Controlling the evaporation pressure of a heat pump to improve thermal comfort at low cooling load condition

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Abstract: In order to develop a control method for air-source heat pumps that can be used to achieve better indoor thermal comfort at a low cooling load condition than the current control method, a new method of the evaporation pressure control based on the evaporator outlet pressure reading was developed. The changes in the stability of indoor air temperature and power consumption were measured changing the compressor frequency in accordance with the new control method. The new control method appeared to improve the stability of indoor air temperature and have a potential to reduce power consumption than the current evaporation pressure control method based on the evaporator outlet temperature reading,.

Key Words: heat pump, thermal comfort, control, cooling mode, evaporation pressure

1 INTRODUCTION

A lot of research on the heat pump has been being conducted. Previous studies on heat pumps usually focused on improvement in the energy efficiency. Recently, not only energy saving but also indoor thermal comfort are considered. In an existing heat pump, the system was controlled through an on-off operation which turns on or off the power of the fixed-speed type compressor used for the heat pump. The heat pump controlled based on the on-off control method is not able to condition the air at the same level of temperature. In addition, the on-off control method has low energy efficiency. Recently, variable speed compressors which control the motor speed using an inverter have been developed and are used for heat pumps. One of the advantages an inverter heat pump has is that a comfortable indoor environment can be maintained by adjusting the rpm of the compressor. Previous works showed that the inverter heat pump is superior to the fixed speed type heat pump in the aspects of energy efficiency and thermal comfort. Tassou et al. (1983) and Nagamatsu et al. (2012) reported that the energy efficiency of the inverter-driven heat pump was higher during low speed operation since fixed speed type heat pump consumed much electric power due to the on-off operation at a low air-conditioning load.

Recently, studies are conducted to maximize the system efficiency through improvement in the control strategy using fuzzy control, proportional-integral (PI) control, and proportional-integral-derivative (PID) control. In order to construct a control algorithm of the variable-capacity multi-heat pump, Chang et al. presented a characteristic equation of the cooling/heating load which is defined by the capacity of the indoor unit, indoor and outdoor temperatures, and the difference between the set temperature and the indoor temperature.

The characteristic equation expressed the frequency of the compressor and the openness of the electrical expansion valve (EEV) as a function of the cooling/heating load (Chang et al. 2001). Koury et al. conducted a numerical study to simulate the transient and steady state behavior of a vapor compression refrigeration system. The result of the simulation indicates that the control of refrigeration capacity by varying the compressor rotational speed leads to an increase in the degree of superheat and hence impaired the COP of the system (Koury et al. 2001).

The evaporation pressure of the heat pump needs be controlled appropriately to match the cooling load in order to enhance the energy efficiency and the indoor thermal comfort. For effective control of evaporation pressure, the variables required for identification of the system condition are needed to be detected. In the past, the temperatures such as the refrigerant temperatures at the inlet and outlet of the compressor, the evaporating temperature of the refrigerant, and the condensing temperature were measured and used to control the evaporation pressure (evaporation pressure control based on evaporator outlet temperature reading: EPCT). However, as such temperature variables change sensitively following the change in the outdoor and indoor temperatures, it is difficult to achieve accurate control for the evaporation pressure. In order to supplement the weak point of EPCT method and to achieve efficient control of the evaporation pressure, an evaporation pressure control based on the evaporator outlet pressure reading (EPCP) method was developed. The EPCP method uses the refrigerant pressure at the outlet of the evaporator as the control input.

The studies which have applied the EPCP method to the actual heat pump is rare. In this paper, we intend to propose a novel EPCP method and present the performance of the heat pump controlled by EPCP method. And comparisons will be made between the performances of heat pumps controlled by the EPCT method and the EPCP method in terms of stability of indoor air temperature and energy consumption.

2 Heat pump control method

It is important to control the working frequency of the compressor since the evaporation pressure is influenced by the compressor speed. The initial frequency of the compressor is determined in accordance with the indoor and outdoor temperatures as well as the difference between the set temperature and the indoor temperature. As the indoor temperature approaches the set temperature reducing the cooling load while the system continues to run at the initial compressor frequency. As the cooling load decreases, the evaporation pressure is varied by changing the compressor frequency to allow the indoor temperature to stably reach the set temperature.

The indoor load is calculated as follows: The indoor air temperature ($T_{i,air}$) to be controlled is measured, which is compared with the set temperature ($T_{i,target}$) to calculate the error (e(t)). The load is calculated considering the proportional value ($K_P \cdot e(t)$) which is proportional to the size of the error and the rate of change of the error ($K_D \cdot de(t)/dt$). The indoor load (L) is calculated as shown in Equation (1) after estimating the correction value ($f(T_i,T_o)$) depending on the indoor and outdoor temperatures.

$$L=(K_p \cdot e(t)+K_D \cdot de(t)/dt)\times f(T_i,T_o) \qquad (1)$$

The evaporation pressure is adjusted by reducing the compressor frequency as the load decreases. When the indoor load (L) is calculated using Equation (1), the relevant correction value (g(L)) is determined. Finally, the determined compressor frequency ($f_{comp,n}$) is expressed as Equation (2).

$$f_{comp,n}=f_{comp,n-1}\times g(L) \qquad (2)$$

The current frequency of the compressor ($f_{comp,n}$) is determined by multiplying the previous frequency ($f_{comp,n-1}$) and the correction value (g(L)) for the indoor load. The bigger the difference between the set temperature and the indoor temperature is, the higher the compressor frequency is operated to maintain low evaporation pressure. When the indoor load is reduced by high speed operation of the compressor, the optimum evaporation pressure which matches the load is controlled by operating the compressor at a lowered frequency.

