Theoretical Study of A Thermoelectric-assisted Vapor Compression Cycle for Air-source Heat Pump Applications

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ABSTRACT

In this paper, a thermoelectric-assisted vapor compression cycle (TVCC) is proposed for applications in air-source heat pump systems. Compared with the basic vapor compression cycle (BVCC), the TVCC using a thermoelectric heat exchanger (THEX) could enhance the heating capacity of the system in an energy-efficient way. To demonstrate the performance characteristics of TVCC, a case study on this cycle applied to a small air-source heat pump water heater has been conducted based on the developed mathematical model. Performances of both the new TVCC and BVCC are also compared. The simulation results show that the TVCC has 46.3%-103.0% increase and 14.7%-52.5% reduction in heating capacity and COP compared with those of the BVCC, respectively, under given conditions. Especially, at a higher evaporating or condensing temperature, the TVCC has better improvements in heating capacity. When there is no significant difference in COPs among the two cycles, the TVCC still performs better than BVCC by 13.0% in heating capacity by selecting the appropriate intermediate temperature. In addition, the TVCC can also achieve an improvement of 16.4%-21.7% in both the heating COP and capacity under the above given conditions, when compared with the BVCC with an assistant electric heater that is provided with the equivalent power input of THEX. Thus, the advantage of TVCC in heating capacity could be beneficial to the applications in small heat pumps if there is always need for auxiliary electric heat to solve the problem of low heating capacity of a heat pump at a low ambient temperature.

Keywords: Heat pump; Heating capacity enhancement; Thermoelectric modules; Vapor compression cycle.

1.INTRODUCTION

In heat pump applications, the air-source heat pump water heaters have significant advantages in residential heating over the conventional fossil-fueled or electric heating equipment due to a more efficient use of energy. Thus, air-source heat pump water heaters (AHPWH) have been an attractive saving technology in either domestic hot water or space heating applications [Hepbasli and Kalinci, 2009; Bourke and Bansal, 2010]. However, there a main problem with the heating performances of AHPWHs, i.e. their heating capacity and coefficients of performance (COPs) are degraded when they operate at low ambient temperature conditions [Bertsch and Groll, 2008]. In order to solve this problem, lots of methods to improve the heating performance of vapor compression based heat pump systems (including AHPWHs) have been proposed over the past years, such as the refrigerant injection technique, ejector enhanced heat pump systems, multistage and hybrid systems [Heo et al., 2011; Chua et al., 2010; Sarkar, 2012; Wang et al., 2009]. Among these techniques, there has been interest in development of hybrid heat pump system, like dual source coupled systems and compression/absorption heat pump systems [Lazzarin, 2012; Satapathy and RamGopal, 2008]. Thus, there are various options to set up a combined or hybrid heat pump system as well as categories for improving overall system energy efficiency. The main purpose of technical development of hybrid systems is connected with the combining different heat pump/refrigeration systems and optimization of the operations for their optimal use in the facility.

As known, thermoelectric technology has been widely used for small refrigeration/ heat pump applications. Thermoelectric coolers (heat pumps) offer the advantages of compact size, high reliability, flexible shape and no moving parts. Their main disadvantage is lower coefficients of performance than vapor compression systems, particularly in larger capacity applications [Riffat and Ma,2004]. However, the thermoelectric coolers operated at a smaller operating temperature difference can provide higher efficiency. Considering this characteristic of the thermoelectric coolers, the combined vapor compression and thermoelectric cooling systems make it possible to improve overall system efficiency [Schoenfield, 2012; Okuma, 2012; Sarkar, 2011; Vián and Astrain , 2009]. Thus,

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an integrated vapor compression refrigeration (heat pump) system with thermoelectric cooler could have potential benefits for developing convectional refrigeration/heat pump technology.

This research has developed a hybrid heat pump system with a combination of basic vapor compression and thermoelectric cooling systems for domestic water heater applications. In the hybrid heat pump system, thermoelectric cooler is utilized to enhance the heating performances of AHPWHs. In this paper, the heating performance of the developed hybrid heat pump system has been investigated theoretically. The evaluations of heating capacity and coefficients of performance for the hybrid heat pump system are performed with simulation. The operating characteristics of the hybrid heat pump system are also compared with that of a basic vapor compression system in case study. It is expected that the presented combination method will allow AHPWHs to operate at wider ambient temperature conditions, especially at low ambient temperature conditions in winter.

