Influence of the expansion device on the performance of a heat pump using R407C under a range of charging conditions

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Abstract

The objective of this study is to investigate the effects of the expansion device on the performance of a water-to-water heat pump using R407C, which has been considered as one of the alternative refrigerants to replace R22 with “soft-optimization”, at various charging conditions. The heat pump applying the expansion devices of a capillary tube and an EEV was tested by varying refrigerant charge amount from $-20\%$ to $+20\%$ of full charge and changing water temperature entering the condenser from 30 $^\circ\text{C}$ to 42 $^\circ\text{C}$, while maintaining water temperature entering the evaporator at 25 $^\circ\text{C}$. The R22 capillary tube system is utilized as a baseline unit for the performance comparison with the R407C system. The performance of the capillary tube system is more sensitive to off-design charge than that of the EEV system. As the refrigerant charge deviates from the full charge, the R407C EEV system shows a much lower degradation of capacity and COP as compared to the R22 and R407C capillary tube systems due to an optimum control of superheat by electronically adjusting the EEV opening. In addition, the R407C EEV system shows more a stable compressor discharge temperature at off-design charge than the R407C capillary tube system.

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Keywords: Experiment; Electric expansion device; Capillary; Heat pump; R407C; Performance

Influence du dispositif de détente sur la performance d’une pompe à chaleur utilisant le R407C dans un éventail de conditions de charge

Mots clés : Expérimentation ; Détendeur électrique ; Capillaire ; Pompe à chaleur ; R407C ; Performance

1. Introduction

Due to the phaseout of CFCs (chlorofluorocarbon) and HCFCs (hydrochlorofluorocarbon), the systems must be redesigned to satisfy design requirements for alternative refrigerants. System modifications can be classified into three categories: “drop-in” with no hardware change, “soft-optimization” with moderate hardware changes, and “hard-optimization” with major hardware changes. R407C has the similar thermodynamic properties as those of R22 with an exception of the temperature gliding during the phase change process at a constant pressure [1]. Therefore, R407C has been considered as one of the alternatives with “soft-optimization”.

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An expansion device controls refrigerant flow and balances the system pressures in heat pumps and refrigeration systems. Conventional expansion devices, such as capillary tubes, short tube orifices, and thermostatic expansion valves (TXV) are being gradually replaced with electronic expansion valves (EEVs) due to increasing focus on comfort, energy conservation, and application of a variable speed compressor [2,3]. Therefore, the performance of the system with a conventional expansion device and an EEV has to be investigated with new alternative refrigerants. In addition, the amount of refrigerant charge in a heat pump is another primary parameter influencing energy consumption. The effects of refrigerant charge are closely related with the expansion device. Undercharge or overcharge of the refrigerant into a heat pump will degrade system performance and deteriorate system reliability [4,5]. Therefore, an investigation on the optimum amount of refrigerant charge with respect to expansion devices must be conducted for new alternative refrigerants.

The performance of a heat pump with alternative refrigerants has been reported by many investigators [6–9]. Jung et al. [6] assessed the performance of R407C along with other refrigerant mixtures in a breadboard type heat pump. Devotta et al. [7] executed experimental work to compare the performance of R22 and R407C for a window air conditioner. Spatz [8], and Motta and Domanski [9] conducted simulation studies on an air-conditioner using alternative refrigerants. In addition, the effects of charge amount on the performance of a heat pump have been investigated with conventional expansion devices [4,5,10,11]. Houcek and Thedford [4] conducted the experiments at three charging conditions: −23%, nominal, and +23% of nominal charge. Stoecker et al. [5] compared the performance of an air conditioner with a capillary tube and TXV when the system was charged based on manufacturer’s guideline. Farzard and O’Neal [10,11] also studied refrigerant charging effects on the performance of a heat pump with a capillary tube, short tube orifice, and TXV. They observed that the TXV system showed a small variation of the COP with respect to refrigerant charge. Recently, Choi and Kim [12] experimentally investigated the performance of a heat pump with a capillary tube and EEV using R22 under various charging conditions.

Most previous studies regarding the effects of refrigerant charge were focused on a heat pump with a capillary tube, a short tube orifice, and a TXV using R22. However, a study on the characteristics of the system with an EEV using alternative refrigerants under various charging conditions is very limited. The objective of this study is to investigate the effects of the expansion device on the performance of a heat pump using R407C under various charging conditions, providing information on the design of an expansion device and refrigerant charge. A water-to-water heat pump using R407C is tested in steady state, cooling mode operation by applying the expansion devices of a capillary tube and an EEV under various charging conditions. The performance of the R407C system is compared with that of the R22 system, which is the baseline unit using a capillary tube, at various charging conditions.

