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## Effects of Flash and Vapor Injection on the Air-to-Air Heat Pump System

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### ABSTRACT

A heat pump has received much attention as substitute for the conventional boiler or heating coil because of its high efficiency. For the wide application of the heat pump, the most important design factor is the performance degradation upon its installation in tropical and cold regions. In this study, the effects of phase separator type injection and internal heat exchanger type injection on the heating performance of a two-stage heat pump with an inverter-driven twin rotary compressor were measured and analyzed for compressor frequency ranging from 50 to 95 Hz at ambient temperatures of -20, -15, -10, -5 and 7°C. The COP and heating capacity of the phase separator type injection cycle were enhanced by 17% and 25% than non injection cycle respectively, at the ambient temperature of -15°C. The internal heat exchanger type injection cycle has shown more improvement than phase separator type injection cycle. The COP and heating capacity of the internal heat exchanger type injection cycle were enhanced by 10% and 25% than non injection cycle, respectively at the same condition.

### 1. INTRODUCTION

Demands about the efficient energy consumption are on the increase continuously by reason of the exhaustion of fossil fuel and global warming. To meet these demands, each government is working hard on strengthening by CO<sub>2</sub> emission controls and the standard about certification of products and each company spur the development of new technology to the high efficiency. Also, the same demand is increasing for the high efficiency in heating and cooling system by a growing customer's recognition about the energy saving. The changing from existing system using fossil fuel to a heat pump for the heating and cooling is the result of these efforts. The heat pump has a disadvantage which is that the structure is complicated and the performance of product and the change of building load have an opposing trend. But the demand of it is increasing continuously because it has the high efficiency comparing with the existing heating system and can heat and cool by the same product. Also, the utility of heat pump is standing out by a technology development like inverter to respond effectively to the building load. Comparing with two methods for realization of two stage injection cycle and the way for reliability improvement were suggested in this paper.

The basic concept of two stage cycle is to pass through evaporator refrigerant which can absorb heat from outside and to compress the refrigerant which is needed compression. The two stage cycle is consisted of two compression process and the refrigerant is injected between the first and the second compression process. According to the separated way of refrigerant for injection, a phase separator (flash tank) is applied in case of the gas phase separation

and internal heat exchanger (economizer) is applied in case of the liquid phase separation. The basic concept is the same in these two kinds of way but realization method and performance limitation in real product. The performance is changed according to the separation efficiency of gas and liquid phase in the method using the phase separator and according to the heat transfer rate in the method using the internal heat exchanger. The phase separator and the internal heat exchanger are major components needed for composition of two stage cycle. Therefore, they have to be selected by accurate analysis about their characteristics. And the reliability is secured moreover the performance in injection which means refrigerant is sucked to a compressor. Refrigerant has to be injected into compressor in superheated status. It means that wet or liquid compression isn't happened in a compressor. In this study, it is suggested that the reliability evaluation index of the phase separator and the internal heat exchanger and prepared that the standard of control to keep with the product reliability.

## 2. EXPERIMENTAL SETUP AND TEST PROCEDURE

It was made to the experiment equipment that was able to replace only the phase separator and the internal heat exchanger in the same system to evaluate effect of each component. Also, the performance test was doing after decision about optimal refrigerants by reason of difference of the internal volume between the phase separator and the internal heat exchanger.

### 2.1 Test Equipment

The test equipment is air to air heat pump system using R410A and two-stage rotary compressor. Fin-tube type heat exchangers were used as evaporator and condenser. Heating and cooling capacity of this system are 16.0kW and 14.5kW. Figures 1, 2 show a system diagram of the experimental equipment with the phase separator or internal heat exchanger and the structure of themselves, respectively. The shape of phase separator is like cylinder. Pipes for separation of liquid and vapor phase are inserted on top plate of bombe. The IHEX is a double-pipe type of heat exchanger which is composed of counter-flow path to achieve higher heat transfer rate. The test equipment was set in psychrometric chamber which was able to control indoor and outdoor temperature to the set point. T-type thermocouples were attached on the pipe at cycle 4-points (compressor suction and discharge, condenser outlet and evaporator inlet), condenser inlet, compressor U-tube, injection line inlet and outlet. Tests were carried out in the same condition to evaluate only the effect of phase separator and IHEX. The sight glass on the phase separator was used to check the status of refrigerant and exclude the possibility of performance deviation. T-type thermocouples were attached on the liquid inlet and outlet pipe of IHEX to evaluate heat transfer rate. Injection mass flow rate according to EEV openness was measured in advance. The indoor unit was connected to a wind tunnel to evaluate cooling and heating capacity by measuring air mass flow rate, dry bulb and wet bulb temperature.

