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School of Mechanical Engineering

2014

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ABSTRACT

A heat pump system requires proper refrigerant charge amount. Once refrigerant is charged into a heat pump system, its charge amount is fixed. For this reason, prediction of optimal refrigerant charge amount is very important in order to yield best performance. Too low charge amount degrades capacity of heat pump. On the other hand, excessive charge amount decreases coefficient of performance (COP). The optimal value of refrigerant charge amount highly depends on secondary fluid temperature conditions. Consequently, fixed charge amount of refrigerant in heat pump shows the best performance only at certain temperature condition. Several ideas have revealed to change charge amount of the heat pump system. One is to have an additional reservoir to store or release refrigerant which is attached to a heat pump system. This method may seem simple but to measure exact amount of refrigerant in reservoir, additional pressure transducer, temperature measurement device, level sensor and other apparatus are required that increase the cost of heat pump. Another idea is to have reservoir between condenser outlet and expansion device.

In this study, a new method for refrigerant charge amount control technique is presented. It has very simple control logic and requires only a few additional cost factors; several valves and additional tubes are only required. This method is based on different refrigerant phase distribution at each point of inlet and outlet of components in heat pump system. In a single cycle heat pump system, refrigerant at condenser outlet (before expansion device) is in a subcooled liquid state at high pressure, while refrigerant is in a superheated vapor state at evaporator outlet (before compressor inlet) at low pressure. This technique regulates refrigerant charge by holding some volume of refrigerant in the connecting tube of considerable volume installed between the condenser outlet and the evaporator outlet. Using several solenoid valves (on/off) desired amount of refrigerant can be stored into a volume provided by a connecting tube. This connected volume is referred as 'stagnation volume'. When one of this installed valve is closed and the rest of the valves are open, certain amount of refrigerant is stored in the stagnation volume while operating heat pump system. If closed valve is adjacent to condenser outlet, charge amount to the heat pump system increases while the charge is reduced when the valve adjacent to evaporator outlet is closed. This method is numerically verified in this study and the maximum COP matches with optimal charge amount. Therefore, heat pump can be operated at optimized circulating amount of refrigerant in spite of the secondary fluid temperature variation during heating or cooling operation.

1. INTRODUCTION

A heat pump system requires proper refrigerant charge amount. Once refrigerant is charged into a heat pump system, its charge amount is fixed. For this reason, prediction of optimal refrigerant charge amount is very important in order to yield the best performance. Too low charge amount degrades capacity of heat pump. On the other hand, excessive charge amount decreases coefficient of performance (COP). Cho *et al*. (2005) studied the performance change for different charge amount of heat pump systems with various refrigerants and showed the existence maximum COP. Kim *et al*. (2007) also showed COP variation (with maximum value) with respect to the charge amount of CO_2 and CO_2/propane mixtures in an air-conditioning system. Corbera´n *et al*. (2008) performed charge optimization study with an experiment of a water-to-water heat pump system. In the COP point of view, optimal charge amount is shown in both cooling and heating conditions. On the other hand, in the capacity point of view, cooling capacity has maximum value but heating capacity increases as charge amount increases and this is mainly due to the increase in condensing pressure. Heo *et al*. (2008) showed that optimal charge amount also exists at the system with vapor injection cycle.

Even though existence of optimal charge amount in the system it only applies to a certain condition. The optimal value of refrigerant charge amount varies with different conditions and this highly depends on secondary fluid temperature. O'Neal and Farzad (1991) performed an experimental study on the performance of air conditioner with different refrigerant charge amount and showed the optimal charge amount differs with outdoor air temperature. Corbera´n *et al*. (2011) studied the COP change of water-to-water heat pump system with different water temperature entering the evaporator. The optimal charge amount decreases with decreasing evaporator entering water temperature. Kim *et al*. (2014) performed an experiment on single and cascade cycle and showed the effect of the refrigerant charge amount in air-to-water heat pump systems. With different temperature condition, the optimal point of charge amount for each cycle changes. Consequently, fixed charge amount of refrigerant in heat pump shows the best performance only at certain temperature condition. At the point of seasonal coefficient of performance (SCOP), which represents the efficiency of heat pump system throughout the year round, it will show better performance if we can control charge amount in heat pump.