2. Experimental setup and test procedure

2.1. Experimental setup

An experimental setup was designed to measure the performance of the water-to-water heat pump under variable operating conditions. As shown in Fig. 1, the test rig includes the heat pump and water flow loops. The nominal cooling capacity of the heat pump is 3.5 kW using R22 as a working fluid. The heat pump consists of a scroll compressor, two heat exchangers (condenser and evaporator), and an expansion device. The detailed specifications of the major components of the tested heat pump are given in Table 1. The condenser and evaporator are double tube type heat exchangers with a counter flow pattern between the refrigerant and water. Water is selected as a heat source and sink for the heat pump system because of their simplicity in capacity measurements. Water flow loops (secondary flow loops) for the evaporator and condenser include a magnetic

<table>
<thead>
<tr>
<th>Components</th>
<th>Specifications</th>
</tr>
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<tbody>
<tr>
<td>Compressor</td>
<td>Manufacturer: Daikin Co.</td>
</tr>
<tr>
<td>Condenser</td>
<td>Manufacturer: Donghwa Co.</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Evaporator</td>
<td>Manufacturer: Donghwa Co.</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Capillary tube</td>
<td>Manufacturer: Donghwa Co.</td>
</tr>
<tr>
<td>EEV</td>
<td>Manufacturer: Saginomiya Co.</td>
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<td></td>
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</tbody>
</table>
A variable speed pump and a constant temperature bath. A variable speed pump and a manual needle valve control the water flow rate supplied to the condenser and evaporator to establish test conditions based on Refs. [13–15].

The R22 heat pump system with a capillary tube was used as a baseline unit for the performance comparison of the R407C system. Either an EEV or a capillary tube was utilized as an expansion device in the R407C heat pump system. Control system for driving EEV unit includes an A/D card, a stepping motor driver, and a computer.

Temperatures in the test setup were monitored at the selected locations using thermocouples according to ASHRAE Standard 41.1 [16], and refrigerant pressures were also measured according to ASHRAE Standard 41.3 [17]. A mass flow meter to measure refrigerant flow rate was installed between the condenser and expansion device. The pressure drop across the mass flow meter was approximately 3.92 kPa, which was less than the value of 82.7 kPa allowed in ASHRAE Standard 116 [18] at full charge condition. A volumetric flow meter was installed to measure water flow rate in the secondary flow loop. Each sensor was calibrated to reduce experimental uncertainties. The specifications and uncertainties of sensors are summarized in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
<th>Full scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (T type thermocouple)</td>
<td>±0.1 °C</td>
<td>−270–400 °C</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>±0.2% of full scale</td>
<td>3447 kPa</td>
</tr>
<tr>
<td>Mass flow meter (Coriolis meter)</td>
<td>±0.2% of reading</td>
<td>5 kg/min</td>
</tr>
<tr>
<td>Turbine flow meter</td>
<td>±0.5% of reading</td>
<td>57 LPM</td>
</tr>
<tr>
<td>Power meter</td>
<td>±0.01% of full scale</td>
<td>20 kW</td>
</tr>
<tr>
<td>Electronic balance weight</td>
<td>±0.5 g</td>
<td>41 kg</td>
</tr>
</tbody>
</table>

#### 2.2. Test procedure

The first step of the test procedure was to determine full charge under a standard condition, water temperatures of 34 °C and 25 °C entering the condenser and evaporator, respectively. The full charge condition was selected to have a maximum COP. For the heat pump with the capillary tube using R22 and R407C (called as “the R22 capillary tube system” and “the R407C capillary tube system”, respectively), the refrigerant was added into the heat pump in a 50 g increment until the maximum COP was obtained for each system. Once the full charge was determined, the heat pump was evacuated and then the refrigerant charge was varied from −20% to +20% of full charge for each refrigerant. In this study, the tests for the heat pump with the EEV using R407C (called as “the R407C EEV system”) were performed by setting the same full charge as the capillary tube system in order to compare characteristics of R407C at the same basis of charge amount. During the tests, the EEV opening was manually changed to maximize the COP at each operating condition and charge amount.