### 2.2 Test Procedure

First, the capacity and efficiency was measured in steady state of cycle after the temperature of the indoor and outdoor chamber was stabilized. The middle pressure was controlled by 1<sup>st</sup> EEV and the injection EEV was opened to maximize the EER or COP after the operation started. In process of this, the middle pressure was compensated by controlling 1<sup>st</sup> EEV openness when the change of middle pressure was happened. The max efficiency point was found by repeating a chain of these processes.

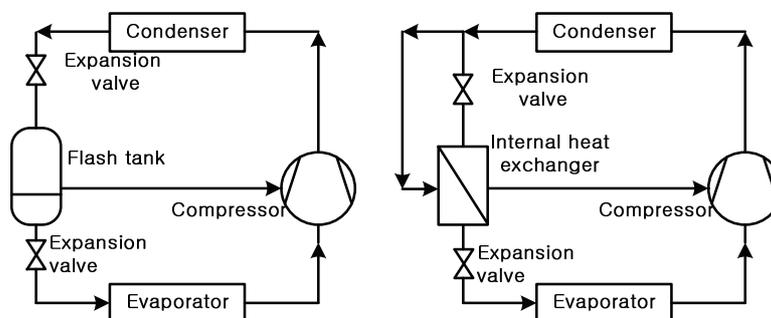


Figure 1 Schematic diagram of 2 stage vapor injection systems

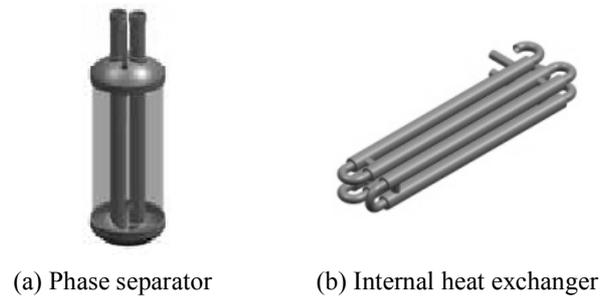


Figure 2 Phase separator and internal heat exchanger

Table 1 Specifications of measuring equipments

Sensor		Range	Deviation
Temperature		-200 °C~400 °C	±0.2
Pressure	Low	1.7MPa(250PsiG)	0.5% of Full Range
	High	3.4MPa(500PsiG)	0.5% of Full Range
Electric power		600V / 50A	0.1%

Table 2 Test conditions for optimal refrigerant charging

Component	Cooling mode	Heating mode
Outdoor temperature	35 °C/24 °C	7 °C/6 °C
Indoor temperature	27 °C/19 °C	20 °C/15 °C

### 3. RESULTS AND ANALYSIS

Test result was distinguished into the performance and the reliability. The performance result includes that the cooling and heating capacity improvement was evaluated from the experiment results about the phase separator and IHEx. The correlation was drawn from capacity and efficiency change by the middle pressure. The evaluation about the accuracy of simulation was performed by comparing with the test result. The test set and simulation were matched to improve the accuracy of simulation result about an operating condition besides a test condition. The dimensionless reliability index of test equipment was suggested about the reliability. The reliability index was distinguished between the index about cycle and instrument and the index about cycle was suggested by the present state of cycle on pressure-enthalpy diagram and the worst condition possible to guarantee the reliability standards.

#### 3.1 Performance Comparison

The tests for optimization of refrigerant were performed in the same test condition before the phase separator and IHEx test. The evaluation of refrigerant charging test was verified by calculating the optimization refrigerant according to internal volume of the system with the phase separator and IHEx together the evaluation about experiment. Each internal volume of the phase separator and IHEx is 1.8L and 0.5L. The test condition was shown in Table 2. The calculated optimization refrigerant charge by using internal volume and the measured optimization refrigerant charge by experiment was evaluated separately in the cooling and heating standard condition. And the difference was 0.40kg in the cooling and 0.25kg in the heating. It was necessary that an accurate evaluation was performed about the injected refrigerant mass flow rate to evaluate the performance improvement by injection. Normally, mass flow meter was used in two-phase flow of refrigerants but in this case, the mass flow meter was able to have an effect on cycle because of the pressure drop. Therefore, correlation about the EEV openness and mass flow rate was developed and used to analysis of the result to minimize an influence of external measuring equipment in the cycle.

