Heat Pump Control Algorithms for a Heat Pump Boiler System

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Abstract: - A heat pump boiler system consists of a heat pump, a boiler and a storage. The effective control of a heat pump boiler system is necessary. In this study, the heat pump control algorithm was developed. Control algorithms for a compressor, an EEV, a storage pump, an outdoor fan and an indoor fan were developed for the cooling and heating operation. In order to verify the performance of control algorithms, tests were performed under the standard cooling and heating conditions. Test results showed the effective control of a heat pump system.

Key-Words: - Heat pump boiler system, Control algorithm, Cooling mode, Heating mode, Heat pump

1 Introduction

Because the performance of existing heat pump systems is greatly affected by the external temperature, it is necessary to develop a heat pump boiler system for improving this characteristic. However, heat pump boiler systems add a boiler, storage, and a heat pipe to the existing heat pump; thus, they require an effective algorithm for stable system control [1]. Thus, the present study aims to develop and validate the performance of a control algorithm for the compressor, EEV, storage pump, and outdoor and indoor fans.

2 Heat Pump Boiler System

As shown in Fig.1, the heat pump boiler system is composed of a compressor, EEV, heat exchanger, and pump for the heat pump; heat exchanger, burner, and three-way valve for the boiler; and heat exchanger and three-way valve for the storage.

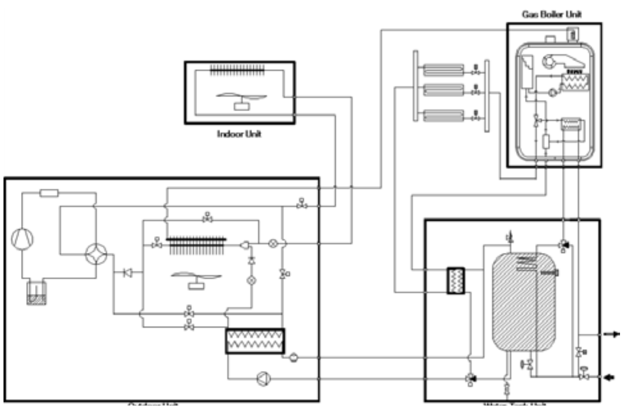

Fig. 1 Heat pump boiler system.

3 Mathematical Model

To develop the heat pump boiler system control algorithm, a mathematical model is required that can simulate the static and dynamic phenomena of the heat pump.

Hence, a mathematical model was utilized that considers the static and dynamic properties of each element, and a dynamic model that assumes a primary system with time delay and ε-Ntu law were specifically used for the heat exchanger model [2].

4 Heat Pump Control algorithm

Algorithms for the compressor, EEV, storage pump, and outdoor and indoor fans were developed and utilized to control the heat pump of this heat pump boiler system.

4.1 Compressor Algorithm

Indoor unit cooling supply temperature control and compressor cooling algorithms, as shown in Fig.2, and condensing water supply temperature heating control and compressor heating algorithms, as shown in Fig.3, were developed and utilized to control the cooling and heating modes, respectively, of the compressor [3].

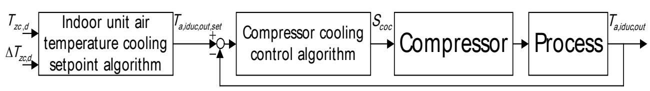

Fig. 2 Compressor cooling algorithm.

ISBN: 978-1-61804-268-2

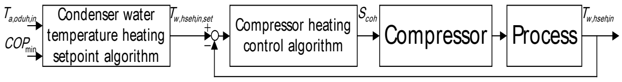

Fig. 3 Compressor heating algorithm.

4.1.1 Compressor cooling algorithm

An indoor unit cooling supply temperature control algorithm was developed using fuzzy logic, which has indoor temperature difference, $T_{\_zc,d}$, and change in indoor temperature difference, $\Delta T_{\_zc,d}$, as input variables and indoor unit cooling supply temperature setting change, $\Delta T_{\_a,iduc,out,set}$, as output variable to establish the indoor air supply temperature required for controlling the indoor unit cooling temperature. Figs.4, 5, and 6 show the membership used for the input and output variables, while Table 1 lists the rule base in use. The Min-Max method was used as the inference method and the centroid method was used for defuzzification.

