Applied Thermal Engineering 115 (2017) 393–405

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental performance study on a dual-mode CO_2 heat pump system with thermal storage

Fang Liu [a,*], Weiquan Zhu [a], Yang Cai [a], Eckhard A. Groll [b], Jianxing Ren [a], Yafeng Lei [c]

[a] *College of Energy and Mechanical Engineering, Shanghai University of Electric Power, 2103 Pingliang Road, Yangpu District, Shanghai 200090, China*
[b] *School of Mechanical Engineering, Ray W. Herrick Laboratories, Purdue University, 177 S. Russel Street, West Lafayette, IN 47907, USA*
[c] *VisionBEE, 13640 Briarwick Drive, Austin, TX 78729, USA*

HIGHLIGHTS

- High compressor frequency leads to high overall COP during energy charging process.
- EEV opening affects the coupled system performances significantly.
- Low hot and cold water flow rates are both beneficial for the overall COP.
- The overall system COP reaches up to 5.49 at certain control parameters.

ARTICLE INFO

Article history:
Received 30 August 2016
Revised 9 December 2016
Accepted 16 December 2016
Available online 23 December 2016

Keywords:
CO_2 heat pump
Thermal storage
Dual-mode
Optimization

ABSTRACT

Performances of a water-source CO_2 heat pump coupled with hot and cold thermal storage were investigated experimentally in this study. This combined system was tested by controlling compressor frequency, expansion valve opening, and hot and cold circulated water flow rates. Experimental results shows that higher compressor frequency leads to a shorter energy charging time and a higher overall coefficient of performance (COP) of the combined system during the charging process. Expansion valve opening affects the COPs significantly but affects the thermal stratification in thermal storage tanks slightly. Low hot and cold water flow rates lead to the good thermal stratification in storage tanks, which is beneficial for the overall COP of the combined system during the charging process, although high water flow rates are beneficial for the transient COP of heat pump at the beginning of the charging process. The overall COP reaches maximum when the hot and cold water flow rates were set as 0.1 m^3/h and 0.2 m^3/h respectively at the compressor frequency of 50 Hz and at the expansion valve opening of 330 pulses. Based on the test data, the correlations of COP with the outlet water temperature of thermal storage tanks were developed for further optimizing this combined system.

1. Introduction

The electricity utility industry is undergoing massive changes. Increasing penetration levels of intermittent renewables (wind and solar power) in the energy system call for the development of Smart Grid enabling technologies. The market for energy system intelligence and flexibility – Smart Grid enabling technologies and services – becomes one of the fastest growing markets within just a few years [1]. From an energy system perspective, energy storage is the most critical for Smart Grid technology area. The specific cost of thermal storage is easily 1% or less of the costs of electrochemical or mechanical storage. Furthermore, thermal storage offers advantageous characteristics, including longer life time, no degradation in capacity, and higher charge–discharge efficiency. In 2012 Blarke et al. [1] proposed to use the water source CO_2 heat pump system as a ‘Thermal Battery’ with smart grid option, which has the capability of simultaneous cooling and heating, along with minimizing operational cost and CO_2 emissions. This kind of thermal batteries can be applied to buildings, such as hospitals, hotels, and data centers, which require both heating (for hot water supply or space heating) and cooling (for electrical equipment or space cooling) purposes.

Carbon dioxide (CO_2) has environmentally friendly characteristics, ozone depletion potential (ODP) and extremely low global warming potential (GWP), and is being advocated as one of the natural refrigerants to replace CFCs and HCFCs in vapor compression systems. Study of Sarkar et al. [2] shows that the CO_2 heat

---

* Corresponding author.
E-mail addresses: fangliu@shiep.edu.cn, fangliu_shiep@163.com (F. Liu).

http://dx.doi.org/10.1016/j.applthermaleng.2016.12.095
1359-4311/

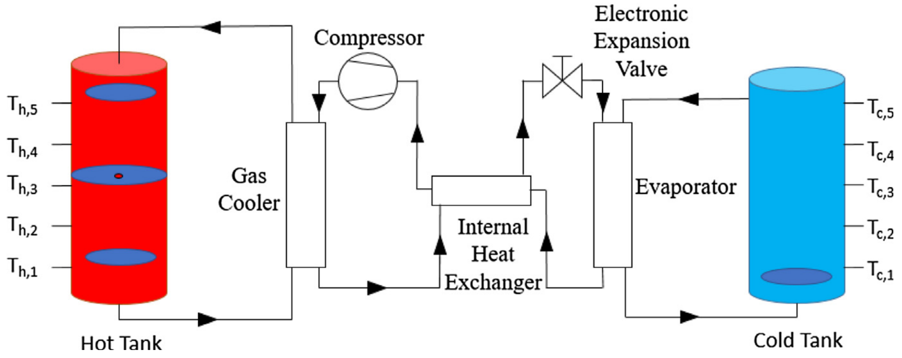
Nomenclature

COP	coefficient of performance (–)
Cp	specific heat at constant pressure (J/kg/K)
EEV	electric expansion valve
f	compressor frequency (Hz)
GWP	global warming potential
$\dot{m}$	mass flow rate (kg/s)
n	pulse number (pulse)
ODP	ozone depletion potential
P	pressure (MPa)
$\dot{Q}$	capacity (kW)
Q	overall capacity (MJ)
T	temperature (°C)
$\dot{V}$	volumetric flow rate (m^3/h)
$\dot{W}$	power (kW)

Subscripts

c	cold, cold tank
clg	cooling
comp	compressor
evap	evaporator
h	hot, hot tank
htg	heating
i	inlet
o	outlet
w	water

(a) Photograph of experimental test setup



(b) Schematic of experimental test setup

Fig. 1. Experimental test setup of heat pump coupled with thermal storage tanks.

Table 1
Uncertainty analysis for the combined system test.

Measured data	Value	Absolute uncertainty	$\dot{Q}_{clg}$ (W) uncertainty	$\dot{Q}_{clg}$ (W) uncertainty	COP (–) contributions
$t_{c,o}$ (°C)	15	0.1	43.73%	0.00%	15.01%
$t_{c,i}$ (°C)	4.29	0.1	43.73%	0.00%	15.01%
$t_{h,i}$ (°C)	59.46	0.1	0.00%	21.58%	3.75%
$t_{h,o}$ (°C)	37	0.1	0.00%	21.58%	3.75%
$\dot{V}_{w,c}$ (m^3/h)	0.2	0.001	12.54%	0.00%	4.30%
$\dot{V}_{w,h}$ (m^3/h)	0.1	0.0005	0.00%	56.84%	9.89%
$\dot{W}_{comp}$ (W)	1068	6.77	0.00%	0.00%	36.63%
$\dot{W}_{pump,c}$ (W)	52.5	2.71	0.00%	0.00%	5.87%
$\dot{W}_{pump,h}$ (W)	47.1	2.69	0.00%	0.00%	5.78%
Calculated results			2491	3775	5.367
Absolute uncertainty			5.17	5.04	0.05142
Relative uncertainty			0.21%	0.13%	0.96%