Several ideas have revealed to control charge amount in the heat pump system. One is to have an additional reservoir to store or release refrigerant which is attached to a heat pump system. This method may seem simple but to measure exact amount of refrigerant in reservoir, additional pressure transducer, temperature measurement device, level sensor and other apparatus are required that increase the cost of heat pump. Another idea is to have reservoir between condenser outlet and expansion device which is usually called liquid receiver. Rajapaksha and Suen (2004) showed that existence of reservoir at this point helps improve capacity while reducing the system COP. Accumulator, which is installed before compressor in order to prevent wet compression, can also be count as refrigerant control device but little impact on performance is shown according to Kim and Braun. (2010)

In this study, a new method for refrigerant charge amount control technique is presented. It has very simple control logic and requires only a few additional cost factors; several valves and additional tubes are only required.

2. CHARGE AMOUNT CONTROL METHOD

This method is based on different refrigerant phase distribution at the point of inlet and outlet of each component in heat pump system. Figure 1 and 2 shows the newly suggested charge amount control method. In a single cycle heat pump system, refrigerant at condenser outlet (before expansion device) is at a subcooled liquid state at high pressure, while refrigerant is at a superheated vapor state at evaporator outlet (before compressor inlet) at low pressure. This technique regulates refrigerant charge by holding some volume of refrigerant in the connecting tube of considerable volume installed between the condenser outlet and the evaporator outlet. This connected volume can be referred as 'stagnation volume' in Figure 1 where the refrigerant stagnates and does not circulate through the system. Using several solenoid valves (on/off) desired amount of refrigerant can be stored into a volume provided by a connecting tube in Figure 2. When one of these installed valves is closed and the rest of the valves are open, certain amount of refrigerant is stored in the stagnation volume while operating heat pump system. For example in Figure 2, there are two valves through the stagnation volume. If closed valve is adjacent to condenser outlet (valve 1), charge amount to the heat pump system increases while the charge is reduced when the valve adjacent to evaporator outlet (valve 2) is closed. In this case, two valves provide two different state of charge amount. Therefore, 'N' valves can make 'N' different states. Ideally, if continuous change is possible, charge amount can be freely regulated by heat pump designers.

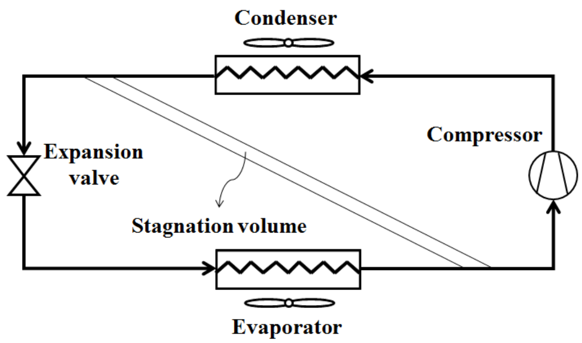


Figure 1: Stagnation Volume

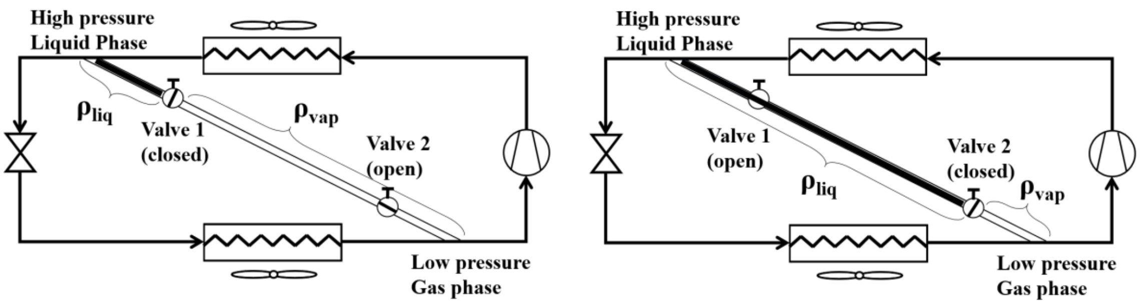


Figure 2: Charge amount control method

3. NUMERICAL METHOD AND CONDITIONS

In order to verify this refrigerant charge control method, the calculation of performance on single heat pump system with different refrigerant charge amount is required for comparison. The refrigerant charge control method can be numerically verified by eliminating refrigerant mass inside the stagnation volume from the total mass of charged refrigerant. Detail specifications of each part are shown in Table 1 and simulation conditions are shown in Table 2. Throughout the calculation, the temperature difference between water inlet and outlet were kept 5°C Flow chart is also shown in Figure 3. In order to match DSH and charge amount, evaporating and condensing pressure is adjusted respectively. Through this numerical procedure, the performance of heat pump system was calculated as COP which is represented as following equation.