A compressor cooling algorithm was developed using fuzzy logic, which has indoor unit cooling supply temperature difference, $T_{\_a,iduc,d}$, and change in indoor unit cooling supply temperature difference, $\Delta T_{\_a,iduc,d}$, as input variables and change in compressor cooling operating rate, $\Delta S_{\_coc}$, as output variable to establish the indoor supply temperature as that set by the indoor unit cooling supply temperature control algorithm. Figs.7, 8, and 9 show the membership used for the input and output variables, while Table 2 lists the rule base in use.

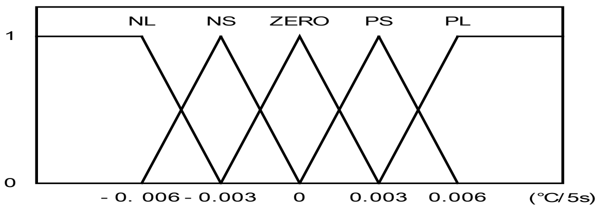

Fig. 4 Membership for $T_{\_zc,d}$

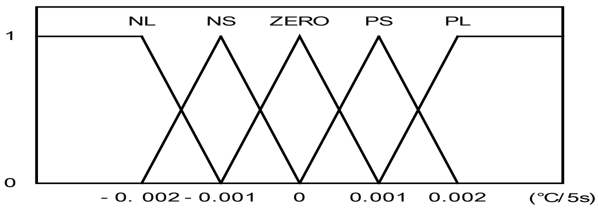

Fig. 5 Membership for $\Delta T_{\_zc,d}$

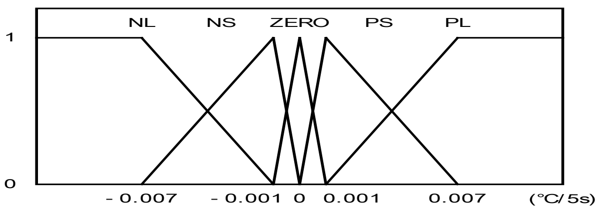

Fig. 6 Membership for $\Delta T_{\_a,iduc,out,set}$

Table 1 Rule base for the cooling setpoint algorithm

$\Delta T_{\_a,iduc,out,set}$		$T_{\_zc,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_zc,d}$	NL	PL	PL	PL	PL	PL
	NS	PL	PS	PS	PS	NS
	ZR	PL	PS	ZR	NS	NS
	PS	PS	NS	NS	NS	NL
	PL	NL	NL	NL	NL	NL

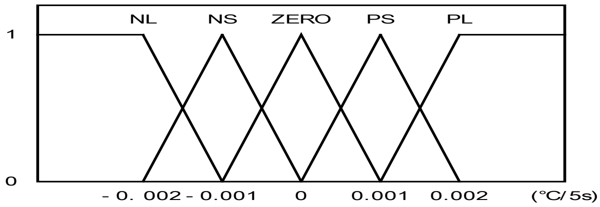

Fig. 7 Membership for $T_{\_a,iduc,d}$

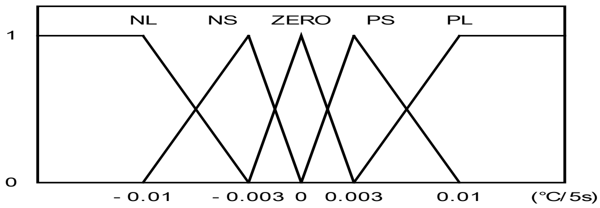

Fig. 8 Membership for $\Delta T_{\_a,iduc,d}$

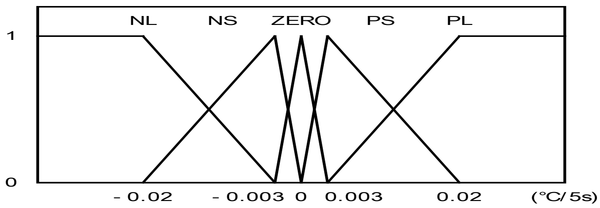

Fig. 9 Membership for $\Delta S_{\_coc}$

Table 2 Rule base for the cooling control algorithm

$\Delta S_{\_coc}$		$T_{\_a,iduc,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_a,iduc,d}$	NL	NL	NL	NS	ZR	ZR
	NS	NL	NL	NS	ZR	ZR
	ZR	NL	NS	NS	ZR	PS
	PS	NS	ZR	ZR	PS	PS
	PL	NS	ZR	ZR	PS	PS

4.1.2 Compressor heating algorithm

A condensing water supply temperature control algorithm, which uses outdoor temperature, $T_{\_a,oduh,in}$, as input variable and condensing water supply temperature setting, $T_{\_w,hseh,in,set}$, as output variable, was developed by considering the cost of the energy used by the heat pump and boilers during heating. Table 3 lists some of the performance data of the utilized heat pump; Fig. 10 shows the COP

