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Experiment on the performance improvement of air-to-air heat pump adopting the hot gas bypass method by outdoor fan speed variation †

Jinho Lee[1,*] and Ju-Suk Byun[2]

[1]*School of Mechanical Engineering, Yonsei University, Seoul 120-749, Korea*
[2]*Ansan Technology Appraisal Center, Kibo Technology Fund, Gyeonggi 138-844, Korea*

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Abstract

This study focuses on the effect of outdoor coil fan speed on the performance variation of the heat pump system by adopting the hot gas bypass method, and on the performance improvement with hot gas bypassing using the time step method to defrost. Tests were conducted for fan speeds 90, 60 and 30% of the normal speed of the outdoor coil together with the stationary case. Performance of the heat pump is compared with the conventional time step defrosting method for coefficient of performance (COP) and total heat capacity. Results show that the integrated heating capacity with hot gas bypassing is highest at 60% (780 rpm) of the fan speed and is 8.6% higher than that of the time step defrosting method. The averaged COP of the heat pump in this case is higher by 3.8% than the time step defrosting method and 2.8% higher than that of the stationary fan.

***Keywords*: ** Heat pump; Frost; Hot gas bypass; Fan speed; COP; Heating capacity

1. Introduction

A heat pump is an environmental energy technology that extracts heat from low temperature sources, discharges it to a higher temperature and releases it when it is required for space and water heating. Much less electricity is used to move the heat rather than create it, making heat pumps more economical than the resistance heating. However, in all but the most moderate climates, the heating ability of the heat pump is limited by freezing outdoor temperatures. So the electric resistance heater is used to supplement the air-source heat pump during the coldest weather, preventing “cold blow” phenomenon. Depending on the climate, air-source heat pumps are about 1.5 to 3 times more efficient than the electric resistance heating alone. When the air-source heat pump is operating in the heating mode, refrigerant is evaporating in the outdoor coil. If the temperature of the coil falls below 0℃, the frost will begin to form on the coil. Eventually, the frost can build up enough on the coil to restrict the air passing through the coil, reducing its efficiency. The frost will also act as an insulator on the finned surface and retard heat transfer, thus reducing its coil efficiency even further. Therefore, the heat pump requires an auxiliary heat source and its use is restricted by local climate [1]. To reduce the decrease in the thermal performance of the evaporator due to the frost formation, the frost should be periodically removed. The frosting and the defrosting can reduce its performance over steady-state conditions where the frost does not form. Also, in many circumstances, frosting and defrosting processes cause significant problems [2-4], such as reduced energy efficiency, or worst of all, the heat pump breakdown. In addition, frosting increases the equipment cost due to the addition of auxiliary heating elements, reduces equipment reliability and increases the loss of operational load

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*Corresponding author. Tel.: +82 2 2123 2816, Fax.: +82 2 312 2159
E-mail address: jinholee@yonsei.ac.kr

during the defrosting process. Therefore, how to prevent or delay the frosting process has been one of the important issues for engineers and researchers. The methods for removing frost on the outdoor coil of the heat pump are reverse-cycle defrosting, electric heat defrosting, and hot gas bypass defrosting, in general. The reverse cycle defrosting method has been the most commonly used defrost method for a long time. The method changes the roles of a condenser and an evaporator by sending the high temperature refrigerant at the compressor outlet into an evaporator by using a 4 way-valve. However, the disadvantage of the method is that during the defrost operation the auxiliary heater is needed for room heating, which obviously decreases the energy efficiency. Electric heat defrosting can defrost the outdoor coil surface by using an electrical heating device. The method takes more defrosting time than the reverse cycle defrosting method, and also has low energy efficiency due to the electrical heating device. Hot gas bypass defrost uses the high temperature refrigerant from the compressor outlet as a defrosting source. The main difference between the hot gas bypass method and the reverse cycle method is the former method does not change the role between the evaporator and the condenser as the latter one. The method's advantage is that no extra defrosting device is needed for heating. However, the method requires an accurate control of the system to prevent the influence of bypass refrigerant to the whole system.