$$\mathrm{COP} = \frac{Q}{W}$$

Table 1: Simulation method and correlations

Component	Specifications
Compressor	Isentropic efficiency = 0.6 Volumetric efficiency = 0.08
Condenser	Finite volume method R410A condensing HTC in plate heat exchanger Longo (2009)
Expansion valve	Isenthalpic assumption
Evaporator	Finite volume method R410A evaporating HTC in plate heat exchanger Longo (2007)
Charge amount	Zivi correlation (1964)

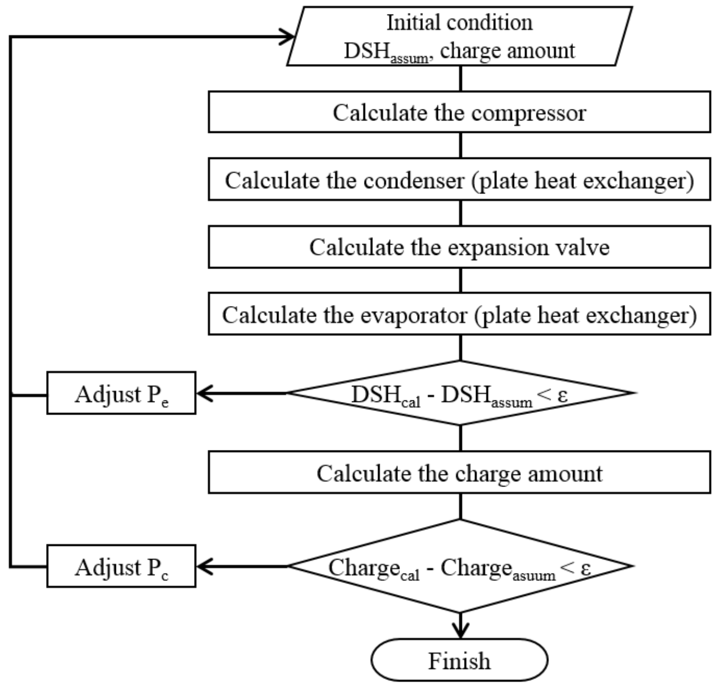


Figure 3: Flow chart of refrigeration cycle simulation

4. RESULTS AND DISCUSSIONS

4.1 Characteristics of the system with different charge amount

The system performance depends on its charge amount. Figure 4 shows P-h diagram with respect to charge amount change. As the charge amount increases, condensing pressure increases. However, evaporating pressure hardly changes. In Figure 4, charge amount of 1.1 kg is too low that only partial condensation is possible instead of full condensation of refrigerant at condenser. Therefore, proper amount of refrigerant is required in order to prevent two-phase expansion which negatively influences expansion process. As the charge amount increase to 1.3 kg, condenser outlet is fully saturated. In addition, refrigerant is in subcooled state at the condenser outlet if charge amount becomes 1.5 kg. As the charge amount increases the DSC becomes larger. However, the optimal charge amount does not exist at the saturated liquid condition of condenser outlet. At the optimal charge amount condition DSC was about 6.7 ~ 8.8^{o}C.

Table 2: Simulation conditions

Parameters	Value				
Refrigerant	R410A				
Charge Amount (kg)	1.10 ~ 1.60 (Δ=0.05)				
The number of valves (charge control)	11 (with 1.65 kg charge)				
$T_{e,w,i}$ (^{o}C) / $T_{c,w,i}$ (^{o}C)	12 / 30	12 / 40	20 / 40	20 / 50	30 / 50
$\Delta T_{e,w}$, $\Delta T_{c,w}$	5				
Degree of superheat (^{o}C)	10				

