International Journal of Heat and Mass Transfer 54 (2011) 1896–1906

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Development and validation of static simulation model for CO_2 heat pump

Seiichi Yamaguchi *, Daisuke Kato [1], Kiyoshi Saito [1], Sunao Kawai [1]

Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1-58-210 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan

A R T I C L E I N F O

Article history:
Received 10 July 2009
Received in revised form 2 September 2010
Accepted 17 December 2010
Available online 12 February 2011

Keywords:
CO_2
Heat pump
Water heater
Simulation
Validation

A B S T R A C T

A simulation model for the CO_2 heat pump water heater was developed and validated in this study. Component models of the gas cooler, evaporator, compressor, and expansion valve were constructed with careful consideration for the heat transfer performances. To validate the simulation model, experiments were carried out using an actual CO_2 heat pump water heater (water heating capacity: 22.3 kW; hot-water temperature: 90 °C). In simulations and experiments, the effects of the inlet water temperature and outside air temperature on the system characteristics were discussed. As a result, the average difference in COP between the simulation results and experimental results is 1.5%.

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1. Introduction

The effectiveness of the CO_2 heat pump water heater in controlling global warming is being recognized in Japan. The use of this water heater in place of the ordinary water heater, which is mainly driven by gas, can lead to a significant reduction in the primary energy consumption. Therefore, the CO_2 heat pump is gaining popularity in Japan. In order to improve the system performance of the CO_2 heat pump, it is necessary to develop an optimum design and a control method for the CO_2 heat pump water heater. For this purpose, high-precision and general-purpose simulation model is required. In this study, we have developed a high-precision and general-purpose system simulation model for the CO_2 heat pump water heater and investigated the validity of this model with detailed experiments.

Some previous studies have discussed system simulations for the CO_2 heat pump water heater. White et al. [1] developed a simulation model for the CO_2 heat pump water heater. In their system model, model of each component was derived based on the experimental data. For instance, they experimentally clarified that the pressure head (m) and the isentropic efficiency of the compressor were expressed as linear functions of swept volume, and the heat transfer rate (W/K) of the gas cooler was a linear function of only refrigerant flow rate. These were only adopted to their prototype heat pump. The average difference between the predicted COP and the measured COP was 4.1%. Cecchinato et al. [2] compared the performance of the CO_2 heat pump water heater with that of the R134A heat pump by carrying out simulation studies. However, they did not investigate the validity of their simulation model. Yokoyama et al. [3] developed a simulation model for the CO_2 heat pump water heater with using a domestic hot water storage tank and analyzed the effect of the outside air temperature and tap-water temperature on the performance of the heat pump. The validity of the model was investigated by comparing the simulation results with experimental results. In this study, the overall heat transfer coefficients of the gas cooler and the evaporator were constant, i.e., they used the experimental values. Sarkar et al. [4] formulated certain guidelines for the design and optimization of the water-to-water CO_2 heat pump on the basis of simulations. Their model employed the supercritical heat transfer correlation proposed by Pitla Srinivas et al. [5] and the Watelet-Carlo correlation for two-phase flows. However, they did not investigate the validity of the model. Agrawal and Bhattacharyya [6] compared the performance of a water-to-water CO_2 heat pump that used a capillary tube with that of a water-to-water CO_2 heat pump that used an expansion valve. The simulation model used in their study was the same as that used by Sarkar et al. [4]. They compared the results of their simulation with a small amount of experimental data in order to confirm the validity of the model.

The general versatility and validity of the conventional models are yet to be confirmed because these models estimate the heat transfer performance using a simple equation that is derived for a particular system. In addition, in the validation studies, sufficient experimental data were not available for comparison with the simulation results. Furthermore, it is important for the system simulation to select the appropriate heat transfer correlations to predict the system characteristics. Pitla Srinivas et al. [5] proposed a heat transfer correlation by observing the heat transfer in the

* Corresponding author. Tel.: +81 3 5286 3247; fax: +81 3 5286 3259.
E-mail address: sei_yamaguchi@aoni.waseda.jp (S. Yamaguchi).
[1] Tel.: +81 3 5286 3247; fax: +81 3 5286 3259.

