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Study on performance of a heat pump water heater using suction stream liquid injection

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ABSTRACT

Liquid refrigerant injection into a suction line is an effective and practical method to reduce the discharge temperature when a scroll compressor operates at high compression ratios. In the present study, correlations among the compressor suction temperature, discharge temperature, heat pump heating capacity, power consumption, coefficient of performance (COP) and the quantity of suction liquid injection are established. The paper presents experimental analysis and a comparison with calculated results of the heat pump water heater (HPWH) performance with suction liquid injection in different conditions. It is found that the suction liquid injection explicitly lowers the discharge temperature of the compressor and the heating capacity of the unit, but the power consumption increases with COP decreasing. In addition, the highest injection ratio must be controlled fewer than 5%. The suction liquid injection has a better effect on the HPWH at the temperature ranging from −15 °C to 20 °C. Within this temperature range, the 5% ratio suction liquid injection decreases the discharge temperature of the compressor by 10 °C, while the heating capacity of the HPWH decreases by less than 5%, power consumption increases by less than 1.5%, and COP decreases by less than 7%.

1. Introduction

An air source heat pump water heater (HPWH) is an all-year unit that absorbs heat from air to heat water. When the unit works in cold season, the pressure ratio and discharge temperature increase, causing the compressor to fail. Therefore, it is more effective to use liquid injection and gas compensation to lower the discharge temperature of the compressor [1–3]. Cho et al. [4] investigated the performance of an inverter-driven scroll compressor with liquid refrigerant injection. It was found that liquid injection under high frequency was very effective at attaining higher performance and reliability of the compressor, but injection under low frequency showed some disadvantages. Park et al. [5] developed a thermodynamic model for a variable speed scroll compressor with refrigerant injection using continuity, energy conservation and real gas equation. The developed model was verified by comparing the predicted results for no injection condition with the experimental data. The effects of refrigerant injection on the performance of the compressor were also discussed as a function of frequency, injection conditions, and injection geometry. Dutta et al. [6] conducted theoretical and experimental investigations on a scroll compressor with liquid injection, creating a compressor model that considered heat transfer. Dutta et al. then conducted an experiment to study the effect of the liquid injection on the performance of the compressor. Winandy and Lebrun [7] compared the performance of a compressor in a normal system, liquid injection system and economizer gas compensating system. The research indicated that a gas compensating system could improve the refrigerating capacity of a compressor and the liquid injection could lower the discharge temperature. It was found that the compressor discharge temperature decreased by 1.2 K for each percentage of liquid injection. Ma et al. [8] researched the air source heat pump, showing that with the gas compensating system, the unit works reliably at −15 °C. The heating capacity and coefficient of performance (COP) increased and the discharge temperature decreased. Ayub et al. [9] conducted experimental research and theoretical simulations of the liquid injection scroll compressor in high pressure ratio conditions.

The past literature indicates liquid injection and economizer gas compensating systems are important for a high pressure ratio scroll compressor. However, the major studies focus on the gas compensation system and require a special compressor with a liquid compensating hole. In a practical application, injecting liquid into a suction pipe is simple and practical method to improve reliability of the compressor. The fundamental effect of the suction stream liquid injection on the performances of the compressor and heat pump has not been discussed in the open literature. This paper is a theoretical and experimental analysis of the HPWH with suction stream liquid injection. The aim of this study is to develop

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Nomenclature

h	enthalpy (kJ kg^{-1})
M	mass flow rate (kg s^{-1})
n	polytropic exponent
p	pressure (Pa)
Q	heat capacity (kW)
R_m	ratio (–)
R_g	gas constant (kJ kg^{-1} K^{-1})
T	temperature (°C)
V	gas displacement (m^3)
v	specific volume (m^3 kg^{-1})
W	power consumption (kW)
Z	compressibility factor

Subscripts

A	point A
A'	point A′
B	point B
B'	point B′
C	point C
c	condense
d	discharge
e	evaporate
g	gas
inj	injection
m	mass
s	suction
T	isothermal
mes	measure
sim	simulate

a generalized correlation in simple form that can be used in the prediction of the impact on the performance of the HPWH with suction liquid injection.