Since the heat pump is normally charged in the cooling mode [10], the tests in this study were carried out in the cooling mode only. Water temperature entering the evaporator was kept at 25 °C, and that entering the condenser was varied at 30 °C, 34 °C, 38 °C, and 42 °C. Water flow rates through the condenser and evaporator was kept constant at 9 lpm and 7 lpm, respectively. Temperature, pressure, mass flow rate, and power input

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**Fig. 1.** Schematic of the experimental setup.
of the heat pump were monitored using a data acquisition system. The test data were recorded continuously for 40 min with 2-s intervals.

Cooling capacity was calculated by using water flow rate and temperature difference between evaporator inlet and outlet. To confirm the calculation, the capacity was also determined by refrigerant flow rate and enthalpy difference between evaporator inlet and outlet [13–15]. The maximum difference between the water-side and the refrigerant-side capacity was less than 5% which was consistent with ARI Standard 320 [14]. Ninety percent of the data was within 2.7%. The uncertainties of cooling capacity and COP estimated by the single-sample analysis according to ASHRAE Guideline 2 [19] were approximately 3.1% and 3.2%, respectively.

3. Results and discussion

Fig. 2 shows the variations of cooling capacity for the R22 and R407C capillary tube systems as a function of refrigerant charge. The full charge amount of the R407C capillary tube system was lower than that of the R22 capillary tube system due to a lower density of R407C at a given condition. In this experiment, the full charge amount of the R407C and R22 systems were 1250 g and 1350 g, respectively. The cooling capacity of the R407C capillary tube system is from 89.2% to 101.6% of the R22 capillary tube system with a variation of refrigerant charge.

For both the R22 and R407C capillary tube systems, the slope of the capacity with a charge amount is much steeper at undercharged conditions than that at overcharged conditions. For overcharged conditions, the capacity drops due to a decrease of the temperature difference between the refrigerant and the water in the evaporator with increasing refrigerant charge. For undercharged conditions, the capacity rapidly decreases with a reduction of refrigerant charge due to a drop of refrigerant flow rate and compressor efficiency. Since the superheat at undercharged conditions is higher than that at overcharged conditions, a more significant degradation of evaporator efficiency occurs at undercharged conditions.

Normally, the capacity of a heat pump is expected to drop at off-design refrigerant charge. However, the capacity of the R407C capillary tube system remains nearly constant with a rise of charge amount beyond full charge while the COP drops. For a non-azeotropic mixture of R407C, both temperature gliding and pressure drop decrease saturation temperature in the condenser. Besides, the pressure drop of R407C shows more influence on the reduction of saturation temperature than that of R22 [20]. Due to a lower saturation temperature for the R407C system, the reduction of heat transfer performance at the end section of the condenser and reduce the drop of temperature difference between the refrigerant and the water in the condenser.

Fig. 3 shows the capacity ratio for the R407C capillary tube and EEV systems based on the capacity of the R407C capillary tube system at the standard condition, water temperatures of 34 °C and 25 °C entering the condenser and the evaporator, respectively. For all water temperatures entering the condenser, the R407C EEV system shows much lower degradation of capacity as compared with the R22 and R407C capillary tube systems as the refrigerant charge is altered from −20%
to +20% of full charge. When the deviation of charge amount from full charge increases, the EEV system shows much more refrigerant flow rate at undercharged conditions and lower evaporator inlet temperature at overcharged conditions than the capillary tube system (Fig. 4). The capacity for the R407C EEV system is higher by 5.2% to 21% at a −20% charge condition than that for the R22 capillary tube system.

Fig. 5 shows the COP of the R22 and R407C capillary tube systems as a function of water temperature entering the condenser and refrigerant charge. For the capillary tube system, as the charge amount deviates from the full charge, the reduction of COP is a little more significant at undercharged conditions than that at overcharged conditions. This trend was also reported by Farzard and O’Neal [10] for a R22 system. The COP decreases by 16.1% and 4.8% at −20% and +20% of full charge, respectively, at a water temperature of 34 °C. For overcharged conditions, even though the capacity of the R407C capillary tube system remains nearly constant (Fig. 2), the COP is gradually reduced with an increase of charge amount due to a rapid increase of power consumption, which is caused by a rise of pressure ratio and a higher friction loss in the compressor. However, the COP degradation of the R407C capillary tube system with respect to charge amount at overcharged conditions is a little less pronounced than that for the R22 system because the rise of the evaporator inlet temperature in the R407C capillary tube system is lower than that in the R22 capillary tube system.