2. SYSTEM DESCRIPTION AND ANALYTICAL MODEL

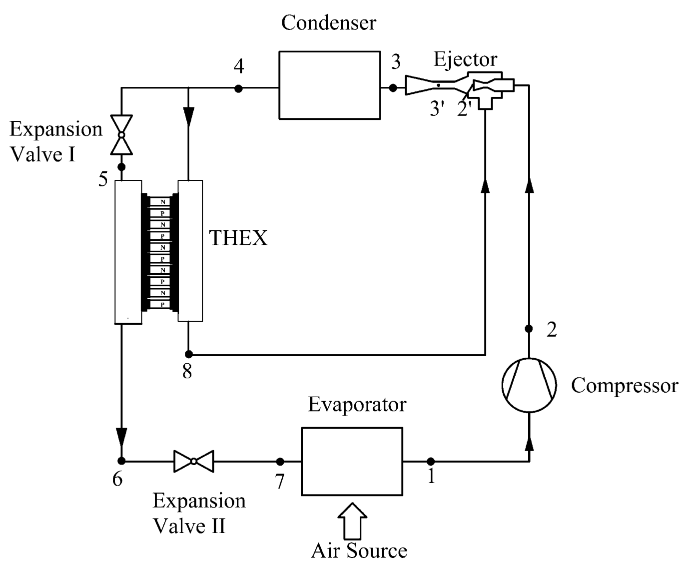


Figure.1 The schematic diagram of TVCC

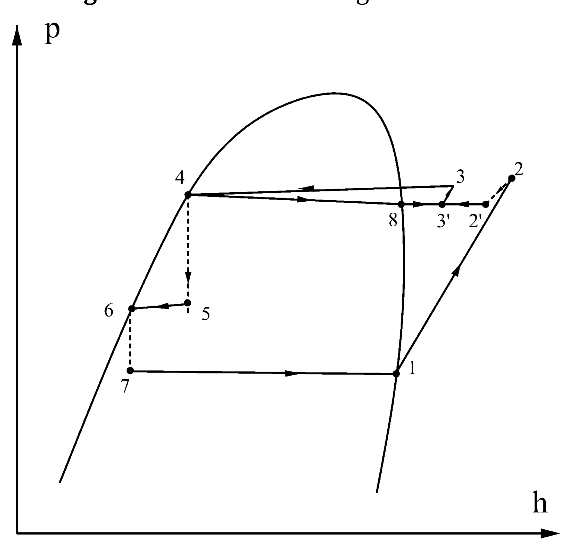


Figure.2 Pressure-enthalpy diagram for the TVCC

Figure 1. shows the schematic diagram of a hybrid heat pump system, i.e. the thermoelectric-assisted vapor compression cycle (TVCC) system. The TVCC system consists of a compressor, an ejector, a condenser, a

thermoelectric cooling system, two expansion valves and an evaporator. The cycle configuration includes both a main refrigerant circuit and a bypass refrigerant circuit, which are combined by the thermoelectric cooling system. In the thermoelectric cooling system, a group of thermoelectric modules (TEMs) and two microchannel heat exchangers are integrated into a thermoelectric heat exchanger (THEX) unit to pump heat from one refrigerant circuit to another refrigerant circuit. The ejector is used for driving the refrigerant to flow through the bypass circuit. Fig. 2 shows the detailed working process of the TVCC on pressure-enthalpy diagram. The main circuit flow is circulated by the compressor through the ejector, condenser, expansion valve I, THEX, expansion valve II and evaporator (process 1-2-3-4-5-6-7), whereas the bypass circuit flow is circulated by the ejector through the THEX (process 4-8-3). Process 2-2′, (2′, 8)-3′ and 3′-4 represent the ejector working process. Due to the cooling and heating function of the THEX, the two-phase refrigerant stream from the expansion valve I is condensed (process 5-6) in the cold-side microchannel heat exchanger, while the refrigerant liquid from the condenser is evaporated (process 4-8) in the hot-side microchannel heat exchanger. Thus, the THEX enables heat to be pumped from the main circuit to the bypass circuit, resulting in the increase of the amount of rejected heat in the condenser. Theoretically, the TVCC could improve the heating capacity with the electric power consumption of the THEX. However, the increase in power consumption for the TVCC would also lead to effects on its coefficient of performance (COP). This means the benefits of using the THEX should be evaluated synthetically.

