INTERNATIONAL JOURNAL OF REFRIGERATION 67 (2016) 77–89

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

Optimum compressor cylinder volume ratio for two-stage compression air source heat pump systems

Shuang Jiang [a], Shugang Wang [a,*], Xu Jin [b], Yao Yu [c]

[a] *Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China*
[b] *School of Energy and Power Engineering, Northeast Dianli University, Jilin 132012, China*
[c] *Department of Construction Management and Engineering, North Dakota State University, Fargo, ND 58108-6050, USA*

A R T I C L E I N F O

Article history:
Received 2 February 2016
Received in revised form 16 March 2016
Accepted 19 March 2016
Available online 23 March 2016

Keywords:
Two-stage system
Volume ratio
Air-to-water heat pump
Optimum
Subcooler

A B S T R A C T

With the outstanding performance potential and excellent modulation capacity, the Two-Stage Air Source Heat Pump (TSAHP) may become a substitute for fossil fuels for space heating in cold climates. In TSAHP, the design cylinder volume ratio is closely related to the evaporating and condensing conditions and will determine the average heating seasonal coefficient of performance ($\overline{COP}$). In this paper, based on weather data and a two-step optimization approach, a volume-ratio selection method was presented. Eight typical cities in the cold region of North China were selected for demonstrating the impacts of the optimum cylinder volume ratio at different outdoor design temperatures on $\overline{COP}$. The results show that the appropriate outdoor design temperature is between −4 °C and −8 °C, and the corresponding design cylinder volume ratio is between 2.0 and 2.1. The $\overline{COP}$ with the volume ratio of 2.0 is 10.3% and 17.6% higher than that with the volume ratio of 3.0.

Rapport volumique optimal de cylindre compresseur pour des systèmes de pompe à chaleur aérothermique à compression bi-étagée

Mots clés : Système bi-étagé ; Rapport volumique ; Pompe à chaleur air-eau ; Optimal ; Sous-refroidisseur

* *Corresponding author.* Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China. Tel.: +86 411 84706407; Fax: +86 411 84706407.

E-mail address: sgwangln@aliyun.com (S. Wang).

http://dx.doi.org/10.1016/j.ijrefrig.2016.03.012

Nomenclature

a_1-a_4, c_1-c_4	coefficients in the efficiency formulas [-]
Bo	boiling number [-]
COP	coefficient of performance [-]
h	specific enthalpy [kJ kg^{-1}]
f	frequency [Hz]
$\dot{m}$	refrigerant mass flow rate [kg s^{-1}]
Nu	Nusselt number
n	polytropic exponent [-]
p	pressure [kPa]
Pr	Prandtl number
$\dot{Q}$	heat transfer rate [kW]
Re	Reynolds number [-]
R_m	refrigerant mass flow ratio [-]
R_{cy}	compressor cylinder volume ratio [-]
T	temperature [°C]
V	volume [m^3]
$\dot{w}$	work [kW]
w	specific work [kJ kg^{-1}]
x	refrigerant quality [-]
ε	heat exchanger subcooling parameter [-]
η	efficiency [-]
v	specific volume [m^3 kg^{-1}]
μ	viscosity [Pa·s]
ρ	density [kg m^{-3}]

Subscripts

a	air
cy	cylinder
d	design
dis	discharge
el	electric
eq	equivalent
H	high-stage compressor
h	heating
in	input
inj	injection
L	low-stage compressor/liquid
m	intermediate/mass
max	maximum
min	minimum
n	indoor
rat	ratio
suc	suction
th	theoretical
T	total
vol	volume
w	wall

Superscript

*	parameters at base frequency

1. Introduction

Applying heat pumps to space heating for residential buildings in cold regions will reduce the combustion of gas, oil and other fossil fuels and the emissions of greenhouse gases. An Air Source Heat Pump (ASHP), which uses the widely available air as heat source, is more easily deployed and applied than other types of heat pumps, such as geothermal heat pumps. Nevertheless, in the cold areas where space heating is required, the outdoor temperatures are extremely low, and could be below −20 °C in the northern parts of China. In this case, the evaporating temperature of the ASHP decreases and the temperature difference between the heat source and sink increases, which result in the deteriorated heating capacity, declining coefficient of performance and even abnormal shut down due to the high discharge temperature.

Different approaches regarding how to improve the thermodynamic performance of high temperature lift heat pumps were presented, experimentally compared and deeply analyzed by Zehnder (2004). These approaches included one stage compression with intermediate injection of saturated vapor, two-stage economizer cycle and booster concept, and liquid subcooling through an auxiliary cycle. Zehnder concluded that the two-stage compression cycle represents the next generation of heat pump due to its modulation capacity and the potentially higher system performance. Tian et al. (2006) proposed a two-stage compression variable frequency air source heat pump. The low- and high-stage variable frequency compressors were used, which had the capacities of 5HP and 3HP, respectively. The experimental results show that the COP is higher than 2.0, the discharge temperature of the high-stage compressor is below 120 °C, and the heating capacity is able to meet the heating load when the condensing and evaporating temperatures are 50 °C and −25 °C, respectively. The tested system works in a stable state and the lubricant return is performed well, and is able to meet the heating demand without auxiliary heat sources in cold regions where the outdoor temperature is not lower than −18 °C. Bertsch and Groll (2008) simulated, designed, constructed and tested a two-stage air-source heat pump for water and air heating, which is able to operate at ambient temperatures between −30 °C and 10 °C with the supply water temperatures of up to 50 °C. This system uses a subcooler as the inter-stage structure and could be operated in either single- or two-stage mode. At the same ambient temperature, two-stage mode operation approximately doubles the heating capacity compared to the single-stage mode operation. The discharge temperatures of the compressors in the two-stage mode maintain below 105 °C at all times. Based on this technology, Caskey et al. (2012) and their three industrial partners designed and fabricated a new air-source heat pump system optimized for cold climates, which was installed in a military barrack for a field demonstration. A simulation model was developed in EES in order to predict the designed heat pump performance at different ambient conditions. The EES results were incorporated with a TRNSYS model that was used to estimate the military barrack building load. This coupled model has the ability to predict the heating energy consumption of the heat pump system according to different capacities determined by ambient conditions or weather data. The predicted results show that the heat pump performs well in cold climates and the COPs constantly maintain above 3.5 over the entire heating season. Additionally, the savings of a cold climate heat pump compared to a natural gas furnace was anticipated to be over 30% for primary energy consumption and CO_2