The trend about performance improvement was being appeared differently in the existing study about the phase separator and IHEX. While the COP of phase separator type was 4.3% high in outdoor temperature  $-25^{\circ}\text{C}$  (1), efficiency of phase separator way was relatively high in the lower outdoor temperature and the IHEX way was relatively high at the higher outdoor temperature in heating operating mode, efficiency of the phase separator type was high at whole domain in the cooling mode. The cycle using phase separator and IHEX is very a similar concept like Figure 3 except the small difference of cycle parameter (limit of injection mass flow rate). The difference of two kinds of cycle were by the middle pressure according to the change of injection mass flow rate and the isentropic compression efficiency according to the difference about suction temperature in 2<sup>nd</sup> compression process. The COP of system using IHEX is 1.6% higher than the system using phase separator in the outdoor temperature  $-15^{\circ}\text{C}$  and the same capacity by comparison with a simulation about it. This result was shown by coming from the efficiency increase of 2<sup>nd</sup> compression process. The Figure 4(a) shows the COP variations in two kinds of way. It was showed that the COP of IHEX type was 1.6% higher than the COP of phase separator type and the difference became smaller until 0.4% according to rising outdoor air temperature. Because the difference between condensing temperature and evaporating temperature decreased when the outdoor air temperature rose and as a result, isentropic efficiency difference of 1<sup>st</sup> and 2<sup>nd</sup> compression process of compressor decreased and the COP of two kinds of way became similar.

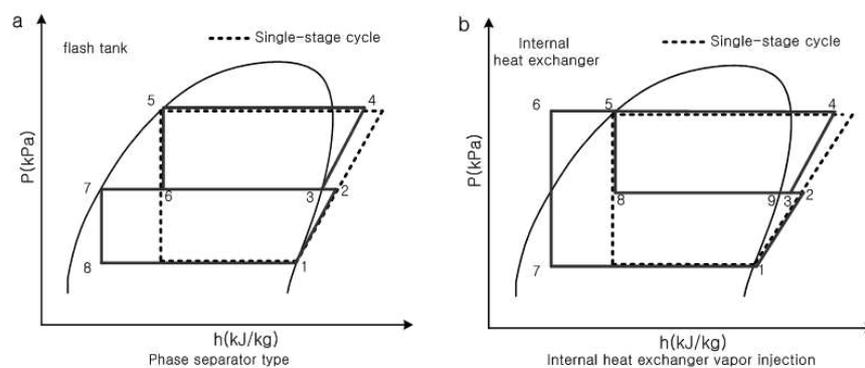


Figure 3: Molier diagrams of 2 stage cycle

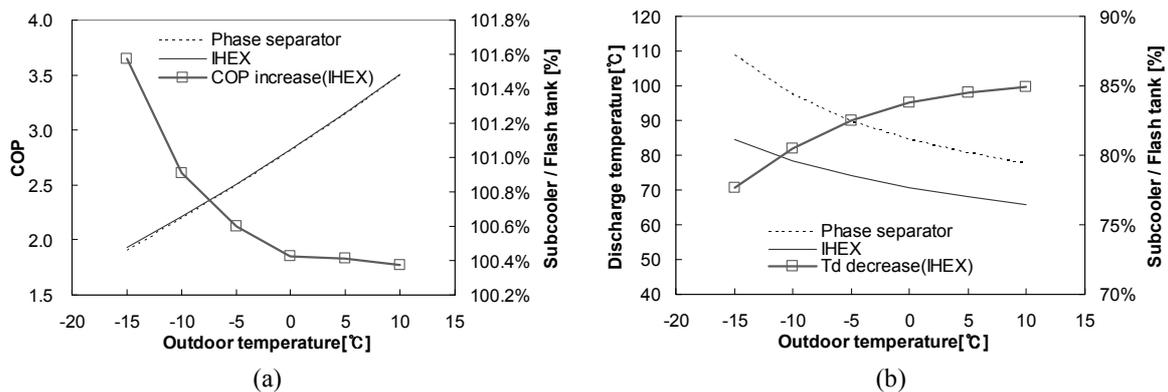


Figure 4 Variation of COP and discharge temperature of phase separator and IHEX type