According to the working process of the TVCC, the following mathematical model for TVCC can be established based on the mass and energy conservations. It should be noted that to avoid the complexity of the theoretical study, the frictional pressure drop in refrigerant circuits are not considered in this modeling. In this case, the mathematical model for ejector can be omitted because the ejector is only taken as a mixing device without the required pumping function. In addition, the widely used standard equations of a thermoelectric cooler performance are employed for modelling the THEX [Riffat and Ma, 2004]. In order to establish the model, the following specific assumptions are also made:

(1) All components are assumed to be a steady-state and steady-flow process;
(2) Heat losses in the cycle are neglected;
(3) The throttling processes in expansion valves are isenthalpic;
(4) Refrigerant states at the outlets of condenser and THEX (points 4, 6, 8) are saturated;
(5) The isentropic and volumetric efficiencies of the compressor are related to its pressure ratio;
(6) The material properties of the thermoelements for THEX are identical and independent of temperature;
(7) The thermal and electric contact resistances in the thermoelectric modules of THEX are neglected.

Based on the above assumptions, the following equations for the main components of the TVCC system can be obtained in terms of the mass and energy conservation. For a TEM in the THEX, the corresponding heat balance equations can be given by:

$$Q_{\mathrm{c,TEM}} = N_t[\alpha I t_{\mathrm{c,TEM}} - K(t_{\mathrm{h,TEM}} - t_{\mathrm{c,TEM}}) - \frac{1}{2}RI^2] \tag{1}$$

$$Q_{\mathrm{h,TEM}} = N_t[\alpha I t_{\mathrm{h,TEM}} - K(t_{\mathrm{h,TEM}} - t_{\mathrm{c,TEM}}) + \frac{1}{2}RI^2] \tag{2}$$

where $Q_{\mathrm{c,TEM}}$ and $Q_{\mathrm{h,TEM}}$ are, respectively, the absorbed and rejected heat at the hot and cold sides of a TEM, N_{t} is the number of thermocouples in the TEM. I is electric current. α, K and R are the Seebeck coefficient, thermal conductance and electric resistance of a thermocouple, respectively. $t_{\mathrm{c,TEM}}$ and $t_{\mathrm{h,TEM}}$ are the cold and hot junction temperatures of the TEM which can be calculated by, respectively:

$$t_{\mathrm{c,TEM}} = t_6 - \Delta t \tag{3}$$

$$t_{\mathrm{h,TEM}} = t_8 + \Delta t_{\mathrm{h}} \tag{4}$$

where t_6 and t_8 are the temperatures of the cold- and hot-side refrigerants in the THEX. Δt_{c} and Δt_{h} are the temperature difference between the refrigerants and the junctions.

For the condenser, the heating capacity can be calculated by:

$$Q_{\mathrm{h}} = \left(\dot{m}_1 + \dot{m}_8\right)\left(h_3 - h_4\right) \tag{5}$$

where $\dot{m}_1$ and $\dot{m}_8$ are the refrigerant mass flow rates in the main and bypass circuits, respectively. h_3 and h_4 are the refrigerant specific enthalpies at the inlet and outlet of the condenser.

For the compressor, the input powers can be written as

$$P_{\mathrm{C}} = \frac{\dot{m}_1\left(h_{2\mathrm{s}} - h_1\right)}{\eta_{\mathrm{C}}} \tag{6}$$

where h_1 is the specific enthalpy of refrigerant at the inlet of the compressor; $h_{2\mathrm{s}}$ is exit enthalpy through an isentropic compression process in the compressor; η_{C} is the isentropic efficiency of the compressor, which also can be calculated by [Paul Byrne et al., 2012]:

$$\eta_{\mathrm{C}} = 0.9962 \times \exp\left(-0.0565 \times \frac{p_2}{p_1}\right) \tag{7}$$

where p_1 and p_2 are the refrigerant pressures at the inlet and outlet of the compressor.