For efficient control of the evaporation pressure, the variables for grasping the system condition are required to be detected. It is important to monitor the conditions of heat pump by selecting the variables which represent the change in the condition of the system. In the past, evaporation pressure was controlled based on the readings of the compressor inlet/discharge temperature, condensing temperature, and the evaporating temperature. Figure 1 shows the block diagram for control of a heat pump using the EPCT method.
Among the variables stated earlier, the compressor discharge temperature was used as the control variable for optimum operation since it showed not only a stable dynamic characteristic for change in the compressor frequency and openness of the expansion valve but also a close relationship with the cooling capacity. Usually, experiments are conducted to relate the variables of the heat pump system with the frequency of the compressor and the openness of the expansion valve at the optimum state of the heat pump. A heat pump is controlled by controlling the compressor discharge temperature ($T_{comp,d}$) at the target level through adjustment of the EEV openness ($EEV_{openness}$). The EEV openness is changed depending on the mid-point temperature of the condenser ($T_{cond,mid}$) and the refrigerant temperature at the evaporator outlet ($T_{eva,out}$). This relation can be expressed as shown in Equation (3).

$$T_{comp,d}=C0+C1\times T_{eva,out}+C2\times T_{cond,mid}+C3\times f_{comp} \qquad (3)$$

Equation (3) defines the optimum temperature of the refrigerant discharged from the compressor ($T_{comp,d}$) during a cooling mode operation in reference to the changes in the compressor frequency(f_{comp}), the mid-point temperature of the condenser ($T_{cond,mid}$), and the refrigerant temperature at the evaporator outlet ($T_{eva,out}$). That is to say, temperatures at several locations are read and refrigerant temperature at compressor discharge is controlled in order to maintain the evaporator pressure at the target level. Such an EPCT method has been widely used since the price of the temperature sensor is cheap.

In order to control the evaporation pressure using the EPCT method, the control value is determined by reading each temperature variable. By the way, the temperature at each location is measured using the thermo-couple installed on the outside wall of tube. The temperature measured on the outside wall of the tube may have an error in monitoring the condition of the refrigerant. Also, it has a disadvantage that the error grows bigger when the load fluctuates. In order to solve this problem, the pressure at the evaporator outlet ($P_{eva,out}$) is directly measured and used for control strategy. The EPCP method is shown in a diagram in Figure 2. In comparison to the EPCT method in Figure 1, the control flow is simplified. The biggest advantage of the EPCP method is that the information about the evaporation pressure is directly obtained using a pressure sensor. Accordingly, if the EPCP method is used, only a little calculation or receipt of data will enable the evaporation pressure to be optimally controlled considering the system change.

3 Experimental apparatus and procedure

The heat pump used in this study comprised of an indoor unit and an outdoor unit. Figure 2 shows the refrigerant circulation circuit of the inverter-driven heat pump used in this experiment. The indoor unit consisted of a fin-tube heat exchanger and a fan while the outdoor unit was comprised of fin-tube heat exchangers, electric expansion device(EEV), compressor, 4-way valve, and an accumulator. An electric expansion valve (EEV) was used of which openness can be varied in the range of 0 – 100%. A twin rotary compressor was used of which capacity could be adjusted by the inverter frequency. Inflow of the liquid refrigerant into the compressor was prevented by installing an accumulator at the inlet of the compressor. R-410a was used as the refrigerant. The 4-way valve was used to select the cooling operation or heating operation of the heat pump by changing the direction of the refrigerant flow. This experiment was conducted in the cooling operation mode.

