough to be used for a combustion engine in the automotive.

Although reciprocating expanders could work under two-phase conditions (Kanno and Shikazono, 2016), these expanders might not be fully suitable for ORC systems because liquid low-boiling working fluid could dissolve the oil film and cause damage to the cylinder and piston rings. Moreover, the working fluid flow inside the working chamber oscillates, that the special methods of machine balancing are necessary to be applied (Weiß, 2015). Badr *et al*. (1984) stated that a rotary volumetric expander is potentially a better choice than a reciprocating one because rotary machines are able to operate with less noise and vibration, smaller friction losses, and limited lubrication. Table 2 shows the comparison of features and characteristics of selected volumetric expanders.

Several researchers have carried out experimental investigations on pumps and compressors operating under two-phase conditions, and from their results, it seems that the two-phase expansion could be implemented in the volumetric expander to develop a wider operating range of ORC systems applied for harvesting energy from low-grade heat sources. It looks that the features and characteristics of rotary volumetric machines tend to adapt better with liquid fractions compared to reciprocating machines. A preliminary experimental study has been conducted by the authors using a small multi-vane expander. In this investigation, it was observed that the multi-vane expander was successfully expanding wet refrigerant vapour and operating without serious problems.

4 CONCLUSIONS

In this paper, a review of literature reports related to volumetric machines that could operate with liquids and two-phase mediums with a special focus paid on two-phase volumetric expanders has been conducted. The mathematical models were also discussed based on the literature review and the mathematical model for two-phase expansion involving conservation of mass and energy, and the efficiency of the volumetric expander was introduced in this study. These models could be applied for modelling the expander operation. The obtained review results show that the rotary volumetric machines (e.g., screw, scroll, multi-vane) could handle wet vapour, which is a good option for the ORC system where the heat source thermal parameters and thermal power is limited (i.e., tend to cause partial evaporation of the working fluid). Encouraged by the obtained review results, the authors decided to perform the preliminary experiment using their own test-stand equipped with a small multi-vane expander. To obtain a two-phase state in this preliminary study, the low-boiling working fluid inside the evaporator was only pre-heated to obtain wet vapour. This investigation observed that the multi-vane expander was successfully expanding wet refrigerant vapour and operating without serious issues. Therefore, the authors decided to continue their research on this topic. For further experiments on this topic, the experimental test-stand has to be redesigned and equipped with a measurement system for two-phase flow and vapour quality. The works on redesigning the test-stand are currently ongoing.

NOMENCLATURE

β	empirical number	(-)
ρ	density	(kg/m^3)
η	efficiency	(-)
σ	ratio	(-)
h	specific enthalpy	(J/kg)
$\dot{m}$	mass flow rate	(kg/s)
m	mass	(kg)
N	rotational speed	(rpm)
p	pressure	(Pa)
P	power	(Watt)
$\dot{Q}$	heat transfer rate	(Watt)
u	internal energy	(Joule)
V	volume	(m^3)
$\dot{W}$	power	(Watt)
x	vapour quality	(-)
y	wetness quality	(-)

Subscript

B	Baumann’s number
c	consumption
cd	condenser
ch	chamber
ev	evaporator
ex	expander
i	inlet
in	input/inlet
is	isentropic
l	liquid
m	measured
o	outlet
out	output/outlet
p	production
pm	pump
pr	pressure
pre	preheater
s	shaft
th	theoretical/ideal
v	vapour
V	volumetric

REFERENCES

Badr, O., O'Callaghan, P. W., Hussein, M., Probert, S. D., 1984, Multi-vane expanders as prime movers for low-grade energy organic Rankine-cycle engines, *Applied Energy*, vol. 16, no. 2, p. 129-146.

Bala, E. J., O'Callaghan, P. W., Probert, S. D., 1985, Influence of organic working fluids on the performance of a positive-displacement pump with sliding vanes, *Applied Energy*, vol. 20, no. 2, p. 153–159.

Balje´, O. E., 1962, A Study on Design Criteria and Matching of Turbomachines: Part A—Similarity Relations and Design Criteria of Turbines, *Journal of Engineering for Power*, vol. 84, no. 1, p. 83–102.

Baumann, K., 1921, Some recent developments in large steam turbine practice, *Journal of the Institution of Electrical Engineers*, vol. 59, no. 302, p. 565–623.

Cengel, Y. A., Boles, M. A., 2007, Thermodynamics: An Engineering Approach 6th Editon (SI Units), The McGraw-Hill Companies, Inc., New York, 1010 p.

Daniarta, S., Imre, A. R., 2020, Cold energy utilization in LNG regasification system using organic rankine cycle and trilateral flash cycle, *Periodica Polytechnica Mechanical Engineering*, vol. 64, no. 4, p. 342-349.

Dumont, O., Dickes, R., Lemort, V., 2017, Experimental investigation of four volumetric expanders, *Energy Procedia*, vol. 129, p. 859–866.

Dumont, O., Parthoens, A., Dickes, R., Lemort, V., 2018, Experimental investigation and optimal performance assessment of four volumetric expanders (scroll, screw, piston and roots) tested in a small-scale organic Rankine cycle system, *Energy*, vol. 165, p. 1119–1127.

Ejim, C. E., Oshinowo, L., Xiao, J., 2020, Modeling Gerotor Pump Performance in Artificial Lift for Single-Phase and Multiphase Conditions. *SPE Production & Operations*, vol. 35, no. 2, p. 393-405.