The refrigerant mass flow rate entering the compressor can be determined by:

$$\dot{m}_1 = \frac{V_{\mathrm{dis}} \times n}{v_1 \times 60} \times \eta_v \tag{8}$$

where V_{dis} is volumetric displacement of a compressor; n is the rotating speed of the compressor; v_1 is the suction specific volume of the compressor; η_v is the volumetric efficiency of the compressor, which can be calculated by [Moreno-Rodríguez et al., 2012]:

$$\eta_v = 0.9 - 0.035 \times \frac{p_2}{p_1} \tag{9}$$

Energy balances for the THEX can be written as:

$$\dot{m}_1(h_5 - h_6) = N_{\mathrm{TEM}} Q_{\mathrm{c,TEM}} \tag{10}$$

$$\dot{m}_8(h_8 - h_4) = N_{\mathrm{TEM}} Q_{\mathrm{h,TEM}} \tag{11}$$

$$P_{\mathrm{T}} = N_{\mathrm{TEM}}\left(Q_{\mathrm{h,TEM}} - Q\right) \tag{12}$$

where h_5, h_6 and h_8 are the refrigerant specific enthalpies at the inlet and outlets of the THEX; N_{TEM} is the number of TEMs, P_{T} is the electric power consumption of the THEX.

For the ejector (as a mixing device), the energy balance is given by:

$$\left(\dot{m}_1 + \dot{m}_8\right) h_3 = \left(\dot{m}_1 h_2 + \dot{m}_8 h_8\right) \tag{13}$$

where h_2 is the refrigerant specific enthalpy at the compressor inlets.

Finally, the heating COP of the TVCC is expressed as

$$\mathrm{COP} = \frac{Q_{\mathrm{h}}}{P} = \frac{Q_{\mathrm{h}}}{P_{\mathrm{T}} + P_{\mathrm{C}}} \tag{14}$$

where P is the total input power of the TVCC.

Thus, the simulation of TVCC can be performed by using the above equations. The simulation program is written in Fortran Language. The refrigerant thermodynamic properties are calculated by using NIST database and subroutines [Lemmon et al., 2007]. In the next section, a case study on TVCC applied to a small air-source heat pump water heater has been conducted. The performances of this cycle are evaluated in detailed at chosen operating conditions. It should be noted that in the calculation for TVCC, the evaporating temperature, the condensing temperature, the superheating degree for evaporator and the intermediate temperature (i.e. the refrigerant temperature of state point 5) are taken as input operating conditions. The mass flow rate of main circuit is calculated by the volumetric displacement and rotating speed of the compressor; while the mass flow rate of the bypass circuit can be calculated based on the energy balance equation for the THEX. In addition, in order to display the performance improvement of TVCC, the simulation results will be compared with that of a basic vapor compression cycle (BVCC), which is simulated under the same operating conditions.

3. SIMULATION RESULTS AND DISCUSSION

In the following simulations, the refrigerant R134a is selected as a working fluid. The selected compressor has a volumetric displacement of $15\,\mathrm{cm^3/rev}$ and a rotary speed of 2900 RPM. Operating conditions are given as: the evaporating temperature t_e varies from -10 to 15 ℃; the superheating degree for evaporator is set at 5 ℃; the condensing temperature t_c ranges from 55 to 65 ℃; the intermediate temperature t_m varies from 20 to 45 ℃; the temperature differences Δt_c and Δt_h are both set at 5 ℃. In addition, the parameters of the TEMs are selected based on a commercial thermoelectric module (CP2-127-06L) [Abramzon，2007]. The performances of TEMs are simulated under the conditions of the maximum COP.

