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Performance comparison among two-phase, liquid, and vapor injection heat pumps with a scroll compressor using R410A

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HIGHLIGHTS

- A numerical model is developed to predict the performance of injection heat pumps with a scroll compressor.
- Performance characteristics of liquid, vapor, and two-phase injection heat pumps are compared.
- The optimum injection quality in the two-phase injection heat pump is analyzed as a function of operating parameters.
- The two-phase injection heat pump exhibits the highest COP among all injection types with a proper discharge temperature.

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ABSTRACT

Although two-phase injection technique is expected to improve the performance and reliability of heat pumps in cold climate conditions, its application is limited due to wet-compression. In this study, a numerical model was developed and validated to predict the performance of liquid, vapor, and two-phase injection heat pumps. The performance characteristics of the liquid, vapor, and two-phase injection heat pumps with a scroll compressor using R410A were compared with the others, based on the predicted data. The optimum injection quality in the two-phase injection heat pump to achieve maximum COP was analyzed as a function of the injection pressure, compressor frequency, and outdoor temperature. The two-phase injection heat pump with the optimum injection quality exhibited the highest COP among all injection types with a proper discharge temperature. In addition, the two-phase injection heat pump with the optimum injection quality was more effective in COP improvement with decreasing outdoor temperature.

1. Introduction

The refrigerant injection technique is widely used to improve the performance and reliability of a heat pump when operated in severe weather conditions [1–7]. The refrigerant injection is performed by injecting a portion of the refrigerant from the condenser outlet to the inlet or middle of a compression pocket [8–10]. The refrigerant injection decreases discharge temperature and approaches the isentropic compression process [11–13]. Injection techniques are classified into liquid injection (LI), vapor injection (VI), and two-phase injections (TPI). A two-phase injection is considered to be more effective in decreasing the discharge temperature when compared to a vapor injection due to the use of latent heat. However, the application of two-phase injection remains questionable due to the wet-compression problem.

Table 1 shows research trends on injection heat pumps [14–24]. Most previous studies focused on vapor injection with scroll and rotary compressors in order to improve the performance and reliability of residential heat pumps in cold climate conditions. Vapor injection is classified as internal heat exchanger (IHX) and flash tank (FT) types [15–22]. Major research issues on vapor injection heat pumps are component optimization, control strategy, and drop-in tests with alternative refrigerants. Navarro et al. [25] evaluated the effects of intermediate gas superheat, intermediate pressure, and wet injection in a vapor injection scroll compressor. Wang et al. [26] investigated the optimization of a vapor injection heat pump. An FT-type vapor injection heat pump exhibited a better performance potential when compared with that of an IHX-type vapor injection heat pump. Studies on applying vapor injection heat pumps to electric vehicles are also actively underway.

Moreover, liquid injection has been investigated extensively to achieve the reliability of the compressor under severe weather conditions. Xu et al. [27] reported that liquid and vapor injections exhibited improvements in the coefficient of performance (COP) and reliability in heat pumps. Lee et al. [28] measured the cooling performance of an

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Nomenclature

A	area (mm^2)
C_d	coefficient of the flow rate (–)
COP	coefficient of performance (–)
D_h	hydraulic diameter (mm)
f	compressor frequency (Hz)
FT	flash tank
h	enthalpy (kJ kg^{-1})
h_c	convection heat transfer coefficient (kJ $m^{-2}h^{-1}$ °C^{-1})
IHX	internal heat exchanger
ISH	injection superheat (°C)
k	conductivity (kJ m^{-1} h^{-1} °C^{-1})
LI	liquid injection
m	mass (kg)
$\dot{m}$	mass flow rate (kg h^{-1})
Nu	Nusselt number (–)
P	pressure (kPa)
Pr	Prandtl number (–)
$\dot{Q}_{heater}$	heater capacity (kW)
$\dot{Q}_{heating}$	heating capacity (kW)
R	gas constant (J mol^{-1} K^{-1})
R_{inj}	injection ratio
Re	Reynolds number (–)
r	radius (mm)
SH	superheat (°C)
T	temperature (°C)
$T_{outdoor}$	outdoor temperature (°C)
t	time (s)
TPI	two-phase injection
V	chamber volume (m^3)
VI	vapor injection
$\dot{W}_{comp}$	work (kW)
x	quality (–)
w	uncertainty (–)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
γ	specific heat ratio (–)
θ	orbiting angle (°)
υ	specific volume (m^3 kg^{-1})

Subscripts

avg	average
c	chamber
cond	condenser
cr	critical
dis	discharge
down	downstream
i	experiment number
IHX	internal heat exchanger
in	inlet
inj	injection
n	number of experiment cases
out	outlet
r	ratio
sat	saturated
suc	suction
up	upstream
x	local point

R22 refrigeration system with liquid and vapor injections at high compression ratios. Cho et al. [29] studied the performance of an inverter-driven scroll compressor with liquid injection. They reported that a liquid injection was extremely effective in achieving higher performance and reliability of a compressor at high compressor frequencies. In addition, numerical models for liquid and two-phase injections were developed to analyze its feasibility as compared with the conventional heat pump [14,23].

There is a paucity of studies on two-phase injection because of the wet-compression problem and experimental difficulties in measuring injection quality. Yang et al. [23] evaluated the effectiveness of two-phase suction, liquid injection, and two-phase injection with respect to decreases in the discharge temperature of an R32 scroll compressor. Lee et al. [24] reported that the compressor power input of a two-phase injection cycle was 22.6% lower than that of a vapor injection cycle at a lower outdoor temperature in the heating mode. However, the variation in the performance of a two-phase injection heat pump with respect to the injection quality and injection pressure under various operating conditions has not been studied in detail.

As stated previously, two-phase injection is expected to improve the performance and reliability of heat pumps. However, at present, it is questionable to apply two-phase injection to an actual heat pump due to the risk of wet-compression. Owing to the limited database for the optimum injection quality and injection pressure under various operating conditions, it is unable to control the injection quality properly without experiencing wet-compression. Therefore, for practical applications of two-phase injection heat pumps, it is necessary to perform a detailed analysis on the optimum injection quality and injection pressure in a two-phase injection heat pump to achieve compressor reliability with improved system performance. Moreover, it is extremely meaningful to perform a direct performance comparison of liquid, vapor, and two-phase injection methods with the same configurations under various operating conditions.

In this study, a numerical model was developed to predict the performance of liquid, vapor, and two-phase injection heat pumps with a scroll compressor. Furthermore, the experiments were conducted for liquid, vapor, and two-phase injection heat pumps under various operating conditions. The numerical model was validated by using measured data in the study. The performance characteristics of the two-phase injection heat pump were analyzed and optimized at various injection parameters and operating conditions in order to solve the wet-compression problem. Moreover, the potential merits of the two-phase injection heat pump were suggested based on the objective function of the maximized COP or minimized discharge temperature. The performance of the two-phase injection heat pump was also compared with those of liquid and vapor injection heat pumps.

2. Numerical model

2.1. Numerical modeling

A numerical simulation model was developed to predict the performance of a scroll compressor with refrigerant injection by using R410A. The numerical model can predict the compressor work, discharge temperature, and refrigerant mass flow rate based on the given operating conditions including the compressor frequency, suction and discharge pressures, injection pressure, suction superheat, and injection superheat (or vapor quality). The following assumptions are used in the model [30]: (1) the refrigerant in the working chambers is homogeneous, (2) variations of gravitational and kinetic energies are neglected, and (3) the effect of oil is neglected.

The governing equations for mass, temperature, and pressure are