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Effect of vapor-injection technique on the performance of a cascade heat pump water heater

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ABSTRACT

In this study, we applied a vapor-injection (VI) technique in a cascade heat pump system. The VI was applied to both upper and lower stage cycles. Test results showed that heating and cooling capacities increased by using the VI technique (12% and 6%, respectively); however, the system COP decreased (6.6% at the injection ratio of 16.7%). The cascade system which has a small compression ratio and a cascade condenser, cannot fully utilize the VI's advantages to improve the system COP. However, the VI is effective for the system reliability and capacity improvement. We also found that the VI in the upper and lower stage cycles had different effect on overall cycle operating characteristic.

Effet de la technique d'injection de vapeur sur la performance d'un chauffe-eau à pompe à chaleur en cascade

Mots clés : Cascade ; Pompe à chaleur ; Injection de vapeur ; R404A ; Chauffe-eau

1. Introduction

Economic development and population growth have increased energy demand. In this situation, energy saving becomes an important issue. As compared to a traditional boiler using fossil fuels or an electric water heater, a heat pump water heater (HPWH) system can generate hot water with two or three times higher efficiency than conventional water heaters. Therefore, it has been predicted that HPWHs will be more widely used in the next-generation residential and commercial buildings (Neksa et al., 1998; Wu et al., 2012).

However, for the effective utilization of an HPWH, it is necessary to solve the issue of reduction in the heating capacity and rise in the pressure ratio with decrease in the temperature of the heat source. A solar-assisted heat pump system can be a solution (Chaturvedi et al., 1998; Kuang et al., 2003; Li et al., 2007; Chow et al., 2010; Li and Yang, 2010; Sterling and Collins, 2012), however, solar energy may not

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Nomenclature

BPHE	brazed plate heat exchanger
C	specific heat (kJ kg^{-1})
COP	coefficient of performance
HPWH	heat pump water heater
IHX	internal heat exchanger
LTC	low temperature cycle
$\dot{m}$	mass flow rate (g s^{-1})
OT	overlap temperature (°C)
P	pressure (kPa)
$\dot{Q}$	capacity (kW)
R	injection ratio
T	temperature (°C)
HTC	high temperature cycle
VI	vapor injection
$\dot{W}$	power consumption (kW)

Subscripts

cond	condenser side
cool	cooling side
eva	evaporator side
heat	heating side
in	inlet
inj	injection stream side
main	main stream side
out	outlet
w	water side

always be available, and in most applications, there is the problem of a time mismatch between availability and demand (Sole et al., 2008). Furthermore, a solar energy collector requires a large amount of space for installation, which limits its general use in high-rise residential buildings or the central area of a city (Wu et al., 2012).

A multistage heat pump cycle can be a solution to improve the HPWH's performance. A multistage heat pump cycle has higher compression efficiency with smaller compression ratio and lower discharge temperature than a single-stage heat pump cycle. Bertsch and Groll (2008) studied three types of multistage cycles: a two-stage heat pump with an intercooler, a two-stage heat pump with an economizer, and a cascade cycle. In their study, the cascade cycle showed the best performance at low ambient temperatures. In severely cold outdoor air conditions, a cascade cycle is one of the good options to supply hot water.

In previous studies on the cascade cycle, there have been many approaches to find optimized designs and combinations of refrigerants. Bhattacharyya et al. (2005) optimized a CO_2–C_3H_8 cascade system for refrigeration and heating; they concluded that the high temperature part of the cascade cycle is very effective in increasing the overall performance. This indicates that the two cycles (the high temperature and low temperature cycles) have different effects on the overall performance of the cascade system. Understanding the effect of HTC and LTC, in terms of operation control, is important to optimize a cascade cycle. Bhattacharyya et al. (2009) also carried out a thermodynamic analysis and optimization for a N_2O–CO_2 cascade system. They analyzed the relative effects of the components on the performance of the system, especially the effects of heat exchangers. In their research, a cascade condenser's performance highly affects the overall system's performance. Kilicarslan and Hosoz (2010) studied the irreversibility of a cascade refrigeration system using various refrigerants. They found that there was an appropriate combination of refrigerants for obtaining a high coefficient of performance (COP) and low irreversibility. Although these previous studies have provided much insight for understanding a cascade cycle, ways to improve the performance of cascade cycles should be further studied, and more cascade cycle studies are still needed in various systems and operating circumstances.

In recent years, the multistage heat pump cycle has been modified to a "vapor-injection (VI)" cycle by using a new type of compressor that is specifically designed to have a dedicated injection port. Wang et al. (2009) studied a two-stage heat pump system with a vapor-injected scroll compressor. They showed the improvement of heating capacity by 30%, with the 20% of COP gain at the ambient temperature of −17.8 °C. Heo et al. (2010, 2011) compared the heating performances of various VI cycles using a flash tank and an internal heat exchanger (IHX). In their research, the COP and heating capacity of the injection cycle were enhanced by 10% and 25%, respectively, at an ambient temperature of −15 °C.

Xu et al. (2011) summarized benefits of the VI technique. First, the capacity improvement in a severe climate is possible. Second, the system capacity can be varied by controlling the injected refrigerant mass flow rate, which permits some energy savings by avoiding intermittent operation of the compressor. Third, the compressor discharge temperature can be lowered. This is the main advantages of the VI technique, because the VI technique can lower the discharge temperature and increase capacities (heating and cooling), simultaneously, in severe climate conditions. Meanwhile, a liquid injection technique (Park et al., 2002; Cho et al., 2003; Gao et al., 2009) has been mainly used for decreasing the compressor discharge temperature without capacity increases.

We applied the VI technique in the cascade cycle, where the cascade cycle was composed of two VI cycles. This is a novel way to combine the two technologies (cascade cycle and VI technique), which resembles a four-stage cycle. Basically, the high temperature cycle (HTC) and low temperature cycle (LTC) operates independently; however, the cycles affect each other to satisfy an energy balance. In particular, we focus on the VI technique's operating features and its effects on the cascade cycle's performance.

2. Experimental system and process

2.1. *Description of experimental setup*

Fig. 1 shows a schematic diagram of a cascade water-source HPWH. Two scroll type compressors were installed, and