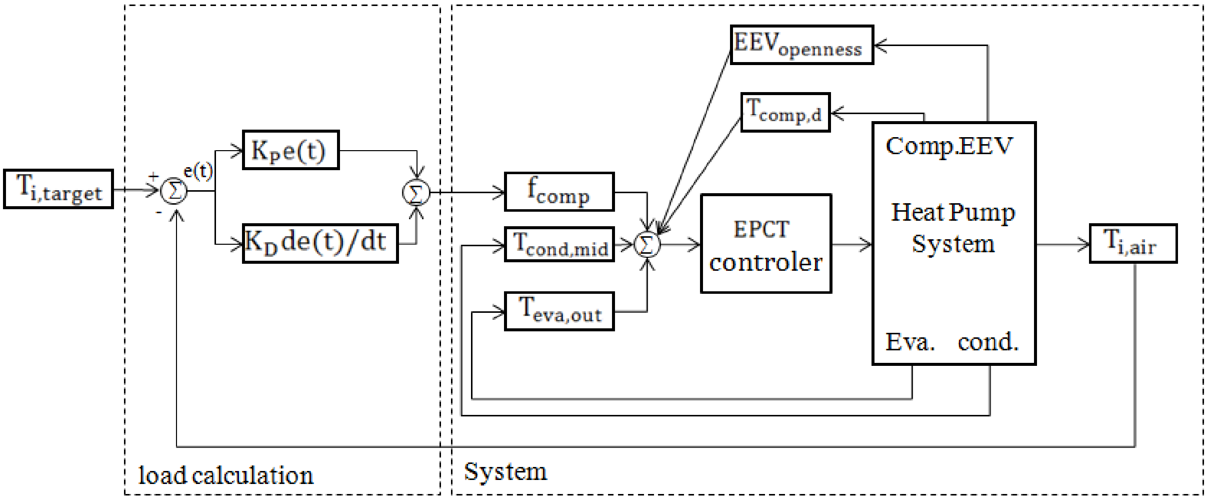

Figure 1: Block diagram for evaporation pressure control based on evaporator outlet temperature reading (EPCT)

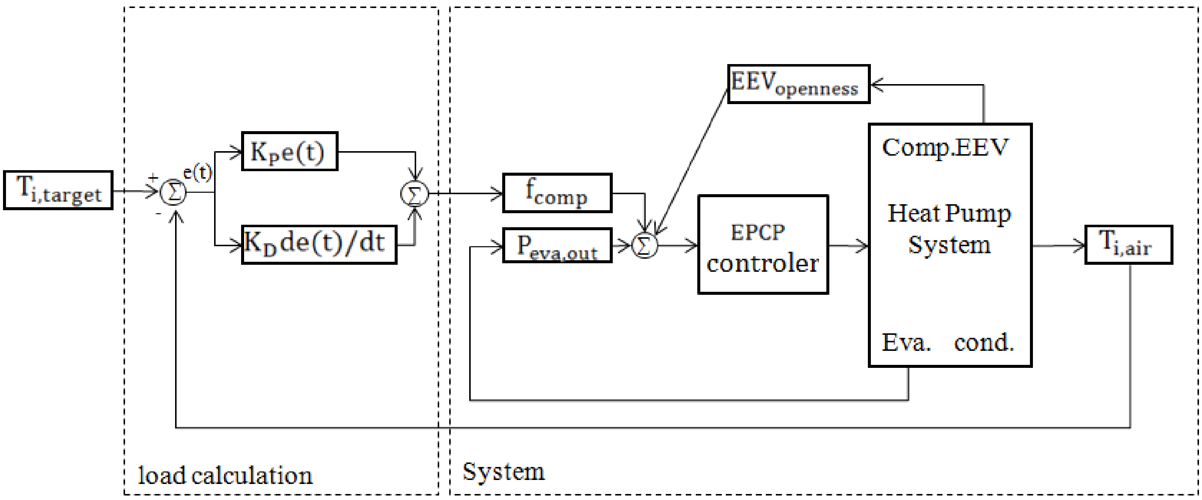

Figure 2: Block diagram for evaporation pressure control based on evaporator outlet pressure reading (EPCP)

Temperatures were measured at various locations including the compressor inlet and outlet, evaporator inlet and outlet, condenser inlet and outlet, and the middle of the evaporator and the condenser. The temperature of the refrigerant was measured using T-type thermocouple attached on the surface of the tube. The error range of the temperature measurement is ± 0.3℃. A pressure transducer was installed at the evaporator outlet to measure the evaporation pressure. The measurement range of the pressure transducer is 0.7 to 4.5 MPa. The pressure transducer provides the information of the current evaporation pressure of the system for the EPCP method.

