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Initial Design of an Optical-Access Piston Expansion Chamber for Wet-Expansion

S. Lecompte[a]*, M. van den Broek[a], M. De Paepe[a]

[a]Department of Flow, Heat and Combustion Mechanics, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

Abstract

High efficiency expanders which can cope with fluid-vapour mixtures (i.e wet expansion) at the inlet and during expansion have the potential to increase the power output from thermodynamic power cycles. Volumetric expanders are considered suitable, yet experimental results are scarce and there is no model that can predict the performance of the expansion process. This is mainly due to the knowledge gap on the fundamental aspects off two-phase expansion and the non-equilibrium effects. Therefore, in this work, a variable volume piston expansion chamber is designed. The influence of the main design parameters are investigated by means of a simple deterministic model. Based on initial figures of merit, the component selection and technical layout is presented. The optical access in a later stage will be crucial to allow investigating the mechanistic process of the nucleation and the interfacial effects. This understanding is essential for generalization of the results to other working fluids and geometries.

Keywords: two-phase expansion, piston expander, flash evaporation

1. Introduction

In the last decade, the organic Rankine cycle (ORC) has become a mature technology to convert low temperature heat to electricity. However these commercially available ORCs are all of the subcritical type. Yet, studies in scientific literature clearly show the potential for increased performance with alternative cycle architectures [1, 2]. The trilateral cycle (TLC) is one of the most promising modifications and can boost the power output up to 35%.

* Corresponding author. Tel.: +32 9 264 32 88; fax: +32 9 264 35 90.
E-mail address: steven.lecompte@ugent.be

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The reason for this can be found in the lower exergy destruction during heat transfer from hot fluid to ORC working fluid. The main challenge however, is the development of high efficiency expanders which can cope with fluid-vapour mixtures (i.e. two-phase mixtures) at the inlet and during wet-expansion.

Nomenclature		**Greek symbols**	
A	area, m²	ρ	density, kg/m³
F	force, N	**Subscripts and superscripts**	
h_{lg}	latent heat, J/kg	0	initial starting values
L	length, m	cyl	cylinder
m	mass, kg	e	equilibrium
$\dot{m}$	mass flow rate, kg/s	i	interface liquid vapour
p	pressure, Pa	sg	saturated vapour
$\dot{q}$	net heat flux, W/m²	sl	saturated liquid

Volumetric expanders are considered suitable, yet few results are presented up to now. Experimental results are scarce and there is no model that can predict the performance of the expansion process. This is mainly due to the knowledge gap on the fundamental aspects of two-phase expansion and the non-equilibrium effects. Mainly for twin screw-expanders some experimental results are available. Smith et al. [3], performed measurements on double screw expanders with inlet vapour qualities from 50% to 25%. They showed adiabatic efficiencies ranging between 40% and 80%. A trend, indicating reduced adiabatic efficiencies under two-phase expansion for high efficiency single phase double screw machines and vice versa, was shown by Öhman and Lundqvist [4]. However, they state that the available test data in literature is scarce and that the actual behaviour of the two-phase expansion is unknown. Smith et al. [3] demonstrated that a model with the assumption of a homogeneous one-dimensional flow gives a good prediction of the p-V diagram. This simplification is valid according to the authors because of the considerable rotational component. Considering a homogeneous flow, the hypothesis is that the liquid part is broken up in sufficient small components which promote a sufficiently mixed flow. The small particles will flash fast to vapour and give rise to an equilibrium temperature between the gas and the liquid phase.

An alternative to the twin-screw expander would be a piston expander. Piston expanders allow for larger built-in volume ratios (between 6 and 14) than twin-screw expanders (between 2 and 8) and are thus more adapted to two-phase expansion. The simple geometry furthermore allows for a reduced construction cost. As such, piston type expanders for two-phase flow are readily found in CO_2 refrigeration and CO_2 power systems [5]. A disadvantage of the reciprocating expander is the inherent dead volume that results in some pre-expansion losses. There is also the complexity associated to actuating and timing the inlet and outlet valves. As there is no direct rotational component, it is furthermore unclear whether the assumption of an equilibrium homogeneous flow is still valid. When looking for example to static flashing, see further in section 1.1, there are clearly non-equilibrium effects. Fortunately, the geometry of the piston expanders lends itself to in-situ flow measurements. The process of the two-phase expansion can thus be experimentally examined and mechanistic models can be validated. To the authors' knowledge there is, alas, no prior research on this topic.

In this work, an experimental test-rig is presented to investigate flashing under changing volume of the flashing chamber during expansion. A possible modelling approach based on the homogeneous relaxation model (HRM) with the extension of flow regime maps is proposed. Finally, an approximate design model is presented and the results are discussed.

1.1. Two-phase flashing fundamentals

The two-phase expansion process consists of a non-equilibrium flashing into a liquid-vapour mixture. This system is in a non-equilibrium state because of the difference in temperature and velocity between the two phases [3, 6]. The vapour fraction can be considered to enter as saturated vapour and during expansion, the vapour becomes partly subcooled before being condensed. The liquid fraction on the other hand partly evaporates during expansion. The rate of evaporation changes according to the number of nuclei during the boiling and the superheat of the liquid. However, the behaviour is more complex as one can expect an interaction between the gaseous and the liquid state