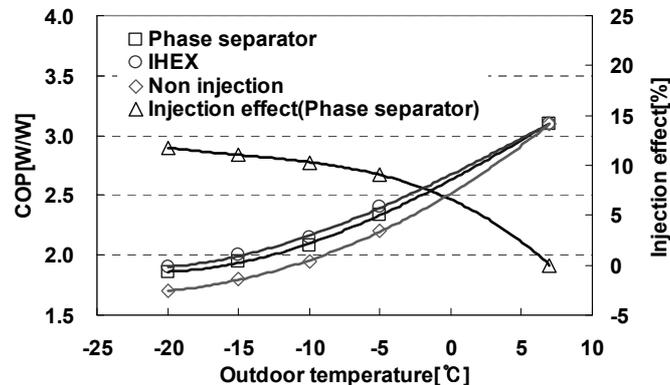


Figure 5 Variations of COP with outdoor temperature at injection cycles

The Figure 4(b) shows the trend of discharge temperature about two kinds of way according to the outdoor air temperature. In the way using IHX, the suction temperature of 2<sup>nd</sup> compression process went down and also discharge temperature went down together because of possible injecting relatively amount of refrigerants comparing with the way using the phase separator. Figure 5 shows the performance results by the experiment using phase separator and IHX. The injection effect was '0' in outdoor air temperature 7°C without the injection and the injection effect of the phase separator type was the COP 8~13% increase in the outdoor air temperature -5°C~-20°C and the bigger effect was shown in the lower outdoor air temperature as the existing study result(2). The difference of COP between the IHX and the phase separator type was 2~3%. The COP increase of the IHX type was from 5% to 20% depending on the injection mass flow rate in the existing study. In the phase separator type, the EEV openness was increased to secure the injection mass flow rate. But the injection mass flow rate didn't increase after reaching a certain mass flow rate. But in the IHX type, it was possible that the wet compression happened when the system was controlled by the same way as this. Therefore, the injection mass flow rate should be controlled proportionally and restrictively for the reliability. For this reason, it was thought that the performance of the IHX applied system was higher than the phase separator applied system.

### 3.2 Cycle Comparison

In the above two kinds of injection cycle characteristic, the maximum injection mass flow rate is decided by vapor quality in the phase separator because only vapor refrigerant can be injected. Therefore, the reduction of discharge temperature after the 2<sup>nd</sup> compression is not large because the decrease of superheat temperature is small after combining 1<sup>st</sup> compressed refrigerants and injected refrigerants. In the outdoor air temperature -15°C, the discharge temperature of IHX way was 24°C lower than the phase separator way. For such a reason, the operating range for the compression ratio and the discharge temperature limit could be expanded by decrease of the discharge temperature and the effect with application expansion of heat pump could be expected in the tropical domain. The IHX way has advantages in the efficiency and the discharge temperature but the phase separator type shows more excellent characteristics than the IHX type in real operation. This is caused by the control method in the IHX type. In the IHX type, the superheat temperature is controlled too high to guarantee the reliability of compressor. In case of the superheat control, the high discharge temperature is appeared in comparing with the phase separator way and this result could be connected to the decrease of performance. Also, in the reliability of phase separator way, it was paying attention that enough safety coefficients were considered to prevent the liquid back through the injection line by the internal liquid level increase. Besides the guarantee of reliability, the quantitative evaluation method which is able to use for the performance maximization is suggested in this study.