Anand et al. [5] investigated the effect of sudden pressure shooting and falling in the compressor suction and discharge lines during the defrost cycle on mechanical shocks to the compressor and the refrigerant lines. Byun et al. [6] investigated the frost perception and the operation of a defrost cycle through the application of a photo coupler for the frost detection. The adoption of the photo-coupler showed 5.5 % higher heating capacity than the time control method, and also indicated that it is best to initiate the defrost cycle before the frost buildup area exceeds 45 % of total front surface of the outdoor coil.

Kirkman [7] suggested various hot gas bypass systems to control load conditions. Yaqub et al. [8-10] examined the capacity control of a refrigeration system by injecting hot gas straight into the compressor suction part and demonstrated that the compressor discharge temperature significantly increases for this set-up. Cho et al. [11] investigated the performance of the showcase refrigeration system with three evaporators during the on-off cycling and the hot-gas bypass defrosting. The hot-gas bypass defrosting method showed higher refrigerating capacity and less temperature fluctuations than the on–off cycling under frosting/defrosting conditions even though it required more compressor power. Tso et al. [12] compared the performance of the hot gas bypass control and the suction modulation control in refrigerated shipping containers. The suction modulation control strategy was shown to be the more energy efficient than the hot gas bypass control. Recently, Byun et al. [13] examined the heat pump performance variations effected by retarding the frost formation and propagation by the intermittent hot gas bypassing for varying operation variables. Though the system becomes easily unstable according to the varying injection rate, they obtained the optimal extraction rate of the bypassing refrigerant, which effectively retards the frost formation and growth and minimizes the temporal performance degradation of the heat pump system, which is largely due to the fluctuations in performance.

Generally, the air-to-air heat pump performance depends much on the air flow rate as well as outdoor air temperature, but there seems to be no report on that yet except Zigler [14], who reported that by varying the fan speed of the air conditioner or heat pump, the size of the system can be reduced and the efficiency of the system can be improved. This study, thus, is conducted to see the effect of the outdoor coil fan speed on the performance variation of the heat pump system, which adopts the hot gas bypass method for defrost. It also focuses on the performance improvement of the heat pump system with the hot gas bypassing after detecting the frost by photo coupler sensor over the heat pump system using conventional time step method for defrost. The results were compared and discussed in terms of the average COP and the integrated heating capacity for the total heating time.

2. Experiment

2.1 Experimental setup

Fig. 1 provides the schematic representation of the heat pump system used in the experiment. Table 1 shows details about the instruments used in the experiment. The indoor and outdoor coils are slit fin-round tube type heat exchanger. Dimensions of the outdoor coil are 40 mm in depth, 610 mm in height,

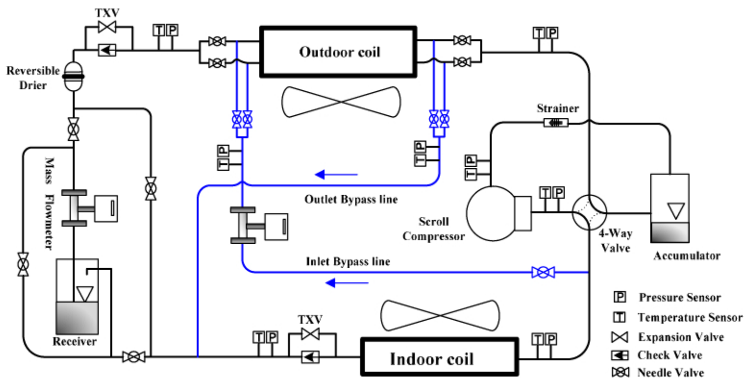


Fig. 1. Schematic of the test heat pump.

