

Performance analysis of a CO₂ heat pump water heating system under a daily change in a standardized demand

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ABSTRACT

Air-to-water heat pumps using CO₂ as a natural refrigerant have been developed and commercialized. They are expected to contribute to energy saving in residential hot water supply. The objective of the research is to analyze the performance of a water heating system composed of a CO₂ heat pump and a hot water storage tank by numerical simulation. In this paper, the system performance is analyzed under a daily change in a standardized hot water demand, and some features of the temperature distribution in the storage tank and the system performance criteria such as coefficient of performance, storage and system efficiencies, and volumes of stored and unused hot water are investigated. It turns out that the daily change in the hot water demand does not significantly affect the daily averages of the COP, and storage and system efficiencies, while it significantly affects not only the daily change in the volume of hot water unused after the tapping mode, but also that in the volume of hot water stored after the charging mode. The influence of the daily change in the hot water demand on the volumes of stored and unused hot water is clarified quantitatively.

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1. Introduction

Air-to-water heat pumps using CO₂ as a natural refrigerant have been developed and commercialized. They are expected to contribute to energy saving in residential hot water supply [1].

Many theoretical and experimental studies have been conducted for the performance analysis only on CO₂ heat pumps [2–10]. The recent technological development has enhanced the performance of CO₂ heat pumps remarkably. However, a residential water heating system is composed of a CO₂ heat pump and a hot water storage tank so that it can supply hot water even in the case of a sudden increase in hot water demand, and its performance is affected significantly not only by instantaneous air and feed water temperatures but also by hourly changes in the heat pump operation, hot water demand, and their resultant temperature distribution in the storage tank. Therefore, it is necessary to conduct the performance analysis on water heating systems in consideration of these items. It takes much time to do it under various conditions by experiment, and it is expected that numerical simulation enables one to do it very efficiently.

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Some studies have been conducted for the performance analysis on water heating systems [11,12]. However, few studies have been conducted in consideration of hourly changes in the heat pump operation, hot water demand, and their resultant temperature distribution in the storage tank [13–15]. First in these studies, simulation models have been proposed, and results obtained by numerical simulation have been compared with those by experiment. Then, the influence of ambient conditions such as air and feed water temperatures on the system performance has been clarified. In addition, the influence of operation conditions such as the outlet water temperature during the heat pump operation and the inlet water temperature for the heat pump shutdown on the system performance has been clarified. However, the system performance has been investigated under the condition without any daily change in a standardized hot water demand. The hot water demand may change daily actually, which may affect the system performance significantly. Therefore, it is also important to investigate the system performance under a daily change in the hot water demand.

In this paper, the performance of a CO₂ heat pump water heating system is analyzed under a daily change in a hot water demand by numerical simulation. Here, an hourly change in a standardized hot water demand is adopted as the first step of the research, and the magnitude for the hot water flow rates is changed daily. The influence of the daily change in the standardized hot water demand on the system performance is investigated. Especially, features of

the temperature distribution in the storage tank and the system performance criteria such as coefficient of performance (COP), storage and system efficiencies, and volumes of stored and unused hot water are investigated.

2. CO₂ heat pump water heating system

Fig. 1 shows the configuration of the CO₂ heat pump water heating system investigated in this paper. This system is composed of a CO₂ heat pump and a hot water storage tank. The CO₂ heat pump is composed of a compressor, a gas cooler, an expansion valve, and an evaporator. The system is equipped with a fan, a pump, and motors M1–M3 as auxiliary machinery. Here, inlet and outlet water is defined as water at the inlet and outlet of the gas cooler, respectively. The system heats water using the refrigeration cycle of the CO₂ heat pump, stores hot water in the storage tank, and supplies it to a tapping site.

3. Numerical simulation

3.1. Simulation model

3.1.1. Modeling of CO₂ heat pump

A simplified static model is adopted for the CO₂ heat pump [13]: i.e., although the CO₂ heat pump includes the aforementioned four components, they are not taken into account explicitly, and it is expressed by one model. The mass flow rates and temperatures of water at the inlet and outlet, COP, heat output, power consumption, and air temperature are adopted as basic variables whose values are to be determined. The mass and energy balance relationships as well as the energy input and output relationship are adopted as basic equations to be satisfied. The remaining equations to be considered are approximate functions of the power consumption and COP, and they are expressed in relation to the air and inlet/outlet water temperatures.