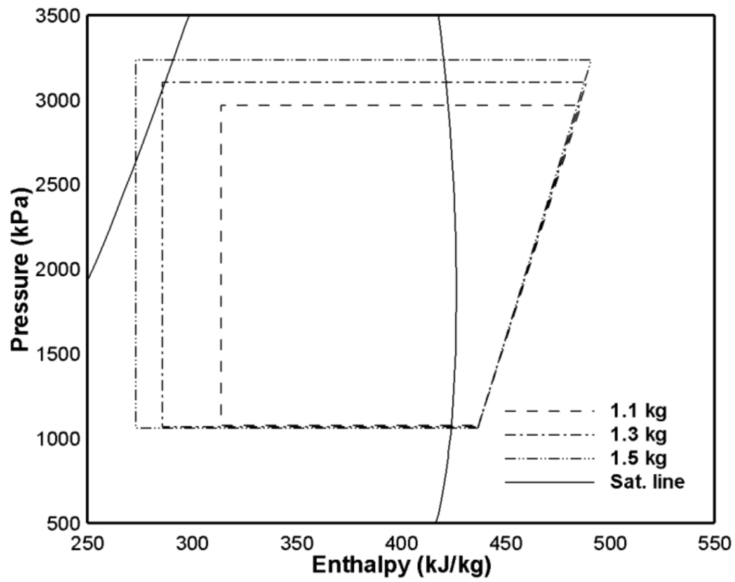
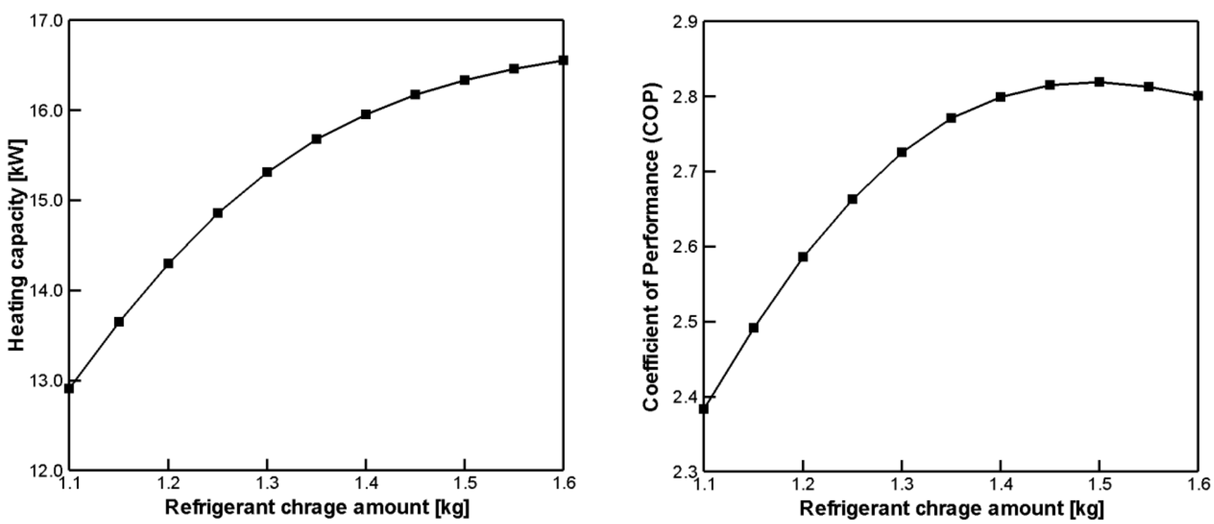


Figure 4: P-h diagram with different charge amount ($T_{e,w,i}$=20^{o}C, $T_{c,w,i}$=40^{o}C)

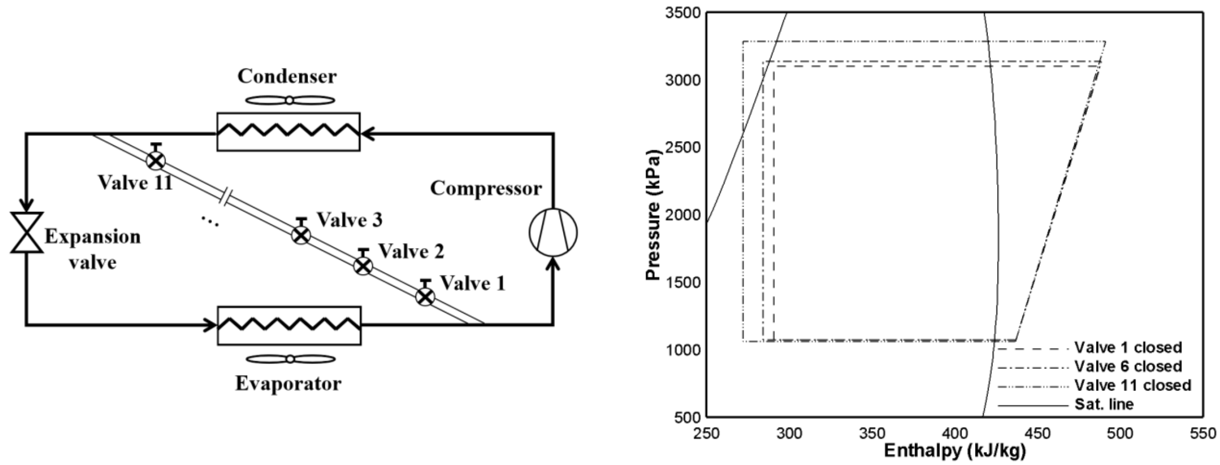
When evaporator and condenser water inlet temperature are 20^{o}C and 40^{o}C respectively, the optimal charge amount is 1.45 kg. Other cases, for 12^{o}C/30^{o}C, 12^{o}C /40^{o}C, 20^{o}C /50^{o}C and 30^{o}C/50^{o}C, the optimal charge amount is 1.35 kg, 1.40 kg, 1.50 kg and 1.60 kg respectively. Clearly, optimal charge amount depends on secondary fluid temperature condition. As evaporator water inlet temperature increases the optimal charge amount also increases. The elevation of condenser water inlet temperature also raises the optimal charge amount. The same phenomenon showed in the experiment of Corbera´n *et al*. (2011)

