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Liquid flooded compression and expansion in scroll machines – Part II: Experimental testing and model validation

Ian H. Bell[a,*], Vincent Lemort[b], Eckhard A. Groll[a], James E. Braun[a], Galen B. King[a], W. Travis Horton[a]

[a] Purdue University, Department of Mechanical Engineering, 140 S. Martin Jischke Drive, West Lafayette, IN 47906, USA
[b] University of Liège, Aerospace and Mechanical Engineering Department, Liège, Belgium

ARTICLE INFO

Article history:
Received 24 November 2011
Received in revised form
10 July 2012
Accepted 18 July 2012
Available online 31 July 2012

Keywords:
Scroll compressors
Scroll expanders
Liquid flooding
Isothermal compression
High efficiency

ABSTRACT

The use of liquid-flooding in the compression and expansion of non-condensable gas in scroll compressors and expanders enables the possibility of quasi-isothermal working processes. Liquid-flooded scroll machines were installed in a fully-instrumented Liquid-Flooded Ericsson Cycle test rig to conduct entire cycle performance tests. In addition, detailed compressor and expander performance data was obtained. Oil mass fractions of up to 92% and 76% were added to the gas entering the scroll compressor and expander respectively. The overall isentropic efficiency of the scroll compressor based on the shaft power with flooding was up to 73% and the volumetric efficiency was above 92%. For the expander, the best overall isentropic and volumetric efficiencies achieved were 66% and 105% respectively. The mechanistic model presented in the companion paper was validated against the experimental data for both the compressor and the scroll expander with good agreement, though the agreement is better for the scroll compressor.

Compression et détente noyées dans les systèmes à spirale – Partie II : essais expérimentaux et validation du modèle

Mots clés : Compresseurs à spirale ; Machines de détente à spirale ; Cycle noyé ; Compression isotherme ; Forte efficacité

1. Introduction

In a four-component gas-phase refrigeration cycle, gas is compressed in the compressor, cooled at a constant high pressure in a heat exchanger, expanded in the expander, and finally, the low-pressure, cooled gas warms up at a constant low-pressure, providing the cooling effect. The Liquid-Flooded Ericsson Cycle provides a few modifications on top of the basic configuration of the gas refrigeration cycle. While the Liquid-Flooded Ericsson Cycle also adds a regenerator to exchange

* *Corresponding author*. Tel.: +1 607 227 7626.
E-mail addresses: ian.h.bell@gmail.com (I.H. Bell), vincent.lemort@ulg.ac.be (V. Lemort), groll@purdue.edu (E.A. Groll), jbraun@purdue.edu (J.E. Braun), kinggb@purdue.edu (G.B. King), wthorton@purdue.edu (W.T. Horton).
0140-7007/$ – see front matter
http://dx.doi.org/10.1016/j.ijrefrig.2012.07.008

Nomenclature

X_d	area correction factor
h	specific enthalpy (kJ kg^{-1})
M	calculated value (varies)
$\dot{m}$	mass flow (kg s^{-1})
N	rotational speed (rev min^{-1})
p	pressure (kPa)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
$\overline{UA}_{amb}$	ambient heat transfer conductance (kW K^{-1})
V_{disp}	displacement volume (m^3)
$\dot{W}$	shaft power (kW)
x	mass fraction
δ	gap width (–)
η	efficiency (–)
ε	effectiveness
ε	absolute uncertainty (varies)
ψ	entrainment fraction
ρ	density (kg m^{-3})
σ	ratio down/upstream area
ω	rotational speed (rad s^{-1})
τ	torque (N m)

Subscripts

amb	ambient
comp	compressor
discharge	discharge
exp	expander
f	flank
g	gas
high	high-side
i	isentropic
in	inlet
int	internal
l	liquid
low	low-side
m	mixture
meas	measured
mix	of the mixture
out	outlet
r	radial
shell	shell
v	volumetric
Υ	parameter under consideration

Abbreviations

HX	heat exchanger
RPM	revolution per minute

heat between the hot and cold sides of the cycle, the most significant change is the addition of liquid loops for both the hot and cold sides of the cycle. The liquid loops allow for quasi-isothermal operation of the compressor and expander, which in the absence of pressure drop and other losses, yields the ideal Ericsson cycle which is composed of four processes: isothermal compression, isobaric heat rejection, isothermal expansion, and isobaric heat addition. If all components perform reversibly, the efficiency of the Ericsson cycle is equal to the Carnot cycle.

Prior experimental work on the Liquid-Flooded Ericsson Cycle (LFEC) has been conducted by Hugenroth (2006, 2007), who developed a first experimental prototype of the LFEC system. During the course of the studies, it was determined that a relocation of the heat exchangers from the oil loops to the gas loop could provide improved performance (LFEC 2 configuration). The system presented here is an embodiment of the LFEC 2 modification. In his studies, Hugenroth noted that the experimental performance of the scroll machines was poor, and suggested from simplified cycle modeling that in order to achieve a COP of the system of 1.25, overall isentropic efficiencies of 87% would be required for all rotating machinery. The work presented here is a step towards achieving the goal of scroll machines with these extremely high efficiencies. Further analysis of the potential for redesign of the scroll compressor for liquid flooding is presented in Bell et al. (2012a).

2. Experimental methods

The flooded scroll machines were installed in a cycle test stand as seen in Fig. 1 to measure the performance of the Liquid-Flooded Ericsson Cycle. Both the scroll expander and the scroll compressor were the same model of automotive scroll compressor seen in Fig. 2. While the primary goal of the testing was to provide system-level data on the performance of the LFEC, detailed data was also available on the performance of the flooded scroll compressor and flooded scroll expander. The system was charged with dry nitrogen as the working fluid, and alkyl-benzene refrigeration oil (Zerol 60) as the flooding liquid. Though other fluid combinations could have been used to achieve superior cycle performance, nitrogen and alkyl-benzene oil are readily available, environmentally friendly and safe. Hugenroth (2006) provides analysis of LFEC system performance for several working fluid pairs.

2.1. *Description of system*

Oil and gas are adiabatically mixed at state point 21. Simultaneously the gas is compressed and the oil is pumped from state point 22 to state point 23, at which point the oil–gas mixture passes into the hot heat exchanger at state point 29 and is cooled to state point 30. The mixture is cooled against an ethylene glycol-water temperature bath. After exiting the hot heat exchanger, the two-phase mixture enters into the hot-side separator (state point 26) where the oil and gas are separated into oil (state point 31) and gas (state point 32) phases. The oil is then expanded from high pressure (state point 24) to low pressure (state point 25) in a hydraulic expander to generate electrical power. The expanded oil at state point 19 is then mixed back into the hot gas stream. The hot gas exiting the separator then enters the regenerator (state point 8) where it is cooled to state point 9.

After exiting the regenerator, the cooled gas (state point 4) is mixed with cool oil (state point 3) to state point 5. This two-