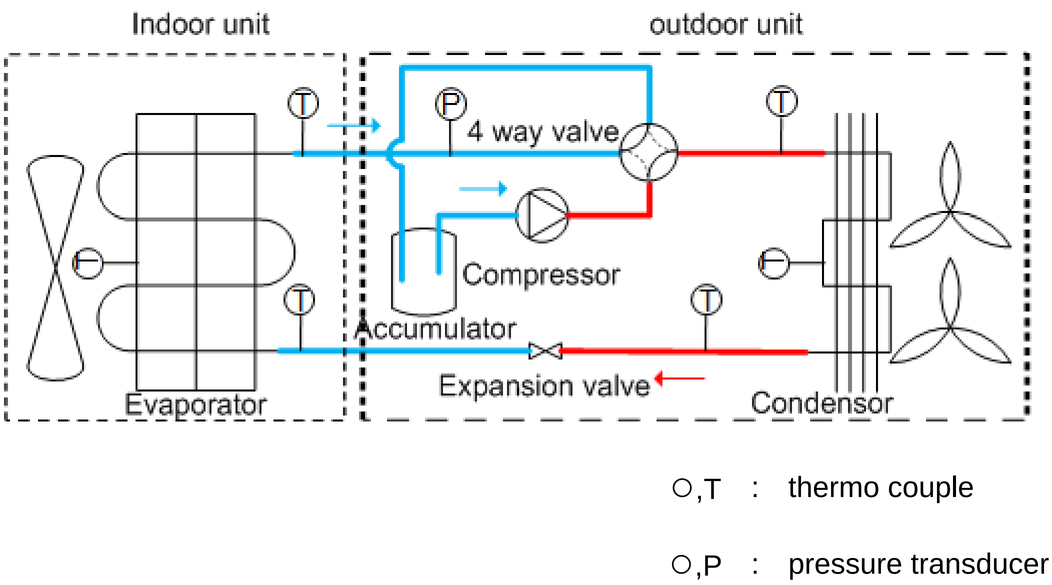

Figure 3: Schematic diagram of heat pump system

The experiment was conducted in a psychrometric calorimeter. The calorimeter has two chambers simulating an indoor environment and an outdoor environment. Before starting the experiment, the temperature and humidity of the indoor chamber and the outdoor chamber were adjusted to the experimental condition of the Korean Standard for air-conditioner performance measurement (Indoor room: DB:27/WB:19; Outdoor room: DB:35/WB:24). After starting the operation of the heat pump, the temperature regulator of the indoor chamber was stopped and the change in the indoor temperature was measured. The temperature in the outdoor chamber was maintained at the set temperature of 35℃ during the experiments.

Even though the capacity of a heat pump is designed to meet the maximum load, a heat pump is operated in a low load condition most of the time. Therefore, it is required to improve the energy efficiency in a low load condition. In order to simulate the cooling load in a low load condition, an electric heater was installed inside the indoor chamber. The thermal load of 2.2 kW, 15% of the maximum cooling capacity (15 kW) of the heat pump, was continuously supplied using the electric heater. The experiment was conducted with the target temperature of the indoor chamber ($T_{i,target}$) of 20 and 22℃.

In order to lower the indoor chamber temperature to the set temperature, the evaporation pressure should be controlled by adjusting the compressor frequency. The indoor temperature can be lowered to the set temperature within a short period of time if the evaporation pressure is maintained as low as possible by operating the compressor at the highest frequency. However, strong cooling should be restrictively used since occupants will feel uncomfortable with the powerful cooling if strong cooling continues even after the indoor temperature has been lowered to some extent. Accordingly, if the difference between the indoor temperature and the set temperature is large, the evaporation pressure is maintained low by operating the compressor at a high frequency in order to rapidly lower the indoor temperature. However, the smaller the temperature difference is, the more it is desirable to gradually lower the indoor air temperature. This can be achieved by lowering the compressor frequency, which results in an increase in the evaporation pressure and evaporation temperature of refrigerant. In order to stabilize the indoor air temperature in the low cooling load range where the indoor temperature is close to the set temperature, the compressor should be operated at low frequency. In order to examine the effect of the compressor frequency on the temperature change in the low frequency range, the experiment was conducted changing the compressor frequency by 2 Hz at a time within the range of 20 to 26 Hz.

In order to implement the control concept explained earlier, the evaporation pressure control point, where control action is taken to increase the evaporation pressure, should be determined considering the difference between the indoor temperature and the set temperature. The evaporation pressure was changed to examine the performance characteristics of the heat pump system when the difference between the indoor temperature and the set temperature, △T, reached a pre-set level. Experiments were performed at three different levels of the temperature difference (△T): 0, 1 and 2℃. After the indoor temperature has reached the set temperature, the heat pump compressor was stopped if the indoor temperature is maintained to be lower than the set temperature by 0.5℃ or more for 3 minutes. The indoor air temperature increased after the compressor stopped due to continuous provision of thermal load. So the heat pump compressor resumed operation if the indoor temperature is maintained to be higher than the set temperature by 0.5℃ or more for 3 minutes.

4 Results and discussions

4.1 System performance depending on the change in the compressor frequency

When the indoor temperature approaches the set temperature, the compressor frequency was changed to a lower value in order to make the indoor temperature stably converge to the set temperature by increasing the evaporation pressure. Such a change in the compressor frequency was made when the difference between the indoor temperature and the set temperature (△T) reaches 2℃. At this time, the compressor frequency was lowered to the range of 20 to 26 Hz considering the low cooling load condition. The experiments were repeatedly conducted changing the compressor frequency by 2 Hz at a time. In addition, a base case experiment was conducted where the indoor air is cooled down to the set temperature without intentional frequency change. For the base case experiment, the compressor frequency (f_{base}) was maintained at 60 Hz and turned on and off depending on the indoor air temperature change. Figure 4 shows the changes in the indoor temperature depending on the change in the compressor frequency when the indoor chamber target temperature ($T_{i,target}$) is 22℃. The lower the frequency is, the longer the time it takes to reach the set temperature. The compressor was operated at 60 Hz at the beginning and at the changed frequency of 20, 22, 24, or 26 Hz when the indoor temperature reached 24℃ (△T = 2℃). In the case the system is operated at a low frequency, it takes more time to lower the indoor temperature to the set temperature than the base case where the system is continued to be operated with the compressor frequency fixed to the initial frequency of 60 Hz. The lower the frequency was, the longer it took to reach the set temperature as the temperature drop gradient decreased. In the case of the base case, the set temperature was reached within the shortest time of 674 seconds. However, the indoor air was rapidly cooled down below the set temperature due to excessive cooling. As the indoor temperature was maintained at the value lower than the set temperature by 0.5℃ or more for 3 minutes, the compressor was stopped after 898 seconds. When the compressor is stopped, the indoor air temperature increases due to the thermal load supplied. When the indoor temperature was maintained at the value higher than the set temperature by 0.5℃ for 3 minutes, the compressor was started again. Then the on-off operation was repeated.