813.5 mm in width, and those of the indoor coil are 61 mm in depth, 561 mm in height, 465 mm in width. A heat exchanger consists of two rows. The needle valves to open and close the refrigerant line are placed at the entrance of the outdoor coil on each distributor. The higher the FPC(fin per centimeter), the faster the frost will form [15, 16]. The outdoor coil has 6.7 FPC and the indoor coil has 7 FPC. The compressor (LG Electronics Inc.) used is a scroll-type compressor with R-22 refrigerant. The capacity of the compressor is 1.5 kW (2 HP), and the rated capacity of receiver, accumulator and expansion device used is also 1.5 kW class. The expansion device used in the test is the thermostatic expansion valve (Danfoss Inc.), which controls the flow of refrigerant into evaporator in exact proportion to the rate of evaporation of the liquid refrigerant in the evaporator. The filter-drier and strainer help filter out impurities and moisture from the refrigerant. The experiment is carried out by installing an air source heat pump in a psychrometric test room, which provides a controlled environment for testing the heat pump system. In accordance with ASHRAE standard 37 [17], it consists of dual chambers (indoor and outdoor) and uses the air enthalpy method to determine the unit capacities and provide heat balances. The code testers, which include nozzles, provide the accurate determination of the test unit air flows and outlet air conditions. A bypass line is connected from a 4-way valve to an inlet side of the outdoor coil and from an outlet side of the outdoor coil to that of the indoor coil. When the refrigerant in low temperature enters into the compressor, the performance of the reciprocating compressor decreases abruptly, but the performance of the scroll compressor stays the same for a certain period [18]. The bypass line is installed with needle valves and a mass flow meter to control the hot gas flow rate. To check the system change due to the bypassing hot gas, T-type thermocouples and pressure transducer are installed at the inlet and outlet of the outdoor coil, along the indoor coil and compressor, respectively. The thermocouple probes are connected to the refrigerant lines with compression fittings and tees so that their measuring junction is directly immersed in the refrigerant stream. The pressure transducers are directly connected to the refrigerant line with compression fittings and tees. To measure the static pressure, the pressure transducers were installed 7.5cm away from the refrigerant stream. An inverter is equipped at the fan motor in order to control the fan speed of the outdoor coil. The fan speed is measured by the tachometer. The pressure transducer's accuracy is ±0.25% and the temperature sensors have an accuracy of ±0.1 °C after being calibrated by the standard thermometer. The mass flow rate of the refrigerant is measured with a mass-flow meter (OVAL Inc.), which is installed at the outlet of the receiver; its accuracy is ±0.1%. The mass flow meter installed at the bypass line has the maximum measurement range of 1kg/min and an accuracy of ±0.1%.

2.2 Experimental method and conditions

The experiment was carried out at the environmental chamber with psychrometric test facility. In the psychrometric calorimeter, the uncertainty in the heating capacity measurement is less than ±2%, and the uncertainty in COP is less than ±1.5%. At this psychrometric calorimeter, the airflow rate measurement is made according to ANSI/ASHRAE Standard 16-