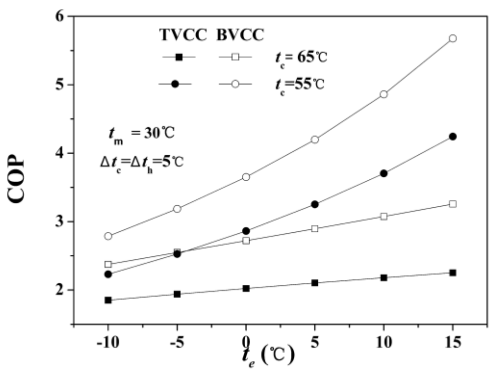


Figure 3 (a) Effects of t_e on the COP at different t_c.

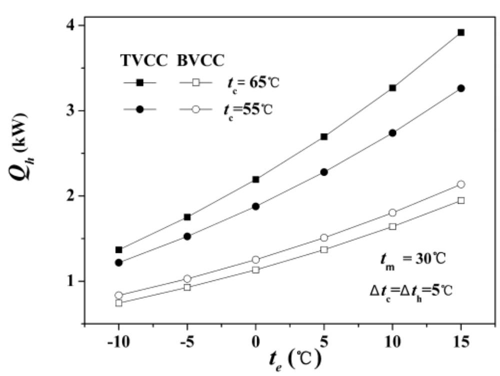
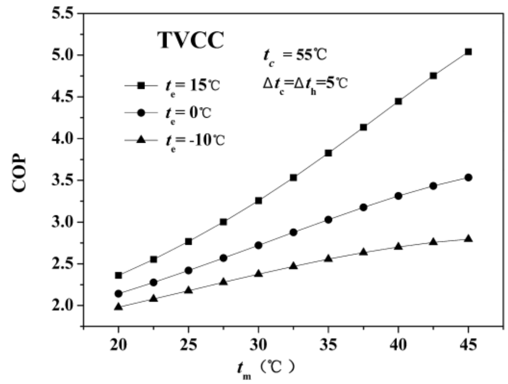


Figure 3 (b) Effects of t_e on the Q_h at different t_c.

Figure 3(a) and (b) show the effects of the evaporating temperature t_e on the COP and Q_h of the TVCC. It can be seen that the COP of TVCC can be kept between 1.852 and 3.257 over the whole operating range. Correspondingly, the heating capacity Q_h of TVCC is between 1.218 and 3.919 kW. Fig. 3(a) and (b) also present the comparison of the performances between the TVCC and BVCC under given operating conditions. It can be clearly seen that compared with the BVCC, TVCC has 46.3%-103.0% increase and 14.7%-52.5% reduction in Q_h and COP, respectively, while t_e ranges from -10 to 15 ℃. This is because that both the Q_h and P increase with an increase of t_e, resulting in the COP decreases. Besides, not only at the high t_e but also at the high condensing temperature t_c, the TVCC has better improvements in heating capacity. When t_c varies from 55 ℃ to 65 ℃, the improvement in Q_h for the TVCC can be achieved from 46.3%-53.4% to 83.9%-103.0%, whereas the decrement of COP is changed from 14.7%-48.7% to 16.9%-52.5%, respectively. The results indicate that the TVCC can have a reduced COP due to the power input of the THEX. However, the TVCC can also achieve an improvement of 16.4%-21.7% in both the heating COP and capacity under the above given conditions, when compared to the BVCC with an assistant electric heater that is provided with the equivalent power input of the THEX. This would make the TVCC more attractive than the BVCC with the assistant electric heater. Therefore, the advantage of TVCC in heating capacity could be beneficial to the applications in small heat pumps at a low ambient temperature.