Figure 5 shows the change in the power consumption. The power is consumed while the compressor is operated, and the power consumption becomes ‘0’ when the compressor is stopped. Though it takes longer time to reach the set temperature than the base case when the frequency is controlled, the time the compressor is stopped is delayed. In addition, the on-off operation is repeated a smaller number of times than that of the base case. When the frequency is controlled, as the compressor is operated in the range of frequency (20 to 26 Hz) lower than that of the base case (about 60 Hz), the power consumption level is also shown to be lower than that of the base case. The reduction in power consumption was caused by the fact that the frequency controlled heat pump operates with less pressure difference between condenser pressure and evaporator pressure than the base case by increasing the evaporation pressure.

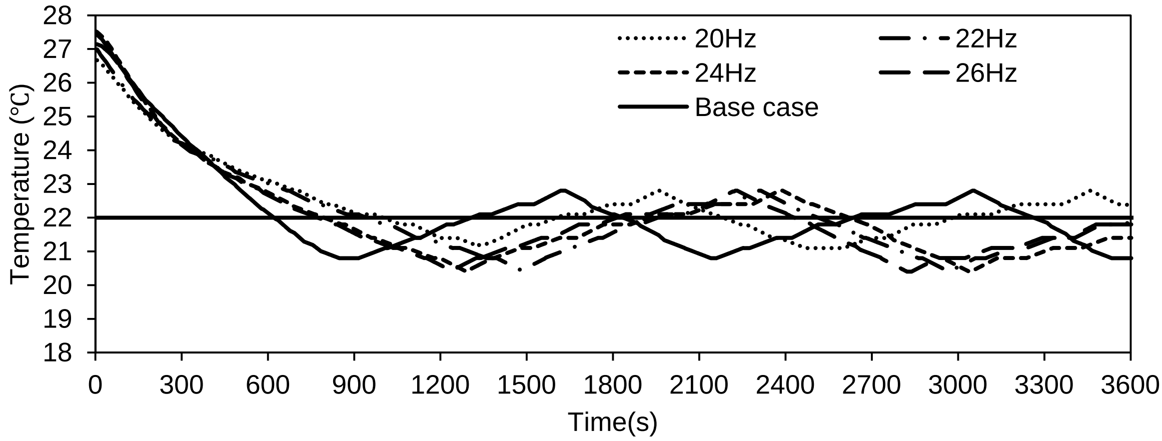

Figure 4: Change in the indoor temperature as response to compressor frequency

($T_{i,target}$=22℃)

The comfortable period ratio is defined in order to compare the stability of indoor air temperature. The comfortable period ratio represents the proportion of time the indoor temperature is maintained between +0.5℃ and -0.5℃ of the target indoor temperature. When the compressor frequency was controlled to be 20 Hz, the comfortable period ratio showed the highest value of 82.4%. The mean power consumption was calculated by integrating the power consumption during the operation time and dividing it by the operation time. The mean power consumption of the base case showed the highest value. When the compressor frequency is controlled, the mean power consumption decreases from that of the base case. The mean power consumption when the compressor frequency was controlled was lower than that of the base case by minimum about 20% to maximum 30%.

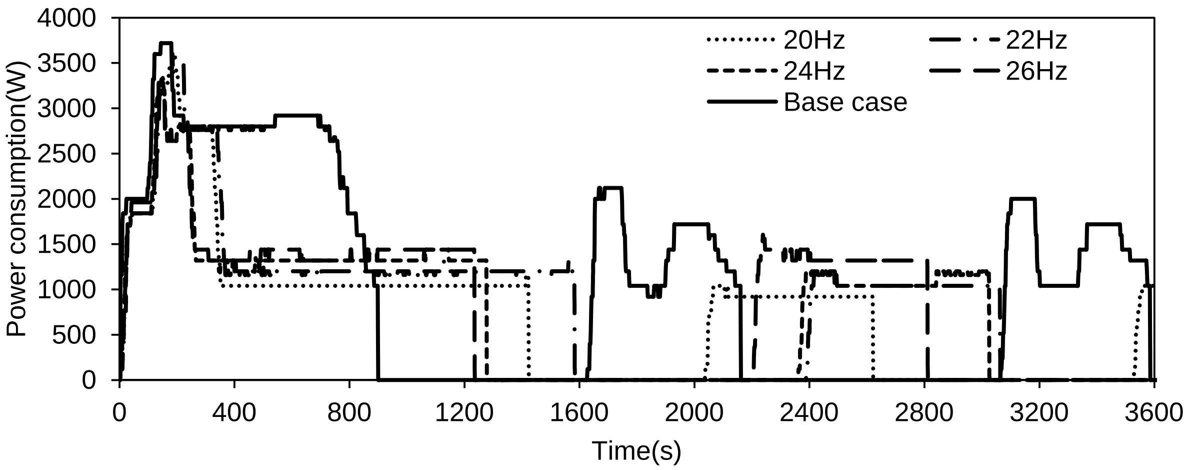

Figure 5: Change in the power consumption as response to compressor frequency ($T_{i,target}$=22□)

4.2 Effect of the evaporation pressure control point

If the indoor temperature approaches the set temperature, the evaporation pressure should be increased to make the indoor temperature stably reach the set temperature. The control point to change the evaporation pressure was determined considering the difference between the set temperature of the heat pump and the indoor temperature. In order to determine to what temperature to maintain the low evaporation pressure, the experiment was conducted at three different levels of the temperature difference between the set temperature and the indoor temperature (△T): 0, 1 and 2℃. When the difference between the indoor temperature and the set temperature reached each difference (△T), the evaporation pressure was changed.