1993(RA99) [19], the accuracy of air flow rate is ±1% , and uncertainty of power meter is ±0.1% of range. Before testing began, the heat pump system was leak-tested with a dry nitrogen charge at 3.1 MPa (450 psi). Vacuum was then created in the system to eliminate the presence of any non-condensable gas. It was charged under the cooling mode with R-22 at varying rate while measuring the Coefficient of Performance (COP) at each rate. The refrigerant rate that showed the highest COP is assumed to be the most suitable one. The refrigerant flow rate for the heat pump in this test is 1.0 kg/min. The condition of air entering into the outdoor chamber of the air-enthalpy calorimeter is set at the dry-bulb temperature of 2℃ and wet bulb temperature of 1℃; and the condition of air entering into the indoor chamber is set at the dry-bulb temperature of 20℃ and the wet bulb temperature of 12℃, according to the automatic defrost test conditions of ISO 5151 [20]. Dry and wet bulb temperatures of air entering the outdoor and indoor chamber in the environment chamber are maintained at an accuracy of ± 0.2℃ and ± 0.3℃, respectively. Three types of heat pump operation methods were adopted in this study. The first one was a general heating mode in which no defrosting was used. The second one was a time step defrosting method, the most widely used defrosting method, which is a reversed operation of the heat pump at regular intervals. It defrosts the outdoor coil automatically after a predetermined amount of running time. In that method, the cooling cycle (reverse cycle) starts and operates for 10 minutes after 60 minutes of heating cycle operation [18]. In this case, the fan of the outdoor coil stops operating. The third one is the hot gas bypass method. In this method, the hot refrigerant gas from the compressor discharge is extracted and injected directly into the inlet of outdoor coil for 4 minutes when the photo sensors attached at the outdoor coil detect the formation of frost. The method for the frost perception and the operation of the defrost cycle using a photo sensor is the same as presented by Byun et al. [6]. The operation mode for defrosting is automatically set by the photo coupler sensor. The hot gas bypass rate is controlled manually with a needle valve. The bypassing refrigerant flow rate was 0.2 kg/min as is 20% of the total refrigerant mass flow rate, which is obtained from preliminary experiment as optimal for the best COP of the system [13]. Also, based on some preliminary adjustment test for the varying injection rate for the stable operation, the hot gas is injected into the outdoor coil for 4 minutes: first 2 minutes for the front row of the outdoor coil and the next two minutes for the rear row. By stable operation is meant that the system soon comes back to normal operation when the hot gas injection stops as the defrost is completed. Otherwise, the system's temperature and pressure continue to be fluctuating for a long time even when the system returns to normal operation with no hot gas injection. The maximum fan speed of the outdoor coil is about 1300 rpm. When the hot gas is bypassed, the fan speed of the outdoor coil is adjusted to 0% (stationary), 30% (390 rpm), 60% (780 rpm), and 90% (1170 rpm) compared with the maximum fan speed using an inverter attached at the fan motor. According to ISO5151, the experiment is conducted after one hour of warming-up running. Tests were conducted for 200 minutes for each case. Data from the respective sensors were recorded via the data acquisition equipment at two-second intervals and stored in the computer for later analysis.

The COP represents performance of the heat pump system, and the COP of the vapor compression heat pump is calculated as follows.

$$COP = \frac{Q_a[output, kW]}{W[input, kW]} \tag{1}$$

where Q_a is the air side heating capacity measured from psychrometric calorimeter, W is the electrical power consumption for running the heat pump, indicating the total power consumed to operate the heat pump system's compressor and fans of the heat exchanger.

The transient total heating capacity is averaged with respect to time for the entire test period. As the indoor coil fan of the heat pump stops during the reverse cycle defrosting mode due to the cold draft, the heating capacity and COP during the interval are considered to be zero, but the elapsed time is included in the total test period for obtaining the average heating capacity.

3. Results and discussion

3.1 COP and heating capacity of heat pump among defrosting methods

Figs. 2 and 3 present the variation of COP and heating capacity of the heat pump with time according to three operation methods: heating mode, time

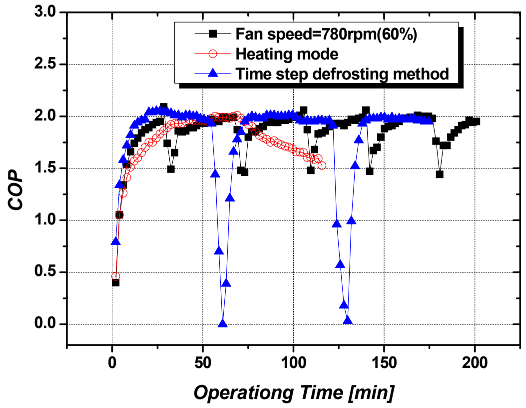


Fig. 2. COP variation with the operating time according to the operation method.