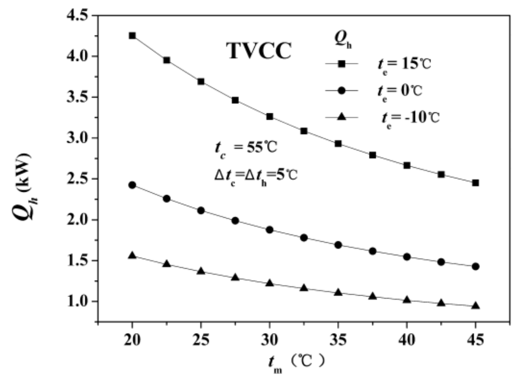
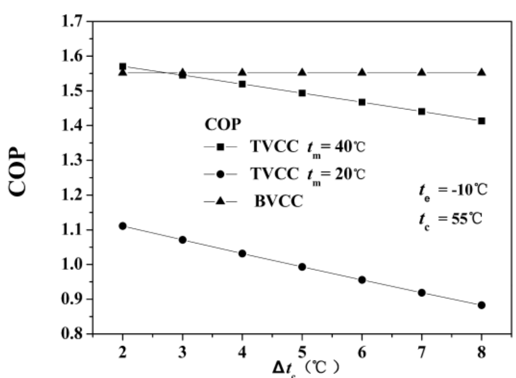


Figure 4(a) The variations of COP with t_m for different t_e. **Figure 4(b)** The variations of Q_h with t_m for different t_e.

The intermediate temperature t_m is an important design parameter in the TVCC. Thus, the effects of t_m on the Q_h and COP is also evaluated at different evaporating temperature t_e, as shown in Fig. 4(a) and (b). It can be seen that with an increases of the t_m, the COP increases while the Q_h decreases. For the case of $t_m = 0$ ℃, the Q_h is decreased from 2.425 to 1.428 kW but the COP is increased from 2.14 to 3.53 when the t_m varies from 20 to 45 ℃. The reason for this is because increasing t_m leads to the smaller absorbed heat of the THEX, but the electric power consumption of the THEX is also reduced because of the smaller junction temperature difference. Despite this situation, TVCC still has 13.0%-99.1% improvement in Q_h compared with that of BVCC under the assumed operating conditions. Especially for the case of $t_e = -10$ ℃ and $t_m = 45$ ℃, the TVCC could achieve Q_h improvements of 13.0% over the BVCC while the two cycles almost have the same theoretical COP. Overall, designing the intermediate temperature t_m should consider the trade-off between the Q_h and COP.



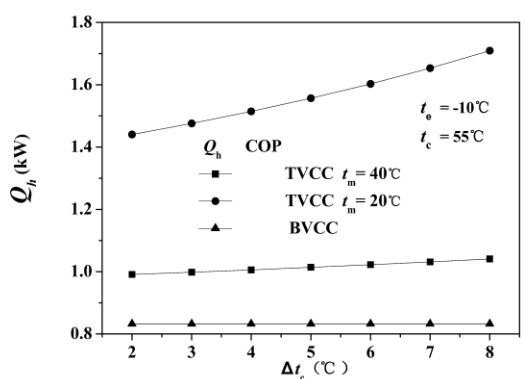


Figure 5(a) Effects of Δt_c on the COP at different t_m. **Figure 5(b)** Effects of Δt_c on the Q_h at different t_m.

As well known, the temperature differences Δt_c and Δt_h has a significant influence on the performance of the TEMs. Thus, we further examine their effects on the performances of the TVCC, as shown in Fig.5 (a) and (b). In the simulation, to avoid the complexity of the theoretical study, Δt_c and Δt_h are assumed to be equal. As a general trend, the heating capacity of the TVCC Q_h increases as the Δt_c increases, whereas the COP decreases due to the increase in power consumption of the THEX. Besides, compared with the BVCC, Q_h of the TVCC is increased from 19% to 105.3% when the Δt_c varies from 2 ℃ to 8 ℃. For the case of $t_m = 40$ ℃ and $\Delta t_c = 2$ ℃, the TVCC also could achieve Q_h improvements of 19.0% over the BVCC when there is no significant difference in COP among the two cycles. This means that under the assumed operating conditions, the performance of TVCC is predicted to be greater than that of BVCC.

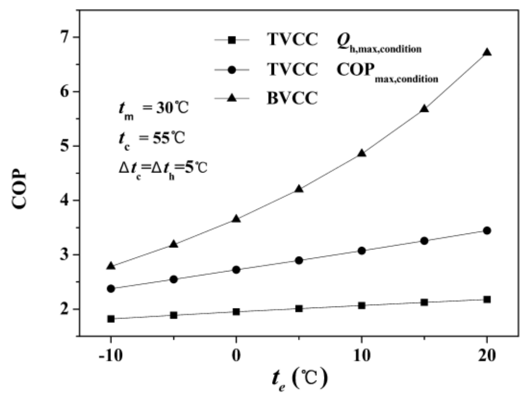


Figure 6(a) Effects of t_e on the COP under two different conditions.