Figure 6 shows the changes in the evaporation pressure depending on the evaporation pressure control point when the indoor target temperature ($T_{i,target}$) is 20℃. The evaporation pressure changes significantly just after start-up of the compressor. After this start-up transient, the evaporation pressure reaches about 700 kPa and remains constant for a while. Even though the evaporation pressure (refrigerant temperature) remains constant, the indoor air temperature continues to decrease as can be seen in Figure 4(b). When the indoor temperature reached 22 ℃ (△T = 2 ℃), 21 ℃ (△T = 1 ℃) and 20℃ (△T = 0 ℃), the evaporation pressure was increased by lowering the compressor frequency at the minimum level of 20 Hz. The reduction in compressor frequency increases the evaporation pressure up to about 1,000 kPa. And then, the evaporation pressure changes depending on the compressor operation.

Figure 7 shows the change in the indoor air temperature. In the case the evaporation pressure is increased at the indoor temperature of 20℃ (△T = 0℃), the indoor air temperature is rapidly cooled down to the set temperature or lower even though the evaporation pressure is increased. As the indoor air temperature was maintained at lower than the set temperature by 0.5℃ for 3 minutes, the compressor was stopped after 1,464 seconds. Then, the indoor air temperature increased due to the thermal load supplied and the evaporation pressure is also increased up to around 1400 kPa. The compressor was started again when the indoor temperature was maintained at higher than the set temperature by 0.5℃ for 3 minutes. Then the on-off operation was repeated. In the cases where the evaporation pressure is increased when the indoor room temperature reached 22 ℃ (△T = 2 ℃) and 21 ℃ (△T = 1 ℃), however, the compressor did not stop but kept running at low frequency since the room air temperature did not drop below the set temperature longer than 3 minutes.

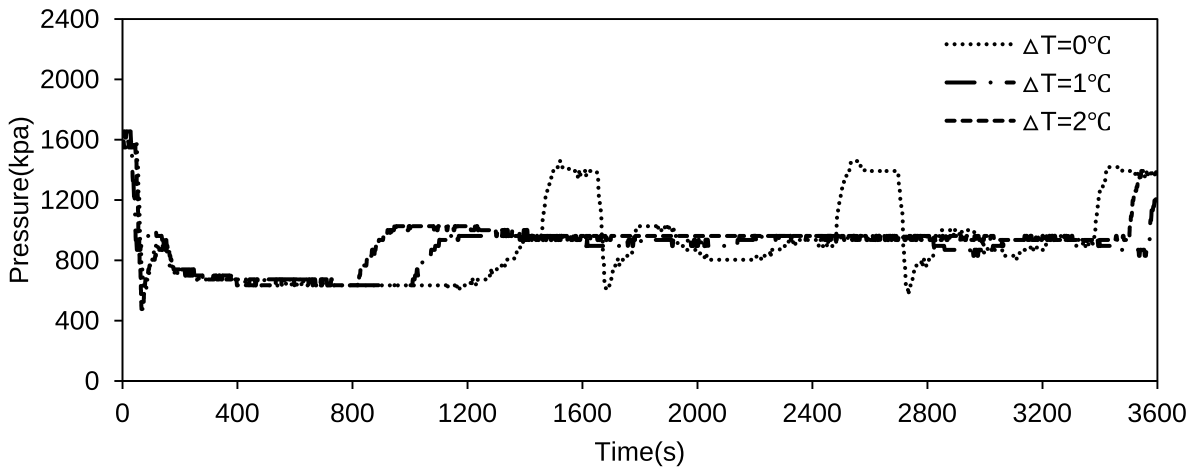

Figure 6: Change in the evaporation pressure as response to evaporation pressure control point change ($T_{i,target}$=20□)