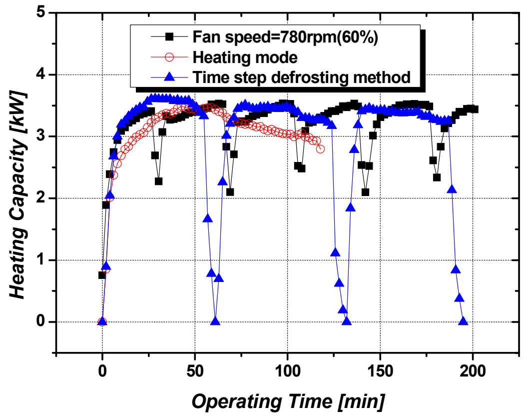
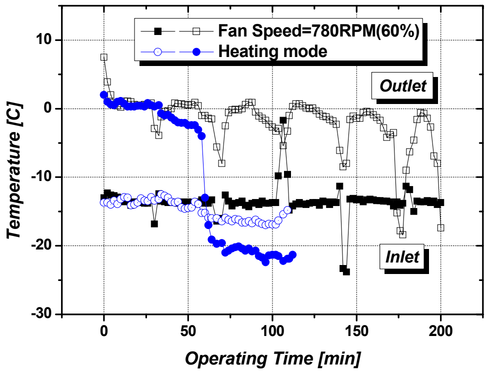


Fig. 3. Heating capacity variation with time according to the operation method.

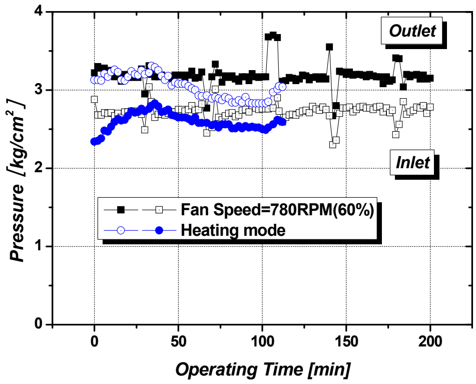
step defrosting method and hot gas bypass method for 60% fan speed(780 rpm). The highest values of the COP and heating capacity are almost the same, but their variation with time differs among the three methods as expected. In the case of the heating mode which does not use any defrosting method, the frost covers about 70 % of the surface area of the outdoor coil after 40 minutes of operation. After 68 minutes, the COP and heating capacity of the heat pump rapidly decreases because the frost covers up to 90% of the surface area. At 120 minutes, the heat pump stops operating. With the time step defrosting method, after 60 minutes of the heating cycle operation, the cooling cycle (reverse cycle) starts and operates for 10 minutes. The reverse cycle removes the frost of the outdoor coil and the performance of the heat pump goes back to the normal state. During this period, the fan of the outdoor coil stops operating and the COP and the heating capacity of the heat pump drops to 0. For the hot gas bypass method, during the hot gas injection period, the COP and the heating capacity decrease by about 25% from their peak value, i.e., COP of the heat pump goes down as low as 1.5, which is due to the reduction in the mass flow rate of the refrigerant entering into the indoor coil. One thing to be noted in Fig. 2 is that the data of all curves at the time period of approximately 25 minutes does not lie on a single curve as it is supposed to before any defrost take places on the outdoor coil. This is due to the following. Generally, the performance test of a heating and cooling system using a calorimeter is conducted after warming the system up until it reaches its normal operating conditions. For example, according to ISO 5151, the test for heat-pump heating system is conducted after one hour of warm-up running. Present experiment is conducted following this and the data in Fig. 2 and Fig. 3 are measured and obtained after 1hour operation, which is after the first frosting and defrosting operation of the system. Then, due to the effect of insufficient defrosting from the previous(first) frosting-defrosting operation, which yields different types of congelation of unremoved frost according to the defrost method, the performance curves of each defrost do not correspond to each other. Besides this, the overall repeatability of this experiment is good.