Figure 5 represents the heating capacity and COP variation with different charge amount when evaporator and condenser water inlet temperature was 20^{o}C and 50^{o}C respectively. Heating capacity elevates as charge amount increases and COP have maximum value at 1.50 kg. The maximum COP value is 2.82 and heating capacity at this point is 16.3 kW.



(a) (b)

Figure 5: (a) Heating capacity and (b) COP with different charge amount ($T_{e,w,i}$=20^{o}C, $T_{c,w,i}$=50^{o}C)



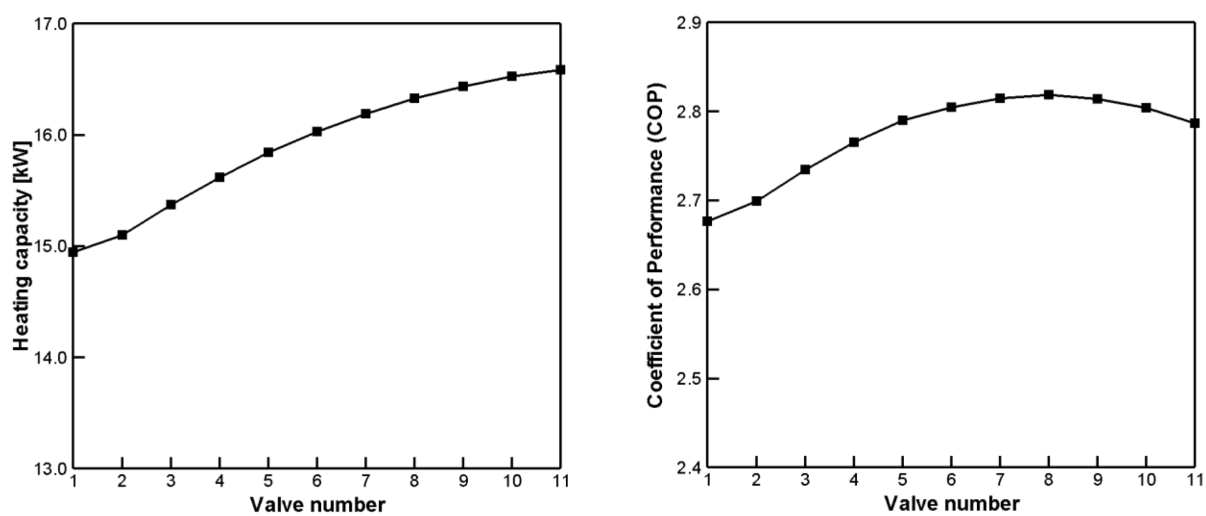
(a) (b)

Figure 6: Refrigerant charge control system with multi-valves (a) schematic and (b) P-h diagram ($T_{e,w,i}$=20^{o}C, $T_{c,w,i}$=40^{o}C)

4.2 Characteristics of refrigerant charge control system

Figure 6 shows both (a) schematics of refrigerant charge control method and (b) P-h diagram of its result of three cases when valve 1, valve 6, valve 11 is closed respectively. Evaporator water inlet temperature is 20^{o}C and condenser water inlet temperature is 40^{o}C. If valve 1 is closed and the rest of the valves are opened, the condenser side of stagnation volume would be filled with liquid refrigerant. At the same time, the evaporator side of the stagnation volume will be at the vapor state. In this case, the amount of refrigerant in stagnation volume maximizes which yield the least amount of refrigerant through the cycle. On the contrary, when valve 11 is closed, the mass in stagnation volume minimizes that the system have the largest amount of refrigerant. As the closed valve changes, the refrigerant amount in heat pump system changes. At the optimal charge amount condition DSC was around 6.2 ~ 8.4^{o}C.