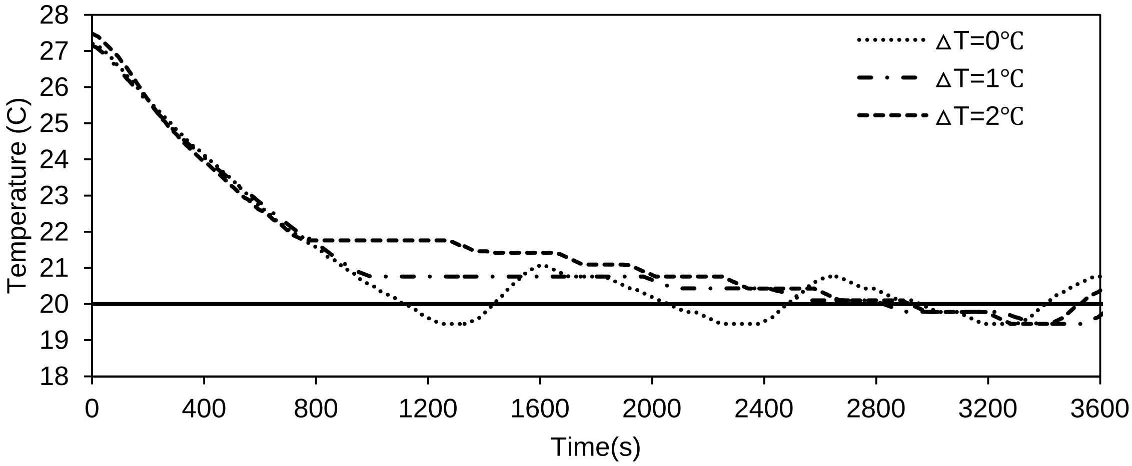

Figure 7: Change in the indoor air temperature as response to evaporation pressure control point change ($T_{i,target}$=20□)

Figure 8 shows the power consumption change. In the case the evaporation pressure is increased at the indoor temperature of 20℃ (△T = 0℃), the power consumption changes dramatically. The power consumption becomes ‘0’ when the compressor is stopped while the power consumption is very high when the compressor runs. In the cases that the evaporation pressure is increased at the indoor room temperature of 22 ℃ (△T = 2 ℃) and 21 ℃ (△T = 1 ℃), however, the compressor is continuously operated at a low frequency and the power consumption is remained at a low level.

The comfortable period ratio showed the highest value of 50.0% when the evaporation pressure was increased at the indoor temperature of 21℃ (△T = 1℃). The lowest comfortable period ratio was observed in the case where the evaporation pressure was increased at the indoor temperature of 22℃ (△T = 2℃). However, the difference was small. The mean power consumption showed the highest value when the evaporation pressure was controlled at the indoor temperature of 20℃ (△T = 0℃). It is because the compressor run at the largest pressure difference between condenser pressure and evaporator pressure during operation compared to other two cases. The smallest power consumption was observed in the case that the evaporation pressure is controlled at the indoor temperature of 22℃ (△T = 2℃). For this case, the mean power consumption was saved by 16.4%. The power consumption was reduced since the heat pump was operated with smaller pressure difference between condenser pressure and evaporator pressure even though the compressor continues to operate.

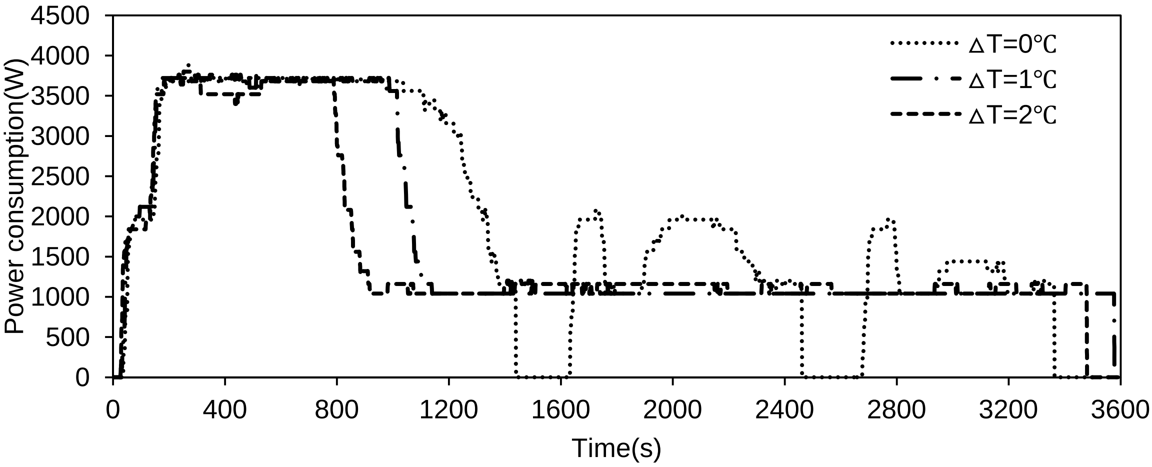

Figure 8: Change in the power consumption as response to evaporation pressure control point change ($T_{i,target}$=20□)

4.3 Comparison of EPCP and EPCT

The result of the experiments described in Section 4.1 and Section 4.2 were used to set up parameters for EPCP method. The performance of a heat pump system controlled by the new EPCP method and conventional EPCT method was measured in the same environmental condition to compare each other.

Figure 9 shows the change in the indoor temperature depending on the evaporation pressure control method when the indoor target temperature ($T_{i,target}$) was set to be 20℃. In the case the heat pump is controlled by the EPCT method, the indoor air temperature is maintained above the set temperature. When the heat pump is operated by the EPCP method, it can be seen that the indoor temperature stably reaches the set temperature. Figure 10 shows the change in the power consumption. When the heat pump was controlled by the EPCP method, the power consumption at the beginning was much smaller than when it was controlled by the EPCT method. After the initial approaching period, the heat pump operated by the EPCT method showed a power consumption level lower than the heat pump controlled by the EPCP method. This is because the evaporation pressure controlled by the EPCT method was maintained at higher than the evaporation pressure controlled by the EPCP method. In the meantime, the heat pump controlled by EPCP method consumes power in a steady manner under low cooling load condition while the power consumption fluctuates when the heat pump is controlled by EPCT method.