3.2 Temperature and pressure variations of the heat pump system

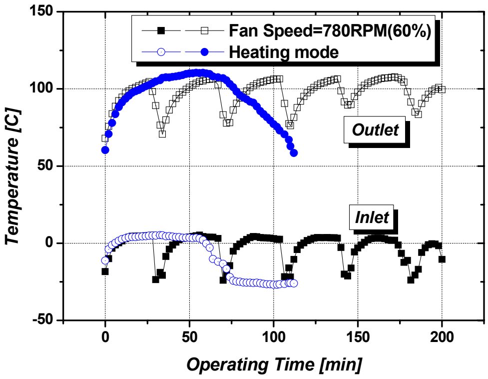
Figs. 4 and 5 show the temperature and pressure variations at the outdoor coil and compressor, respectively, for the two cases: for the hot gas bypass method at maximum performance(60% of the fan speed) and for the heat pump operating in a normal heating mode. From Fig. 4(a), in the case of heating mode, close to 68 minute of operation, the temperature at the outlet of the outdoor coil begins to drops rapidly while the temperature at the inlet of the coil decreases. This rapid drop is due to almost 90% covering of frost over the outdoor coil surface area at the time mentioned above. In the case of hot gas bypass method, though the temperature fluctuates during the period of hot gas bypassing, the temperature at the outdoor coil drops sharply after about 170 minutes from starting operation while at inlet it stays almost the same. This clearly shows the retardation effect of this method on frost forming on the outdoor coil over



(a) Outdoor coil temperature

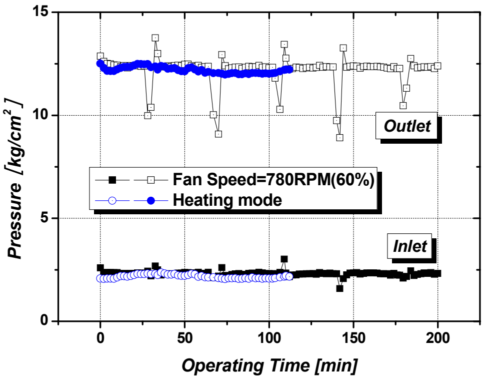


(a) Outdoor coil pressure



(b) Compressor temperature

Fig. 4. Temperature variation at outdoor coil and compress for the heating mode and hot gas bypass method.



(b) Compressor pressure

Fig. 5. Pressure variation at outdoor coil and compress for the heating mode and hot gas bypass method.

the heating mode. Fig. 4(b) shows, in the heating mode, with the initial temperature increase in earlier heating period at compressor outlet, the similar trend of temperature drop at compressor inlet and outlet as the drop of outdoor coil temperature, while the temperature shows less and rather regular fluctuating pattern in the hot gas bypassing case. Less fluctuating pattern of temperature is due to the fact that as the refrigerant enters the accumulator before it enters the compressor, the fluctuation is reduced there. The coil outlet temperature at minute 170 and 200 drops drastically compared to the defrost cycles. This is due to the accumulation of ice during the previous cycle as repetition of the frosting-defrosting cycles would lead to the build-up of the condensate (molten frost), which has not been removed completely from the surface of the fin of the outdoor coil. Fig. 5(a) shows the pressure variations at outdoor coil corresponding to the temperature variations of Fig. 4(a).The decrease of pressure with temperature is clearly seen in the case of heating mode, while pressure remains almost the same except during the hot gas bypassing period in the case of hot gas bypass method. Fig. 5(b) shows pressure variations of each case at the compressor according to the temperature variation of Fig. 4(b). Similar trend as in Fig. 5(a) is seen in both cases, but the variations are much reduced due to the accumulator effect as mentioned above where the variations in pressure and temperature are reduced there.

3.3 Fan speed effect on COP and heating capacity of heat pump

Figs. 6 and 7 show the variation of COP and heating capacity of the heat pump based on the fan speed of the outdoor coil with 200 minutes operating time for the hot gas bypass method. The fan speed is controlled in four steps by the inverter: 90% (1170 rpm), 60% (780 rpm), and 30% (390 rpm) of the normal

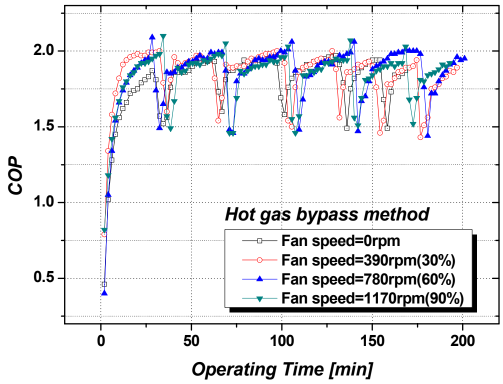


Fig. 6. COP variation with the operating time according to the fan speed of outdoor coil.