The model of the CO₂ heat pump is shown in Fig. 2. The mass and energy balance relationships are expressed by

$$\left. \begin{aligned} \dot{m}_{\text{HPi}} &= \dot{m}_{\text{HPo}} \\ \dot{m}_{\text{HPi}} c T_{\text{HPi}} + \dot{Q}_{\text{HP}} &= \dot{m}_{\text{HPo}} c T_{\text{HPo}} \end{aligned} \right\} \quad (1)$$

where $\dot{m}_{\text{HP}}$ and T_{HP} are the mass flow rate and temperature of water, respectively, and these variables at the inlet and outlet are

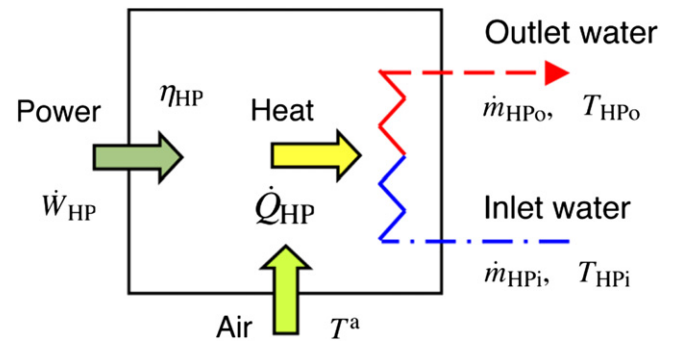


Fig. 2. Model of CO₂ heat pump.

denoted by the subscripts i and o, respectively. In addition, $\dot{Q}_{\text{HP}}$ is the heat output, and c is the specific heat of water, which is assumed to be constant. The energy input and output relationship is expressed by

$$\dot{Q}_{\text{HP}} = \eta_{\text{HP}} \dot{W}_{\text{HP}} \quad (2)$$

where $\dot{W}_{\text{HP}}$ is the power consumption, and η_{HP} is the COP. The approximate functions of the power consumption and COP are expressed by quadratic functions with respect to the air and inlet/outlet water temperatures as follows:

$$\left. \begin{aligned} \dot{W}_{\text{HP}} &= \left(\alpha_1 + \beta_1 T^a + \gamma_1 T^{a^2} \right) \left(\alpha_2 + \beta_2 T_{\text{HPi}} + \gamma_2 T_{\text{HPi}}^2 \right) \\ &\quad \times \left(\alpha_3 + \beta_3 T_{\text{HPo}} + \gamma_3 T_{\text{HPo}}^2 \right) \\ \eta_{\text{HP}} &= \left(\alpha_4 + \beta_4 T^a + \gamma_4 T^{a^2} \right) \left(\alpha_5 + \beta_5 T_{\text{HPi}} + \gamma_5 T_{\text{HPi}}^2 \right) \\ &\quad \times \left(\alpha_6 + \beta_6 T_{\text{HPo}} + \gamma_6 T_{\text{HPo}}^2 \right) \end{aligned} \right\} \quad (3)$$

where T^a is the air temperature, and $\alpha_1 \sim \alpha_6$, $\beta_1 \sim \beta_6$, and $\gamma_1 \sim \gamma_6$ are the coefficients of the quadratic functions, whose values are to be identified based on measured data for an existing device. The modeling results in a set of nonlinear algebraic equations.

3.1.2. Modeling of storage tank

A detailed dynamic model is adopted for the storage tank [13,14]. To consider the one-dimensional vertical temperature

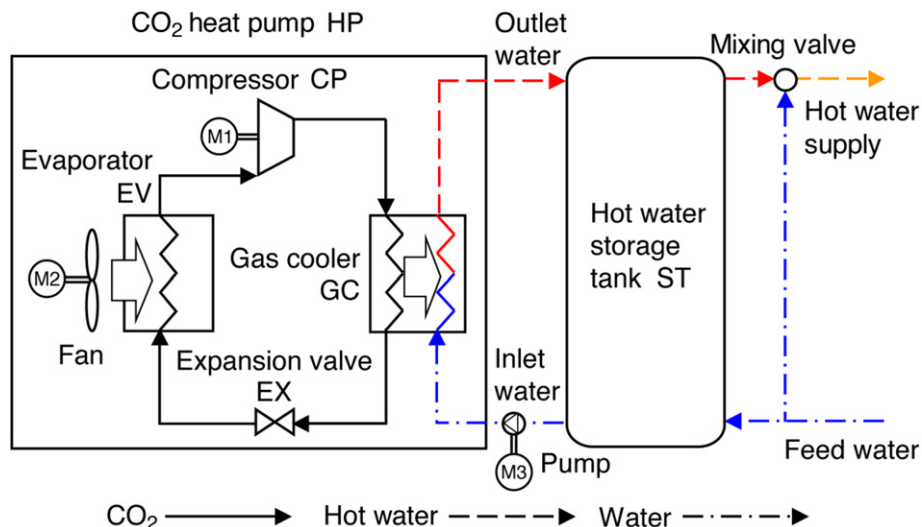


Fig. 1. Configuration of CO₂ heat pump water heating system.

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