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doi:10.1016/j.ijheatmasstransfer.2011.01.013

Nomenclature

A	heat transfer area, m^2
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
c_v	flow rate coefficient
d	diameter, m
E	compressor power consumption, kW
F	friction factor
G	mass flux, kg m^{-2} s^{-1}
h	specific enthalpy, kJ kg^{-1}
K	overall heat transfer coefficient, kW m^{-2} K^{-1}
L	length, m
M	molecular weight, kg $kmol^{-1}$
m	mass flow rate, kg s^{-1}
m	refrigerant mass, kg
N	rotary speed, rps
Nu	Nusselt number
P	pressure, MPa
Pr	Prandtl number
q	heat exchange rate per unit length, kW m^{-1}
Q	heat exchange rate, kW
Re	Reynolds number
T	temperature, K
t	thickness, m
u	velocity, m s^{-1}
V	stroke volume, m^3
W	compressor load, kW
We	Weber number
x	vapor quality

Greek symbols

α	heat transfer coefficient, kW m^{-2} K^{-1}
δ	liquid film thickness, m
ε	cross-sectional vapor void fraction
η	efficiency
λ	thermal conductivity, kW m^{-1} K^{-1}
μ	dynamic viscosity, Ns m^{-2}
ξ	lubricant suppression factor
ρ	density, kg m^{-3}

Subscripts

A	annular flow
a	air or adiabatic
ami	ambient air
b	bulk
c	collar
cb	convective boiling
com	compressor
de	dry completion
di	dry inception
dry	dry area
dryout	dryout region
e	volumetric
eff	effective
eva	evaporator
exp	expansion valve
f	fin, film, or frictional
fp	flow pattern
gc	gas cooler
H	helical or homogeneous
h	high pressure
hwi	supplied water for the system
hyd	hydraulic
I	intermittent flow
ini	initial
IA	intermittent to annular flow transition
i	inside or inlet
LO	considering the total vapor–liquid flow as liquid flow
l	low pressure, longitudinal, or liquid
m	mechanical, momentum, or mean
mist	mist flow
nb	nucleate boiling
o	outside or outlet
r	refrigerant
S	straight or single-phase flow
Slug	slug flow
t	tube
tp	two-phase flow
v	vapor
w	water
wall	wall
wet	wet area

supercritical region of CO_2 using a tube-in-tube counter-flow heat exchanger, which had a stainless-steel inner tube with a diameter of 4.72 mm. Dang and Hihara [7,8] proposed a heat transfer correlation by experiments and investigated the effect of the mass flow rate, pressure, heat flux, and tube diameter on the supercritical region of CO_2 through experiments. They also reported the effect of lubricating oil on the supercritical region of supercritical CO_2. Cheng et al. [9,10] developed a two-phase flow pattern map for CO_2evaporation. They also reported the heat transfer correlations and developed a pressure drop model on the basis of their flow pattern. Katsuta et al. [11] studied the effect of PAG oil on CO_2evaporation. Further, they proposed a heat transfer correlation by modifying the Dittus–Boelter correlation and developed a pressure drop model using the modified Lockhart–Martinelli parameter. Some researchers have reported the effect of lubricating oil on evaporation. However, a widely applicable heat transfer model that takes into consideration the use of oil has not yet been proposed.

In our study, we develop a simulation model by adopting some recently constructed heat transfer correlations, carry out the experiments to obtain sufficient data, and investigate the validity of our model, In the simulations and experiments, we investigate the effect of the inlet water temperature and outside air temperature on COP, heat exchanger rate in the gas cooler and evaporator, power consumption of the compressor, the CO_2 mass flow rate and pressure at the inlet and outlet of the compressor. For our experiment, we used a 22.3-kW CO_2 heat pump water heater.

2. CO_2 heat pump water heater

Fig. 1 shows the system flow diagram of the CO_2 heat pump water heater. This system consists of a gas cooler, an evaporator, an internal heat exchanger, a compressor, and an expansion valve. In the internal heat exchanger, the refrigerant from the evaporator cools the refrigerant that flows in from the gas cooler, and then flows into the compressor, where its pressure and temperature are increased. The heated refrigerant then flows into the gas cooler, where it heats up the supplied water. Subsequently, it flows into the internal heat exchanger and is expanded by the expansion valve. Finally, the refrigerant flows into the evaporator. In the evaporator, the refrigerant absorbs heat from the ambient air, after which it flows back to the internal heat exchanger.

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