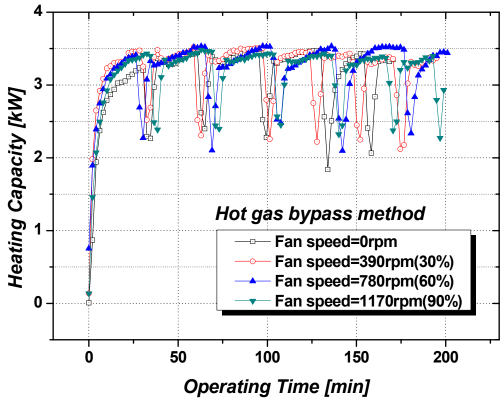


Fig. 7. Heating capacity variation with the operating time according to the fan speed of outdoor coil.

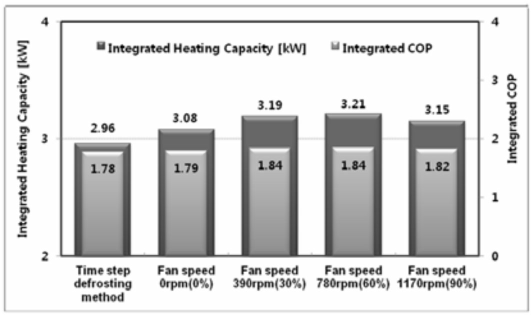


Fig. 8. Integrated heating capacity and integrated COP of heat pump according to the fan speed of the outdoor coil.

speed and the stationary case (0%). It is seen that an increase in the operation period of the heat pump decreases the bypass injection interval. For 90% (1170 rpm) of normal fan speed, the first bypass injection interval of hot gas is about 38 minutes, but after the operation of the heat pump for 170 minutes, the bypass injection interval of the hot gas is 26 minutes. When the hot gas was injected into the inlet side of the outdoor coil, the frost of the outdoor coil was not fully removed. Only a part of the frost was removed. Also, even when the frost was removed, a congelation remained on the fin surface. This makes the next frost formation faster than the previous one. When the fan speed is 0 and 30% (390 rpm) of the normal speed, the COP and heating capacity of the heat pump do not return to the initial peak values after the 4 minutes hot gas bypassing, i.e., the peak value decreases by about 3% of the initial peak values after the operation of the heat pump for 150 minutes. Thus, the longer the operation period of the heat pump, the lower the COP and heating capacity are. But, when the fan speed is 60% (780 rpm) and 90% (1170 rpm) of the normal speed, COP and heating capacity of the heat pump return to the initial peak values after the 4 minutes hot gas bypassing. The COP and heating capacity of the heat pump are highest at 60% (780 rpm) of the fan speed, though the differences are not much among the different cases considered.

Fig. 8 represents the integrated heating capacity and integrated COP for hot gas bypass method during 200 minutes of the operation for each test case together with the time step defrosting method. The case of heating mode is excluded in comparison as it stops operating 120 minutes after starting operation due to almost full frost covering of the outdoor coil surface, as mentioned above. The integrated heating capacity using the hot gas bypass method shows much greater value compared to the conventional time step defrosting method at any fan speed, while the integrated COP shows a little difference between two methods. For 90% (1170 rpm) of the fan speed, the integrated heating capacity is 6.5% higher than that of the time step defrosting method, while the integrated COP shows 2.3% increase. The higher increase in integrated heating capacity occurs because when the time step defrosting method is used, the heating capacity of the heat pump falls to 0 during the reverse cycle operation, while with the hot gas bypass method, the decrease in heating capacity is much less as can be seen from Figs. 6 and 7. The integrated heating capacity is highest at 60% (780 rpm) of the fan speed, and the value is 8.6% higher than that of the time defrosting method and 4.4% higher than that of the stationary fan.