### 3.3 Reliability Index

The obvious definition about reliability was necessary to evaluate the reliability of products with 2 stage cycle. It was very important to find items about reliability to define the guarantee of reliability. In case of the IHX way, reliability items were that state of them after mixing 1<sup>st</sup> compressed refrigerants and injection refrigerants, the change of cycle by the disturbance and evaluation according to mixed behavior of refrigerants inside compressor. In case of the phase separator way, the effect by inside volume of the phase separator was added to them. The CFD

analysis results were used to mixing behavior of refrigerants inside compressor before the theoretical approach. The definition and the domain about reliability were decided to draw the reasonable reliability index. The standard for the reliability guarantee about each way was decided as follows. The IHX way should become superheated state after mixing 1<sup>st</sup> compressed refrigerants and injection refrigerants. Besides it should be included that the limitation about the reliability guarantee range by the CFD behavior analysis after mixing. Liquid phase refrigerants should be not sucked through the injection line in the phase separator way. The quantitative analysis about this was expressed by non-dimensional index about two kinds of item as follows. First, it was the evaluation about the operated cycle had the stability to some degree and second, the change characteristic of cycle was considered according to various control parameters.

### 3.4 Phase Separator Type Injection Cycle

The reliability of heat pump system is decided by amount of liquid refrigerants passed through liquid line from the phase separator and supplied to the phase separator. It is decided by the condenser outlet temperature and pressure, the pressure in phase separator and the EEV openness. The amount of refrigerant discharged from the phase separator and supplied to the phase separator is calculated by EEV correlation on the mass flow rate of refrigerant. The decided mass flow rate of refrigerant is evaluated by the reliability standard as follows. Whether the reliability problem is able to happen is decided by the mass balance in the phase separator. When the refrigerant supplied into the phase separator, if the amount of supplied liquid refrigerant is more than the amount of liquid refrigerant left through liquid line, liquid level in the phase separator increases in the phase separator. As a result, liquid back into the compressor will be occurred in the specific operating condition. Although the condition is causing the liquid level increase, it is necessary to evaluate time (Equation 3) filling inner volume of the phase separator with liquid refrigerant. This time is decided by the volume (Equation 2) of accumulated liquid refrigerant and the empty volume of the phase separator. Max control period should be shorter than this extra time for the reliability guarantee in the specific condition. Therefore the reliability index (Equation 4) is the control period divided by maximum allowable time by the buffer of the phase separator. The reliability guarantee is difficult if this value was smaller than '1'. Additional factor about the cycle changed by various control parameters (EEV, Hz) has to be included within the reliability index (Equation 5).

$$\Delta m_{f,PS} = \dot{m}_{P_{mid}-P_e} - \dot{m}_{PS,in} \quad (1)$$

$$\Delta V_{f,PS} = (\dot{m}_{P_{mid}-P_e} - \dot{m}_{PS,in}) / \rho_f \quad (2)$$

$$\Delta t = V_{v,PS} / \Delta V_{f,PS} \quad (3)$$

$$RI_{inj,max} = \frac{\Delta t_c \cdot \Delta V_{f,PS}}{V_{v,PS}} \quad (4)$$

$$RI_{inj,PS} = \frac{\Delta t_c \cdot \left( \Delta V_{f,PS} - \frac{\partial \Delta V_{f,PS}}{\partial X_{ctrl}} \right)}{V_{v,PS}} \quad (5)$$

In the second place, characteristics of cycle changed by EEV openness and compressor Hz were investigated to evaluate the structural reliability index. Figure 5 shows the simulation results on the variation of cycle with the injection mass flow rate. Figure 5(a) and (b) shows pressure-enthalpy diagrams according to the injection mass flow of 20% and 30% about total mass flow rate passing the condenser. The variation of injection mass flow rate is caused by the change of condensing and middle pressure. As a result, this graph shows the change of refrigerants mass flow rate supplied into the phase separator. The amount of liquid refrigerant in the phase separator is expressed in control variables.