The COP of the R407C EEV system is relatively insensitive to refrigerant charge compared with the capillary tube system as shown in Fig. 6. When the water temperature entering the condenser is 34 °C, the maximum reduction in COP for the R407C EEV system from the full charge is 3.6%, but that for the R407C capillary tube system is 16.5%. The COP reduction of the EEV system is much less than that of the capillary tube system at undercharged conditions because the EEV system shows higher refrigerant flow rate than the capillary tube system. For overcharged conditions, the COP degradation in the EEV system is minimized by lowering evaporating temperature.

Fig. 7 shows the subcooling of the R22 and R407C capillary tube systems, and the R407C EEV system. The condensing pressure increases with an addition of refrigerant charge due to an accumulation of the refrigerant in the high-pressure side, increasing subcooling. This trend was also observed by Stoecker et al. [5] and Farzard and O’Neal [10]. The subcooling decreases when the water temperature entering the condenser increases at all charge conditions except for at −20% of full charge. When the water temperature entering the condenser increases the mean temperature difference between the water and the refrigerant drops and less heat is rejected in the condenser. For +20% of full charge, the subcooling decreases from 10.4 °C to 7.7 °C as the water temperature entering the condenser increases from 30 °C to 42 °C in the R22 capillary tube system.
The subcooling of the R407C capillary tube system is lower than that of the R22 capillary tube system due to a temperature gliding in the condenser even though the condensing pressure of R407C is higher than that of R22. The temperature difference between dew point temperature corresponding to the condenser inlet pressure and bubble point temperature corresponding to the condenser exit pressure in the R407C system is higher than that in the R22 system. Therefore, the R407C capillary tube system represents lower subcooling than the R22 capillary tube system.

Generally, the subcooling of a heat pump with a capillary tube or a short tube tends to drop as the water temperature entering the condenser increases [5,10]. However, the variation of the subcooling for the R407C EEV system is nearly negligible with an increase of water temperature entering the condenser at undercharged conditions. As the water temperature entering the condenser increased, the EEV opening was reduced to maximize the evaporator effectiveness. Therefore, the mass flow rate through EEV did not vary much with an increase of condensing pressure due to an active control of the EEV opening to maximize the system performance. In addition, the mean temperature difference between the refrigerant and the water in the condenser was nearly constant with an increase in water temperature due to a rise of condensing temperature resulted from a reduction of the EEV opening.

Fig. 8 represents the superheat for the R22 and R407C capillary tube systems, and the R407C EEV system as a function of refrigerant charge. For the capillary tube systems, the superheat is reduced as the refrigerant charge increases due to a rise of the refrigerant flow rate through the evaporator. For the capillary tube systems, the superheat is kept at nearly zero for +10% and +20% of full charge, causing wet compression. For the R407C EEV system, the superheat is nearly constant even though both the water temperature entering the condenser and the amount of refrigerant charge increase due to an active control of EEV opening.

Fig. 9 shows the discharge temperature of the R407C capillary tube system and the R407C EEV system with a variation of refrigerant charge. The discharge temperature in the R407C capillary tube system increases continuously with a reduction of charge amount due to a rise of superheat and a decrease of mass flow rate. However, the EEV system represents relatively stable discharge temperature at all charge conditions. Therefore, it can be concluded that maintaining a constant superheat can optimize the performance of a heat pump and enhance the reliability of the system at off-design conditions.

4. Conclusions

The effects of refrigerant charge on the performance of the water-to-water heat pump using R407C were measured by applying the capillary tube and the EEV as
an expansion device under various charging conditions. The R22 capillary tube system was utilized as a baseline unit for the performance comparison with the R407C system. The full charge amount of the R407C capillary tube system is less by 8% than that of the R22 capillary tube system. Generally, the performance of the R22 and R407C capillary tube systems is very sensitive to refrigerant charge and the degradation of the performance is higher at undercharged conditions than that at overcharged conditions due to a relatively higher superheat at undercharged conditions. However, the capacity and COP of the R407C EEV system have little dependence on the refrigerant charge due to an optimum control of superheat by electronically adjusting the EEV opening. The R407C EEV system shows much lower reduction of capacity and COP as compared with the R22 and R407C capillary tube systems as the refrigerant charge deviates from full charge. When the water temperature entering the condenser is 34 °C, the maximum reductions in COP for the R407C EEV and capillary tube systems are 3.6% and 16.5%, respectively. The discharge temperature of the R407C capillary tube system increases with a reduction of charge amount due to a rise of superheat and a drop of mass flow rate. However, the EEV system shows relatively stable discharge temperature at all charge conditions. Generally, the EEV system showed much higher system performance and reliability as compared with the capillary tube system due to an active electronic control of refrigerant flow rate through the EEV to obtain an optimum superheat level.

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References