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Performance optimization of a cascade multi-functional heat pump in various operation modes

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ABSTRACT

A multi-heat pump has been widely used to provide cooling and heating in a building. In addition, the demands for a cascade heat pump water heater have been increased due to its higher energy efficiency with high water temperature. In this study, a cascade multi-functional heat pump, which combines a multi-heat pump using R410A for air heating and cooling with a cascade heat pump using R134a for water heating, is considered to provide simultaneous air heating, air cooling, and water heating in a building. The performance of the cascade multi-functional heat pump was measured and analyzed in four operation modes: full-heating hot water, heating-main hot water, full-cooling hot water, and cooling-main hot water. The performance of the cascade multi-functional heat pump in each of the four operation modes was optimized by adjusting control parameters such as the compressor rotation speed and EEV opening and by modifying the refrigerant flow path.

Optimisation de la performance d'une pompe à chaleur multifonctionnelle en cascade sous divers modes de fonctionnement

Mots clés : Pompe à chaleur ; Eau chaude ; Système en cascade ; R134a ; R410A ; Optimisation

1. Introduction

A multi-heat pump has been widely adopted to provide cooling and heating in a building. Compared to conventional central air-conditioning systems, multi-heat pumps can control the temperature of each room precisely without air and water distribution circuits (Xia et al., 2004). A simultaneous heating and cooling multi-heat pump has been developed to provide the required heating and cooling to different zones of

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Nomenclature

CMHP	cascade multi-functional heat pump
COP	coefficient of performance
CSR	compressor speed ratio (%)
EEV	electronic expansion valve
HX	heat exchanger
IDU	indoor unit
IHX	intermediate heat exchanger
m	mass flow rate (kg h^{-1})
MCU	mode change unit
ODU	outdoor unit
q	capacity (W)
T	temperature (°C)
v	specific volume (m^3 kg^{-1})
W	power consumption (W)
WHU	water heating unit

Subscripts

a	air
c	condenser
CMHP	cascade multi-functional heat pump
e	evaporator
i	inlet
L	low-stage cycle
o	outlet
r	refrigerant
sup	superheat
t	total
w	water
WHU	water heating unit

a building at the same time. The major focus in the research of the multi-heat pump has been to develop advanced technologies to achieve optimum refrigerant flow control, and high system efficiency and reliability (Kang et al., 2009). In addition, a cascade heat pump water heater has been introduced as a substitute for the conventional boiler due to its ability to provide higher water temperatures and improved energy efficiency (Hepbasli and Kalinci, 2009; Aikins et al., 2013). The demands for a cascade multi-functional heat pump (CMHP), which can provide heating, cooling, and hot water at the same time, have increased to save energy. However, the CMHP should be properly optimized in various operation modes so that it can provide heating, cooling, and hot water simultaneously at high system efficiency.

Extensive studies have been conducted to improve the performance of multi-heat pumps by controlling the compressor speed and EEV opening. Kang et al. (2009) optimized the refrigerant flow and compressor speed of a simultaneous air heating and cooling multi-heat pump in five different operation modes. Joo et al. (2011) measured the performance of a simultaneous air heating and cooling multi-heat pump at partial load conditions. Choi et al. (2011) analyzed the heating performance of a multi-heat pump system using R410A. In addition, many studies on cascade heat pumps and heat pump water heaters have been conducted. Kulcar et al. (2008) analyzed the performance of a cascade heat pump using R407C/R600a at low geothermal temperatures. Bertsch and Groll (2008) analytically compared the performances of three types of two-stage heat pump water heaters. Yokoyama et al. (2010) investigated the performance of a CO_2 heat pump water heater under daily changes of the standard demand. Wu et al. (2012) measured the transient behavior of a cascade heat pump water heater with a thermal storage tank using R404A/R134a. Kim et al. (2013) numerically analyzed the optimal intermediate temperature of a cascade heat pump water heater using R134a/R410A under various operation conditions. Stene (2005) designed a CO_2 heat pump having a counter-flow gas-cooler for hot water preheating and measured the performance of the heat pump under three different operation modes. Cho and Choi (2012) investigated the performance of a multi-function heat pump in cooling-hot water and heating-hot water operation modes.

Most previous studies focused on the performance improvement of multi-heat pumps and heat pump water heaters having a single function. However, studies on multi-functional heat pumps providing air cooling, air heating, and water heating at the same time in various operation modes are limited in the open literature. In this study, a cascade multi-functional heat pump (CMHP), combining a simultaneous heating and cooling multi-heat pump using R410A with a cascade heat pump water heater using R134a, was investigated experimentally in four operation modes; full-heating hot water, heating-main hot water, cooling-main hot water, and full-cooling hot water modes. The performance of the CMHP was measured in each of the four operation modes by varying the compressor rotation speed, EEV openings in the outdoor unit and intermediate heat exchanger, and the refrigerant flow path. In addition, the CMHP was optimized to improve the COP by controlling the refrigerant flow rate through each indoor unit and water heating unit in the four operation modes, while satisfying the design capacities of air cooling, air heating, and water heating.

2. Experimental setup and test procedure

2.1. Experimental setup

A cascade heat pump water heater consisted of two separate cycles: a low-stage cycle and a high-stage cycle. As shown in Fig. 1, the heat absorbed in the evaporator of the low-stage cycle is transferred to the evaporator of the high-stage cycle using an intermediate heat exchanger (Messineo and Panno, 2012). Fig. 2 shows a schematic diagram of the CMHP experimental setup adopting the cascade heat pump cycle. The CMHP consisted of an outdoor unit (ODU), three indoor units (IDU), a water heating unit (WHU), and a mode change unit (MCU). The CMHP operated in the cascade heat pump cycle combining the low-stage using R410A and the high-stage using R134a. The CMHP was designed to have an air heating capacity of 6.3 kW in the full-heating hot water mode, an air