The comfortable period ratio appeared to be 70.0% when the heat pump was controlled using the EPCP method while 15.7% for the EPCT method. The comfortable period ratio showed a big difference, and it could be seen that the EPCP method is effective for thermal comfort and load-following operations. Though the mean power consumption was shown to be smaller when the heat pump was operated by the EPCT method, the difference was negligible showing a difference of 0.8%. When the heat pump was controlled by the EPCT method, the indoor air temperature was maintained above the set temperature. In order to lower the indoor air temperature at the level controlled by the EPCP method, the evaporation pressure should be lowered more. If the power consumption is calculated reflecting this difference, the power consumption when the heat pump is controlled by the EPCP method is expected to be lower.

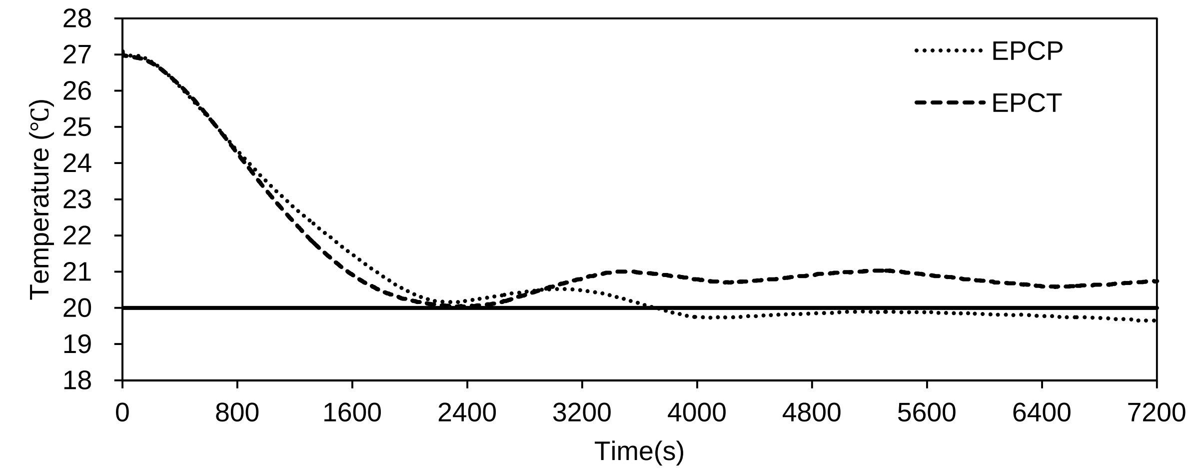

Figure 9: Change in the indoor air temperature as response to heat pump control method ($T_{i,target}$=20□)

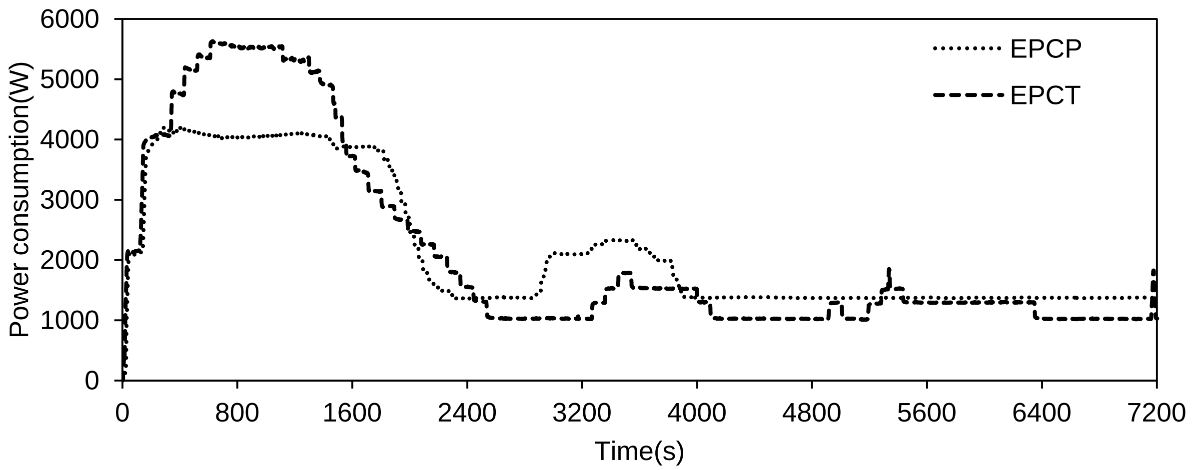

Figure 10: Change in the power consumption as response to heat pump control method ($T_{i,target}$=20□)

5 Concluding remarks

A new heat pump control method, evaporation pressure control based on evaporator outlet pressure reading (EPCP) method, was proposed. The performance of a heat pump controlled by the EPCP method were experimentally measured and compared with that of a heat pump controlled by the EPCT method. The comparisons were made in terms of initial approaching time to set temperature, comfortable period time, and average power consumption. Compared with the evaporation pressure control based on evaporator exit temperature reading(EPCT), the new control method(EPCP) appeared to improve the stability of room air temperature and have a potential to reduce power consumption.

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