Figure 7 shows the heating capacity and COP when applying the refrigerant charge control method at evaporator and condenser water inlet temperature 20^{o}C and 50^{o}C respectively. As the closed valve is changed, the heating capacity and COP varies. The maximum COP value occurs when valve 8 is closed and it value is 2.82. Heating capacity at this point is 16.3 kW.



(a) (b)

Figure 7: (a) Heating capacity and (b) COP with refrigerant charge control method ($T_{e,w,i}$=20^{o}C, $T_{c,w,i}$=50^{o}C)

Table 3: Maximum COP and heating capacity comparison between optimal charge condition and refrigerant charge control method

Temperature condition : $T_{e,w,i}$ (^oC)/ $T_{c,w,i}$ (^oC)		12/30	12/40	20/40	20/50	30/50
Optimal charge (kg)	Optimal charge condition	1.35	1.40	1.45	1.50	1.60
Closed valve at optimal condition	Charge control method	5	6	7	8	10
Maximum COP	Optimal charge condition	3.81	2.98	3.53	2.82	3.44
	Charge control method	3.83	2.98	3.54	2.82	3.45
Heating capacity (kW)	Optimal charge condition	14.6	13.9	17.2	16.3	21.0
	Charge control method	14.7	13.9	17.2	16.3	20.9

4.3 Comparison

Comparing Figure 6 with Figure 4, the case of closed valve 1 shows same performance characteristic with the case of 1.1 kg charge amount that the state of condenser outlet is in two-phase region. Similarly, the case of closed valve 6, and 1.3 kg charge amount shows the saturation condition at condenser outlet. When the valve 11 is closed and charge amount becomes 1.5 kg, the condenser outlet becomes subcooled state. It is proved that the refrigerant charge control method makes possible to regulate charge amount DSC.

Table 3 shows the comparison between fixed charge amount at the optimal condition and refrigerant charge control method. The value of COP and heating capacity of each method are compared. In case of evaporator water inlet temperature 20^{o}C and condenser water inlet temperature 50^{o}C, the maximum COP is 2.82 at 1.35 kg which is optimal charge amount and the same value was calculated when valve 5 is closed in charge control method. The heating capacity of two point have the same value of 16.3 kW. Overall temperature conditions, the maximum COP of refrigerant charge control method matches with that of optimal charge amount. At this point, heating capacities are also the same. This means there is no performance degradation when applying refrigerant charge control controlled method. Although, the performance of optimal point for each temperature condition does not change when applying this method, the seasonal performance of the system increases compare to fixed refrigerant charge amount operation of heat pump system.

5. CONCLUSIONS

In this study, the necessity of charge amount regulation is emphasized and charge amount control method is newly suggested. The major advantage of controlling refrigerant amount in heat pump is seasonal COP increase. The new method utilizes the phase and density difference throughout heat pump cycle. Firstly create certain amount of volume with tubes between condenser outlet and evaporator outlet. By installing several on/off valves and closing one of them, phase separation inside the stagnation volume occurs. With different closing valve, charge amount of the system can be controlled. It is numerically verified that there is no reduction of maximum COP value at different temperature conditions. In conclusion, with refrigerant charge control method it is possible to operate heat pump system with optimal charge amount year-round and seasonal COP value increases compare to fixed refrigerant charge amount operation of heat pump system.

NOMENCLATURE

COP	coefficient of performance	(-)
DSC	degree of subcool	(^{o}C)
DSH	degree of superheat	(^{o}C)
P	pressure	(kPa)
Q	heating capacity	(kW)
T	temperature	(^{o}C)
W	compressor work	(kW)
ρ	density	(kg/m^3)

Subscript

assum	assumption
c	condenser
cal	calculated
e	evaporator
i	inlet
liq	liquid
o	outlet
vap	vapor
w	water

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ACKNOWLEDGEMENTS

This work was supported by the Institute of Advanced Machinery and Design (IAMD) of Seoul National University. Additional support by the BK21 plus program and World Class University (WCU) program through the Korea Research Foundation (R31-2008-000-10083-0) is greatly appreciated. This research was also supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2013R1A2A1A01014589). This study was also supported by Korea Ministry of Environment as "Knowledge-based environmental service (Waste to Energy) Human Resource Development Project".