4. Conclusion

This study reports the results of an experiment to see the effect of outdoor coil fan speed on the performance variation of the heat pump system adopting the hot gas bypass method and on the performance improvement with hot gas bypassing for defrost after detecting the frost by photo coupler sensor over the conventional heat pump system using the time step method to defrost. Results were compared with the conventional on-off time step defrosting method as well as the heating mode with no defrosting in terms of the integrated heating capacity and the average COP for the total heating time.

With the time step defrosting method, the cooling cycle (reverse cycle) starts and operates for 10 minutes after regular 60 minutes of the heating cycle operation. In the hot gas bypass method, the hot refrigerant gas is extracted from the compressor discharge and injected directly into the inlet of the outdoor coil for 4 minutes when the photo coupler sensors detect the frost. The normal fan speed of the outdoor coil in this case was 1300 rpm, and the fan speed of the outdoor coil was adjusted to 0%, 30% (390 rpm), 60% (780 rpm), and 90% (1170 rpm) of the normal fan speed using an inverter attached at the fan motor. Tests were conducted for total heating time of 200 minutes for each case.

In the case of hot gas bypass method, it is observed that the longer the operation period, the shorter the bypass injection interval. This is due to the frost forming and defrosting process on the outdoor coil surface. When the fan speed is 0 and 30% (390 rpm) of the normal speed, the COP and the heating capacity of the heat pump do not return to their initial peak values after 4 minutes hot gas injection, while in the other cases(60 and 90%) return to the initial value. In the former cases, the peak value decreases by about 3% of the initial value at 150 minutes after starting operation. Thus, the longer the operation period of the heat pump at these cases is to lower the COP and the heating capacity. The integrated heating capacity using the hot gas bypass method shows much greater value compared to the conventional time step defrosting method at any fan speed, while the integrated COP shows a little difference between the two methods. . The integrated heating capacity is highest at 60% (780 rpm) of the fan speed; the value is 8.6% higher than that of the time defrosting method and 4.4% higher than that of the stationary fan in the hot gas bypass case. The averaged COP of the heat pump in this case is higher by 3.8% than the time step defrosting method and 2.8% than that of the stationary fan.

For 90% (1170 rpm) of the fan speed, the integrated heating capacity is 6.5% higher than that of the time step defrosting method, while the integrated COP shows 2.3% increase.

Acknowledgments

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Nomenclature

C : Correction factor for nozzle
c_p : Specific heat capacity, J/kg · K
h : Enthalpy, kcal/kg
K : Coefficient of the heat loss
m : Mass flow rate, kg/s
p : Pressure, Pa
Q : Heat transfer rate, kW
q : Flow rate, m^3/s
S : Dimension of nozzle throat
t : Temperature, K
x : Specific humidity, g/g
v : Specific volume, m^3/kg
W : Consumption power, kW

Subscripts

1 : Inlet
2 : Outlet
r : Refrigerant
a : Air

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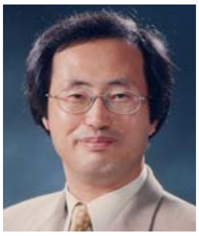

Jinho Lee received his B.S. (1974) and M.S. (1976) degrees at Yonsei University and his Ph. D degree (1982) at Case Western Reserve University. He has been a professor of the school of mechanical engineering, Yonsei University since 1983. He served as vice president of the KSME (2005-2007). He was a senior research fellow of NASA Glenn Research Center and visiting professor of California Inst. of Tech., Univ. of Connecticut, and Keio University.

Ju Suk Byun received his B.S. (1999) degree at KyungHee University and his Ph. D degree (2006) at Dept. of Mechanical Engineering, Yonsei University. He is currently working at the Technology Appraisal Center, Korea Technology Finance Corporation since 2007. His biography will be included in the forthcoming 2010 edition of Marquis Who's Who in the World.