INTERNATIONAL JOURNAL OF REFRIGERATION 68 (2016) 50–58

Available online at www.sciencedirect.com

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Performance analysis of liquid flooded compression with regeneration for cold climate heat pumps

Sugirdhalakshmi Ramaraj *, *James E. Braun*, *Eckhard A. Groll*, *W. Travis Horton*

Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, 177 S. Russell Street, West Lafayette, IN 47907-2099, USA

ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form 13 April 2016
Accepted 17 April 2016
Available online 20 April 2016

Keywords:
Flooded compression
Regeneration
Vapor compression cycle
Heat pumps

ABSTRACT

In regions with sub-freezing winter temperatures, the performance of conventional air-source vapor compression heat pumps drop drastically during extended periods of low outdoor ambient temperatures. Modifying the basic cycle configuration with liquid flooded compression and regeneration reduces the thermodynamic inefficiencies associated with the heat pump equipment and increases energy efficiency with less degradation in heating capacity especially at low ambient temperatures. Flooding non-volatile liquid along with refrigerant vapor stream into the compressor leads to a near isothermal compression process and thereby reduces desuperheating losses in the condenser. Regeneration improves the system performance by reducing throttling losses in the expansion device. The performance of a heat pump operating with flooded compression and regeneration has been analyzed for three sub-freezing outdoor ambient climatic regions: Boston, Indianapolis and Minneapolis. The results indicate that at −10 °C ambient temperature, COP (heating) of the flooded compression with regeneration cycle was approximately 13% higher than the standard vapor compression cycle. The Heating Seasonal Performance Factor (HSPF) of a flooded compression with regeneration cycle for Boston, Indianapolis and Minneapolis was approximately estimated to be 9%, 10% and 13% higher than the standard vapor compression cycle respectively.

Analyse de performance de compression noyée dans du liquide avec régénération pour des pompes à chaleur de climat froid

Mots clés : Compression noyée ; Régénération ; Cycle à compression de vapeur ; Pompes à chaleur

* Corresponding author. Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, 177 S. Russell Street, West Lafayette, IN 47907-2099, USA. Tel.: +1 3175259882; Fax: +1 7654940787.
E-mail address: sramaraj@purdue.edu (S. Ramaraj).
http://dx.doi.org/10.1016/j.ijrefrig.2016.04.017

Nomenclature

c_p	specific heat [kJ kg^{-1} K^{-1}]
h	specific enthalpy [kJ kg^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
n	polytropic exponent [–]
P	pressure [kPa (abs)]
$\dot{Q}$	heat transfer rate [kW]
s	specific entropy [kJ kg^{-1} K^{-1}]
T	temperature [K]
T_H	sink temperature [°C]
T_L	source temperature [°C]
x_{oil}	oil mass fraction [–]
$\dot{W}$	power [kW]
ΔT_{pinch}	pinch temperature difference [°C]
$\Delta T_{subcool}$	subcooling temperature difference [°C]
$\Delta T_{superheat}$	superheat temperature difference [°C]
ρ	density [kg m^{-3}]

Subscripts

1, 2, 3, . . .	state points
1m, 2m	mixture property at state points
aux	auxiliary heating
c	critical
comp	compressor
cond	condenser
evap	evaporator
heating	heating load
ref	refrigerant gas
oil	liquid oil
m	mixture of refrigerant gas and liquid oil
S	solved refrigerant
out	outlet

Acronyms

COP	Coefficient of Performance
COSP	Coefficient of System Performance
EES	Engineering Equation Solver
HSPF	Heating Seasonal Performance Factor
RPM	Revolutions Per Minute
TMY	Typical Meteorological Year

1. Introduction

At very low outdoor temperatures such as –30 °C, the heat output and coefficient of performance (COP) of a heat pump decreases while the compressor discharge temperature increases due to a high pressure ratio. The high discharge temperature can cause degradation of lubricant oil in the compressor. As a result, the compressor is typically shut off when the ambient temperature falls below a certain limit value and an auxiliary heater (e.g., electrical or gas) is used to meet the load requirement. The combination of low COP and compressor lock out leads to significantly higher operating costs for heat pumps in cold climates. Also, a heat pump sized for loads at low outdoor temperatures will have a capacity that is large in relation to the heating demand at higher ambient temperatures and cooling demand when run as an air-conditioner during hot weather conditions. With this sizing approach, a cold climate heat pump that uses on/off cycling for load control will have reduced system efficiency and compressor life due to being oversized throughout the cooling season and for much of the heating season. A better approach for cold climate heat pumps would be to utilize a variable-speed compressor that can more efficiently adjust capacity to match the heating and cooling demand.

Modifications to the basic cycle configuration can provide substantial improvements in both capacity and COP of heat pump systems especially at sub-freezing temperatures. Bertsch et al. (2005) compared eight different concepts to address issues related to the design of heat pumps for low temperature climates. Compressor technology enhancements coupled with the system address the thermodynamic inefficiencies inherent within the simple heat pump cycle and contribute further to the system performance. Cooling of the compression process by flooding a large amount of high specific heat fluid along with the refrigerant stream decreases the discharge temperature and leads to lower compression work for a given pressure ratio. Some positive results have been obtained from experimental testing of oil flooding in screw and scroll compressors (Hiwata et al., 2002; Sawai et al., 2009; Stosic et al., 1990). Hugenroth et al. (2006) showed that it was possible to improve the overall system efficiency of an Ericsson cycle by flooding the compressor with oil. Bell et al. (2011) did a complete system analysis on liquid flooding and predicted that when liquid flooding with regeneration is applied to refrigeration and heat pump systems, the improvement in COP can be greater than 50% for systems that operate at very large temperature lifts. Bell et al. (2013) performed experimental testing of oil injection in a residential air conditioning compressor designed for vapor injection and showed the overall isentropic efficiency increased with oil injection rate over the range considered. Ramaraj et al. (2012) estimated a 10% improvement in the performance of a heat pump with flooded compression and regeneration for cold climatic conditions as experienced in Minnesota. However, the model was based on the assumption that the compressor efficiency was the same for conventional and flooded operation. Ramaraj et al. (2014) showed experimentally that there is an optimal oil flooding rate that yields maximum compressor efficiency. About an 8% relative improvement in isentropic efficiency and greater than 10% improvement in volumetric efficiency with oil flooding were demonstrated for a R410A scroll compressor that was modified for oil flooding. In addition, an empirical model was developed that maps the experimental performance of the R410A compressor with oil flooding. In the previous work, a single constant compressor efficiency was used for both the standard vapor compression cycle and flooded cycle with regeneration. This approach did not consider the benefits of the oil flooding on the compressor performance due to reduced leakage between chambers, which is particularly significant at low outdoor temperatures. Also, no limitation on the compressor discharge temperature was considered in the previous work. However, a cycle with flooded compression has lower discharge temperatures for the same operating conditions and therefore can operate at lower ambient temperatures (i.e., higher pressure ratios) leading to a reduction in auxiliary heat under low ambient conditions where the conventional cycle must shut off. In order to consider these beneficial effects,