2. Suction stream liquid injection analysis

The pressure–enthalpy diagram for the normal operation of the HPWH is A–B–C–D shown in Fig. 1. The operation with suction liquid injection is indicated by A′–B′–C–D. The suction liquid injection causes suction and the discharge temperature of the compressor to decrease. Under operating condition of suction liquid injection, the refrigerant is divided into two parts, one is injected into suction pipe, the other is remained in the main cycle. So from the energy conservation, we can give the following equation:

$$M_{total}h_{A'} = M_{inj}h_{inj} + Mh_A \tag{1}$$

M_{total} is the total mass flow rate of the compressor (kg s^{-1}), $M_{total} = M_{inj} + M$; $h_{A'}$ is the enthalpy after suction liquid injection (kJ kg^{-1}); M_{inj} is the mass flow rate of liquid injection (kg s^{-1}); h_{inj} is the enthalpy of liquid injection (kJ kg^{-1}); M is the mass flow rate through the evaporator (kg s^{-1}); and h_A is the enthalpy before suction liquid injection (kJ kg^{-1}). The enthalpy of liquid injection, h_{inj}, is equal to the enthalpy of the outlet of the condenser (point C in Fig. 1), h_C, so the enthalpy after suction liquid injection can be get from the following equation:

$$h_{A'} = \frac{Mh_A + M_{inj}h_{inj}}{M_{total}} = \frac{Mh_A + M_{inj}h_C}{M + M_{inj}} = \frac{h_A + R_m h_C}{1 + R_m} \tag{2}$$

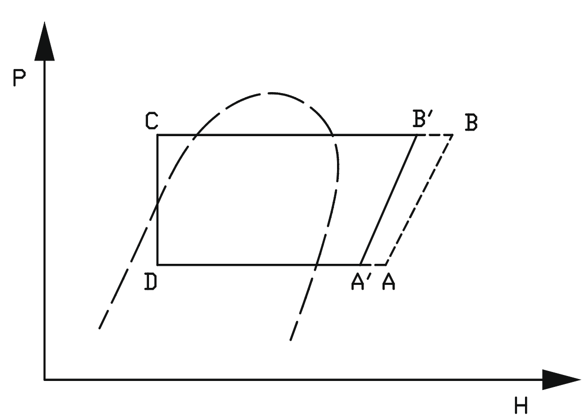

Fig. 1. Pressure–enthalpy diagram of the operation with suction liquid injection.

where $R_m = \frac{M_{inj}}{M} R_m$ is the ratio between the mass flow rate of suction liquid injection and the mass flow rate through the evaporator and $T_A, T_{A'}$ are the suction temperatures (point A and A′ in Fig. 1) without and with liquid injection (°C).

With an implicit curve fitting method and the explicit formulae given in [10,11] for thermodynamic refrigerant liquid and gas, we propose the correlation between the suction temperature of the compressor, $T_{A'}$ and R_m.

As for the HPWH, the difference in temperature between the ambient temperature and evaporating temperature of the unit is $\Delta t \leqslant 15$ °C [12]. Under this operating condition, for the scroll compressor, the polytropic exponent n_T and compressibility factor Z of the compression can be assumed to be a fixed value [11], we can express the power consumptions of the heat pump without and with suction liquid injection, W, W' (kW) as follows:

$$W = \frac{(T_A + 273.15)}{v_A} \frac{n_T}{n_T - 1} R_g V \left[\left(\frac{p_d}{p_s} \right)^{\frac{n_T - 1}{n_T}} - 1 \right] \sqrt{Z_d \cdot Z_s} \tag{3}$$

$$W' = \frac{(T_{A'} + 273.15)}{v_{A'}} \frac{n_T}{n_T - 1} R_g V \left[(\frac{p_d}{p_s})^{\frac{n_T - 1}{n_T}} - 1 \right] \sqrt{Z_d \cdot Z_s} = \frac{(T_{A'} + 273.15) v_A}{(T_A + 273.15) v_{A'}} W \tag{4}$$

where Z_d, Z_s are compressibility factors of the discharge point and suction point of the compressor. From Eq. (4), the effect factor of suction liquid injection on the power consumption of HPWH is $\frac{(T_{A'} + 273.15) v_A}{(T_A + 273.15) v_{A'}}$.

The refrigerant in state B′ and B can be expressed as follows:

$$h_{B'} = h_{A'} + \frac{W'}{M_{total}} \tag{5}$$

$$h_B = h_A + \frac{W}{M_{total}} \tag{6}$$

where h_B, $h_{B'}$ are the enthalpies of refrigerant at the outlet of the compressor (point B and B′ in Fig. 1) without and with suction liquid injection (kJ kg^{-1}).

Along with Eqs. (2) and (4), the effect of suction liquid injection on the refrigerant enthalpy in state B′ can be calculated by

$$h_{B'} = \frac{h_A + R_m h_C}{1 + R_m} + \frac{T_{A'} + 273.15}{T_A + 273.15} (h_B - h_A) \tag{7}$$

Also with an implicit curve fitting method and the explicit formulae given in [10,11] for thermodynamic refrigerant liquid and gas, we propose the correlation between the discharge temperature of the compressor, $T_{B'}$ and R_m.