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Thermodynamic analysis of a liquid-flooded Ericsson cycle cooler

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Abstract

A novel approach to implementing a gas Ericsson cycle heat pump was developed. The concept, termed a liquid-flooded Ericsson cooler (LFEC), uses liquid flooding of the compressor and expander to approach isothermal compression and expansion processes. Analytical models of liquid-flooded compression and expansion processes were developed using ideal gas, constant specific heat, and incompressible liquid assumptions. Special considerations for use of positive displacement compressors with fixed volume ratios are detailed. The unique behavior of a liquid-flooded compressor was explored, including the discovery of an optimum liquid flooding rate that minimizes compression power. A computer model of the LFEC cycle was developed using ideal gas, incompressible liquid, and constant specific heat assumptions. The model was used for a thorough parametric study. The purpose of the study was to explore the feasibility of the concept, identify the optimum operating parameters, and to provide a basis for the design of an experimental system.

Keywords: Heat pump; Thermodynamic cycle; Ericsson; Air; Modelling; Compression; Liquid-vapour

Refroidisseur à cycle d'Ericsson noyé : analyse thermodynamique

Mots clés : Pompe à chaleur ; Cycle thermodynamique ; Ericsson ; Air ; Modélisation ; Compression ; Liquide-vapeur

1. Introduction

A cooling mode Ericsson cycle heat pump (i.e. Ericsson cycle cooler) was explored as an alternative to vapor compression systems. The motivation of the work was the elimination of HFC refrigerants, which are potent greenhouse gases. Gas cycles, such as the Ericsson cycle, can use environmentally benign working fluids, such as air, argon, xenon, or helium. Replacement of HFC refrigerants with natural working fluids would reduce the direct impact of refrigerant leakage on global warming. However, in order to not increase the indirect global warming impact due to

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Nomenclature

a	liquid volume fraction
c	specific heat
C_{ratio}	capacitance rate ratio
f	liquid to gas mass ratio
k	ratio of specific heats
m	mass
$\dot{m}$	mass flow rate
P	pressure
P_{ratio}	pressure ratio
Q	heat transfer
$\dot{Q}$	heat transfer rate
q_v	volumetric capacity
R	gas constant
$\dot{S}_{gen}$	entropy generation rate
T	temperature
U	internal energy
u	specific internal energy
v	specific volume
V	volume
$\dot{V}$	volume flow rate
w	specific work
$\dot{W}$	power

Subscripts, Greek, and miscellaneous

c	compressor
dis	displacement
e	expander
f	final
g	gas
i	in, initial
l	liquid
o	out, final
p	pressure
ref	cold space
reg	regenerator
v	volume
ρ	density
ξ	entropy generation per unit capacity
η	adiabatic efficiency
ω	rotational speed
∞	ambient
*	effective

burning of fossil fuels for electricity generation, alternatives to vapor compression systems should have equal or better operating efficiencies.

The basic reverse Ericsson cycle is composed of four thermodynamic process steps. These are:

1–2 isothermal compression,
2–3 constant pressure regeneration – heat rejected to the low temperature stream,
3–4 isothermal expansion,
4–1 Constant pressure regeneration – heat absorbed from the high temperature stream.

A *Ts* diagram of the cycle is shown in Fig. 1 and a schematic of an Ericsson cycle is shown in Fig. 2. The reverse Ericsson cycle is theoretically attractive because it operates at the Carnot COP.

The liquid-flooded Ericsson cooler (LFEC) is a modification of the basic reverse Ericsson cycle that overcomes the substantial practical difficulties of achieving isothermal compression and expansion processes. In this case, isothermal compression and expansion are approached by mixing a nonvolatile liquid with a noncondensable gas during the compression and expansion processes. A schematic of the liquid-flooded Ericsson cooler is shown in Fig. 3. The term "flooded" comes from the notion that the compressor and expander are flooded with large quantities of liquid. As shown in Fig. 3, the liquid that floods the compressor or expander is separated from the gas and exchanges energy with a sink or source, respectively, through external heat exchangers within liquid loops. A practical approach for achieving liquid flooding would be to utilize oil as the liquid in combination with compressors/expanders that would tolerate high oil volumes, such as scroll technology. Liquid mass flow rates may be significantly greater than gas flow rates. This is in contrast to oil injection schemes in some types of positive displacement compressors where the principle purpose is to improve sealing of the leakage paths and the reduction of friction within the compressor, and the oil flow rates represent only about 1–5% of the total flow by mass.

If the liquid's capacitance rate (liquid specific heat times the liquid mass flow rate) is much greater than the gas' capacitance rate, most of the heat of compression of the gas can be absorbed by the liquid. In the limiting case where the ratio of liquid to gas capacitance rate is infinite and

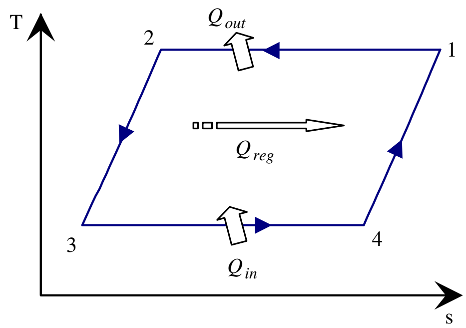

Fig. 1. *Ts* diagram for an ideal Ericsson cycle cooler.