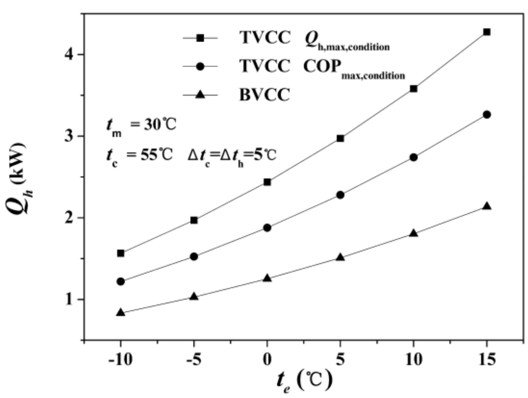


Figure 6(b) Effects of t_e on the Q_h under two different conditions.

Although the TVCC can obtain a relatively high COP under the maximum COP condition of the TEMs, more TEMs in the THEX are required because the absorbed or rejected heat for a TEM are smaller at the condition. In fact, the TEM can be operated at a maximum heating capacity condition that will increase its absorbed or rejected heat. In this case, the number of TEMs in the THEX, N_{TEM}, can be reduced, but at the same time the electric power consumption of the THEX are increased. This also affects the COP and the heating capacity of the TVCC. Fig 6(a) and (b) show the performances of TVCC under the maximum Q_h condition of the TEMs. It can seen that when compared with the BVCC, the TVCC can increase the Q_h by 87.8%-101.3%, whereas the COP is decreased from 34.6% to 67.6%. These results indicate that the TVCC under the maximum heating capacity condition of the TEMs can provide much more heating capacity Q_h than under the maximum COP condition. Of course, this effect also leads to very significant reductions in the COP of the TVCC. Thus, an appropriate operating condition for the THEX should be globally considered when the TVCC is applied in practical air-source heat pump systems.

4. CONCLUSIONS

The TVCC is proposed for small air-source heat pump applications. A theoretical investigation on the TVCC applied in a heat pump water heater is performed using a developed mathematical model. The simulation results show that compared with the BVCC, TVCC has dramatic improvement in heating capacity and a certain amount of reduction in COP, particularly at higher evaporating or condensing temperature. Even when the COP of the two cycles are almost equal, the TVCC still outperform the BVCC in heating capacity by selecting an appropriate intermediate temperature. Because the COP and heating capacity of the TVCC are both higher than those of the BVCC with an assistant electric heater, TVCC would be a good choice for the air-source heat pumps when they needs extra electric heat at a lower ambient temperature. Thus, the proposed cycle may provide potential benefits for the small air-source heat pump water heaters. Certainly, to accomplish this, further experimental study on the characteristics of TVCC is still required.

NOMENCLATURE

COP	coefficient of performance	
h	specific enthalpy	($\mathrm{kJ\ kg^{-1}}$)
I	electric current	(A)
k	thermal conductivity	($\mathrm{W K^{-1} cm^{-1}}$)
$\dot{m}$	mass flow rate	($\mathrm{kg\ s^{-1}}$)
N	number	
p	pressure	(kPa)
P	input power	(kW)
Q	heating capacity	(kW)
n	rotating speed of the compressor	(rpm)
t	temperature	(℃)
V_{dis}	volumetric displacement of a compressor	($\mathrm{cm^3 rev^{-1}}$)
v	specific volume	($\mathrm{m^3\ kg^{-1}}$)

Greek symbols

α	Seebeck coefficient	($\mathrm{V K^{-1}}$)
ρ	electric resistivity	(Ω m)
η	efficiency	

Subscripts

c	cold
comp	compressor
h	hot
TEM	thermoelectric module
v	volumetric
1-8,2s	state points of refrigerant

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