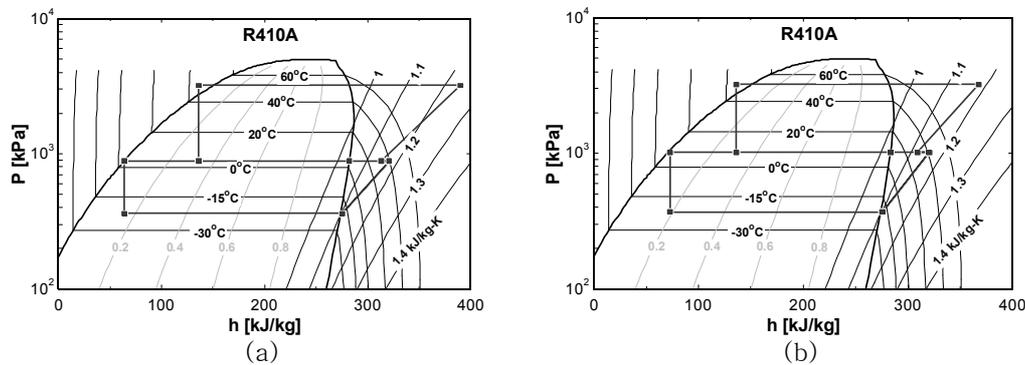


Figure 6 Molier diagrams of phase separator type injection system

### 3.5 Internal Heat Exchanger Type Injection Cycle

The reliability is able to be expressed by polynomial equations which are composed of 1<sup>st</sup> compressed refrigerants by injection EEV openness change, the change of mixed state (Equation 7) of refrigerant is decided by injected refrigerant and the injected mass flow rate. The final RI (Reliability Index) is decided by differences between the enthalpy of mixed refrigerant and the enthalpy of saturated vapor in the same pressure and between the enthalpy of 1<sup>st</sup> compressed refrigerant and the enthalpy of saturated vapor in the same pressure. If the RI is smaller than '0' then it is made a decision that the reliability is not secured and each enthalpy is expressed by  $P_{mid}$ ,  $T_s$ ,  $P_s$ ,  $\eta_{comp}$ ,  $R_{m,inj}$ ,  $Q_{IHEX}$  and  $h_{cond,out}$ . This means that the evaluation of each enthalpy is possible by specification of parts and measured values. Therefore, RI (Equation 8) about the injection is able to be expressed in the IHEX system, as follows.

$$h_{mix} = (\dot{m}_{inj} h_{inj} + \dot{m}_{comp,d1} h_{comp,d1}) / (\dot{m}_{inj} + \dot{m}_{comp,d1}) \quad (6)$$

$$h_{mix,min} = (\dot{m}_{inj} h_{cond,out} + \dot{m}_{comp,d1} h_{comp,d1}) / (\dot{m}_{inj} + \dot{m}_{comp,d1}) \quad (7)$$

$$RI_{inj,IHEX} = (h_{mix} - h_{sat,vapor}) / (h_{sat,vapor} - h_{mix,min}) \cdot \frac{|h_{sat,vapor} - h_{mix,min}|}{h_{sat,vapor} - h_{mix,min}} \quad (8)$$

The IHEX don't have the buffer by the inside volume and it is possible that the mixed state of injection refrigerant and 1<sup>st</sup> compressed refrigerant is two-phase. Therefore RI on the IHEX system is expressed by the enthalpy.

## 4. CONCLUSIONS

The theoretical performance comparison and the limitation about real system were studied about two kinds of way of 2 stage cycle using the phase separator and using the IHEX. The control parameters were decided by evaluating the reliability based on limitation of real system by reliability. As follows, some conclusions were gotten in this study.

1. IHEX type has higher COP about 3% than phase separator type but the phase separator type has little higher performance at real system because of the control problem of IHEX injection system
2. The IHEX type is able to keep the lower until maximum 24°C in the discharge temperature and is able to be applied with advantage in compressor operating range and the tropical condition. But the system of IHEX type is operated in low performance comparing with the phase separator way if injection mass flow rate is not maximized.

3. It is caused by the limitation about injection mass flow rate that the injection effect is not enough in IHEX type. Therefore, the RI (reliability index) is able to contribute to the performance improvement.

### NOMENCLATURE

COP	coefficient of performance	(W/W)	<b>Subscripts</b>
EEV	electronic expansion valve	(-)	c control interval
PSVI	phase separator vapor injection	(-)	comp compressor
h	enthalpy	(kJ/kg)	ctrl control
$\dot{m}$	mass flow rate	(kg/s)	d1 1 <sup>st</sup> discharge
RI	reliability index	(-)	e evaporating
SCVI	subcooler vapor injection	(-)	IHEX internal HEX
t	time	(s)	f fluid
V	volume flow rate	(m <sup>3</sup> /s)	in inlet
X	control parameter	(-)	inj injection
			max maximum
			mid intermediate
			min minimum
			v vapor
			PS phase separator

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