Fischer, J., 2011, Comparison of trilateral cycles and organic Rankine cycles, *Energy*, vol. 36, no. 10, p. 6208–6219.

Kanno, H., Shikazono, N., 2015, Experimental and modeling study on adiabatic two-phase expansion in a cylinder, *International Journal of Heat and Mass Transfer*, vol. 86, p. 755–763.

Kanno, H., Shikazono, N., 2016, Experimental study on two-phase adiabatic expansion in a reciprocating expander with intake and exhaust processes, *International Journal of Heat and Mass Transfer*, vol. 102, p. 1004–1011.

Kanno, H., Shikazono, N., 2017, Modeling study on two-phase adiabatic expansion in a reciprocating expander, *International Journal of Heat and Mass Transfer*, vol. 104, p. 142–148.

Kolasiński, P., 2021a, Application of volumetric expanders in small vapour power plants used in distributed energy generation – Selected design and thermodynamic issues, *Energy Conversion and Management*, vol. 231, p. 113859.

Kolasiński, P., 2021b, *Układy Organic Rankine Cycle (ORC) małej i średniej mocy wykorzystujące rozprężarki wyporowe*, Wrocław University of Technology Publishers, Wrocław, 202 p.

Kolasiński, P., 2020, The Method of the Working Fluid Selection for Organic Rankine Cycle (ORC) Systems Employing Volumetric Expanders, *Energies*, vol. 13, no. 3, p. 573.

Kolasinski, P., 2019, Application of the multi-vane expanders in orc systems - A review on the experimental and modeling research activities, *Energies*, vol. 12, no. 15., p. 2975.

Kolasiński, P., Błasiak, P., Rak, J., 2016, Experimental and Numerical Analyses on the Rotary Vane Expander Operating Conditions in a Micro Organic Rankine Cycle System, *Energies*, vol. 9, no. 8, 606.

Kolasiński, P., Błasiak, P., Rak, J., 2017, Experimental investigation on multi-vane expander operating conditions in domestic CHP ORC system, *Energy Procedia*, vol. 129, p. 323–330.

Mayer, K., 2010, Research, development and demonstration of micro-CHP system for residential applications. *Ecr International*, Incorporated.

Park, K.-T., Kim, Y.-H., Kim, H.-J., 2016, Design and performance analysis of a gerotor expander for power generation from waste heat, Journal of the Korea Society For Power System Engineering, vol. 20, no. 2, p. 17–25.

Parker, D. B., 1994, Positive displacement pumps-performance and application, *In Proceedings of the*

11th International Pump Users Symposium, Texas A&M University, p. 137.

Petr, V., Kolovratnik, M., 2013, Wet steam energy loss and related Baumann rule in low pressure steam turbines, *In Proceedings of the Institution of Mechanical Engineers*, Part A: Journal of Power and Energy, vol. 228, no. 2, p. 206–215.

Saghlatoun, S., Zhuge, W., Zhang, Y., 2014, Review of Expander Selection for Small-Scale Organic Rankine Cycle, *ASME 2014 4th Joint US-European Fluids Engineering Division Summer Meeting collocated with the ASME 2014 12th International Conference on Nanochannels, Microchannels, and Minichannels*, The American Society of Mechanical Engineers, Illinois.

Smith, I. K., 1993, Development of the trilateral flash cycle system: Part 1: Fundamental considerations. *Proceedings of the Institution of Mechanical Engineers*, Part A: Journal of Power and Energy, vol. 207, no. 3, p.179-194.

Smith, I K, Stošič, N., Aldis, C. A., 1996, Development of the Trilateral Flash Cycle System: Part 3: The Design of High-Efficiency Two-Phase Screw Expanders, *Proceedings of the Institution of Mechanical Engineers*, Part A: Journal of Power and Energy, vol. 210, no. 1, p. 75–93.

Smith, I K, Stosic, N., Kovacevic, A., 2001, Power recovery from low cost two-phase expanders. *Transactions-Geothermal Resources Council*, p. 601-606.

Staniša, B., Ivušić, V., 1995, Erosion behaviour and mechanisms for steam turbine rotor blades, *Wear*, vol. 186–187, part 2, p. 395–400.

Tassou, S. A., Qureshi, T. Q., 1998, Comparative performance evaluation of positive displacement compressors in variable-speed refrigeration applications, *International Journal of Refrigeration*, vol. 21, no. 1, p. 29–41.

Vasuthevan, H., Brümmer, A., 2016, Thermodynamic modeling of screw expander in a Trilateral Flash Cycle, *In International Compressor Engineering Conference*, Purdue University, paper 2475.

Verpe, E., Bantle, M., Faanes, S., Slettebø, N., Eikevik, T. M., 2019, Compressor characteristics of an oil-free, two phase rotary vane motor for water-steam applications. Refrigeration Science and Technology, *In Proceeding of the 25th IIR International Congress of Refrigeration*, IIF/IIR, Montreal, p. 1346.

Wang, Q., Wu, W., He, Z., Ziviani, D., 2019, Analysis of the intake process and its influence on the performance of a two-phase reciprocating expander, *Applied Thermal Engineering*, vol. 160, p. 113943.

Weiß, A. P, 2015, Volumetric expander versus turbine–which is the better choice for small ORC plants, In 3rd ASME ORC Conference, Brussels, p. 1–10.