



## Development and validation of static simulation model for CO<sub>2</sub> heat pump

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### ABSTRACT

A simulation model for the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> heat pump is gaining popularity in Japan. In order to improve the system performance of the CO<sub>2</sub> heat pump, it is necessary to develop an optimum design and a control method for the CO<sub>2</sub> 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<sub>2</sub> heat pump water heater and investigated the validity of this model with detailed experiments.

Some previous studies have discussed system simulations for the CO<sub>2</sub> heat pump water heater. White et al. [1] developed a simulation model for the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> heat pump that used a capillary tube with that of a water-to-water CO<sub>2</sub> 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

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**Nomenclature**

$A$	heat transfer area, $\text{m}^2$	ami	ambient air
$c_p$	specific heat at constant pressure, $\text{J kg}^{-1} \text{K}^{-1}$	b	bulk
$c_v$	flow rate coefficient	c	collar
$d$	diameter, m	cb	convective boiling
$E$	compressor power consumption, kW	com	compressor
$F$	friction factor	de	dry completion
$G$	mass flux, $\text{kg m}^{-2} \text{s}^{-1}$	di	dry inception
$h$	specific enthalpy, $\text{kJ kg}^{-1}$	dry	dry area
$K$	overall heat transfer coefficient, $\text{kW m}^{-2} \text{K}^{-1}$	dryout	dryout region
$L$	length, m	e	volumetric
$M$	molecular weight, $\text{kg kmol}^{-1}$	eff	effective
$m$	mass flow rate, $\text{kg s}^{-1}$	eva	evaporator
$m$	refrigerant mass, kg	exp	expansion valve
$N$	rotary speed, rps	f	fin, film, or frictional
$\text{Nu}$	Nusselt number	fp	flow pattern
$P$	pressure, MPa	gc	gas cooler
$\text{Pr}$	Prandtl number	H	helical or homogeneous
$q$	heat exchange rate per unit length, $\text{kW m}^{-1}$	h	high pressure
$Q$	heat exchange rate, kW	hwi	supplied water for the system
$\text{Re}$	Reynolds number	hyd	hydraulic
$T$	temperature, K	I	intermittent flow
$t$	thickness, m	ini	initial
$u$	velocity, $\text{m s}^{-1}$	IA	intermittent to annular flow transition
$V$	stroke volume, $\text{m}^3$	i	inside or inlet
$W$	compressor load, kW	LO	considering the total vapor–liquid flow as liquid flow
$\text{We}$	Weber number	l	low pressure, longitudinal, or liquid
$x$	vapor quality	m	mechanical, momentum, or mean
<i>Greek symbols</i>			
$\alpha$	heat transfer coefficient, $\text{kW m}^{-2} \text{K}^{-1}$	mist	mist flow
$\delta$	liquid film thickness, m	nb	nucleate boiling
$\varepsilon$	cross-sectional vapor void fraction	o	outside or outlet
$\eta$	efficiency	r	refrigerant
$\lambda$	thermal conductivity, $\text{kW m}^{-1} \text{K}^{-1}$	S	straight or single-phase flow
$\mu$	dynamic viscosity, $\text{Ns m}^{-2}$	Slug	slug flow
$\xi$	lubricant suppression factor	t	tube
$\rho$	density, $\text{kg m}^{-3}$	tp	two-phase flow
<i>Subscripts</i>			
A	annular flow	v	vapor
a	air or adiabatic	w	water
		wall	wall
		wet	wet area

supercritical region of  $\text{CO}_2$  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  $\text{CO}_2$  through experiments. They also reported the effect of lubricating oil on the supercritical region of supercritical  $\text{CO}_2$ . Cheng et al. [9,10] developed a two-phase flow pattern map for  $\text{CO}_2$  evaporation. 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  $\text{CO}_2$  evaporation. 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  $\text{CO}_2$  mass flow rate and pressure at the inlet and outlet of the compressor. For our experiment, we used a 22.3-kW  $\text{CO}_2$  heat pump water heater.

## 2. $\text{CO}_2$ heat pump water heater

Fig. 1 shows the system flow diagram of the  $\text{CO}_2$  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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