ISBN: 978-1-61804-268-2

when the control signal of the compressor was 30 Hz, and Equation (1) shows the condensing water supply temperature control algorithm for minimum COP of 3, chosen after considering energy prices.

$$T_{\_w,hseh,in,set} = 0.52T_{\_a,oduh,in}^{2} - 12.8T_{\_a,oduh,in} + 0.23 \qquad (1)$$

A compressor heating algorithm using fuzzy logic, which uses condensing water supply temperature difference, $T_{\_w,hseh,in,d}$, and change in condensing water supply temperature difference, $\Delta T_{\_w,hseh,in,d}$, as input variables and change in compressor heating operating rate $\Delta S_{\_coh}$, as output variable, was developed to control the condensing water supply temperature to that established by the condensing water supply temperature control algorithm. Figs.11, 12, and 13 show the membership used for the input and output variables, while Table 4 lists the rule base in use.

Table 3 Heat pump performance

	$T_{\_w,hseh,in}$	45		54.4		60	
$T_{\_a,oduh,in}$	$S_{\_coh}$	Cap	COP	Cap	COP	Cap	COP
-10	0.33	1205	2.06	1081	1.61	1009	1.40
	0.67	2449	2.16	2197	1.70	2050	1.47
	1	3977	2.07	3568	1.62	3330	1.41
0	0.33	1865	3.19	1671	2.41	1560	2.06
	0.67	3790	3.36	3397	2.54	3170	2.17
	1	6154	3.20	5516	2.42	5148	2.07
10	0.33	2683	4.66	2402	3.35	2239	2.81
	0.67	5453	4.90	4883	3.53	4550	2.95
	1	8854	4.68	7928	3.37	7388	2.82

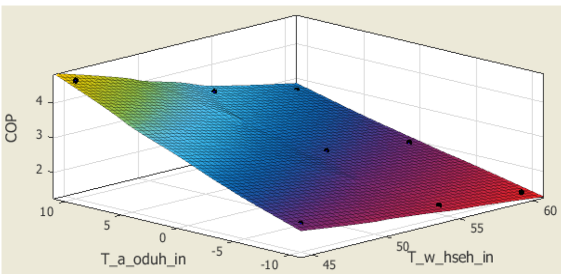

Fig. 10 COP at 30Hz

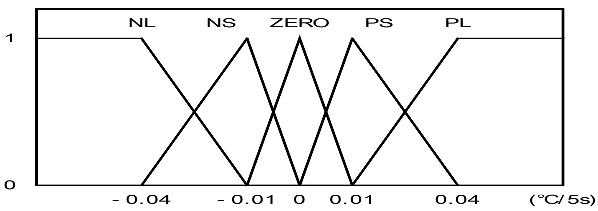

Fig.11 Membership for $T_{\_w,hseh,in,d}$

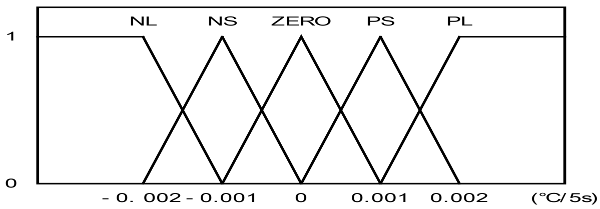

Fig. 12 Membership for $\Delta T_{\_w,hseh,in,d}$

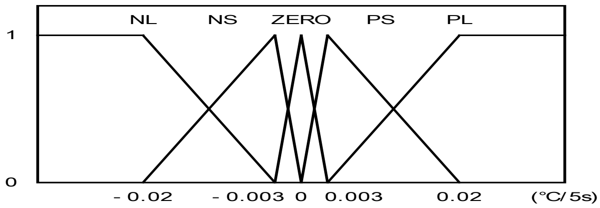

Fig. 13 Membership for $\Delta S_{\_coh}$

Table 4 Rule base for the heating control algorithm

$\Delta S_{\_coh}$		$T_{\_w,hseh,in,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_w,hseh,in,d}$	NL	NL	NL	NL	NL	NL
	NS	NL	NS	NS	NS	PS
	ZR	NL	NS	ZR	PS	PS
	PS	NS	PS	PS	PS	PL
	PL	PL	PL	PL	PL	PL

4.2 EEV algorithm

As COP increases with the decrease of superheat, the minimum superheat setting possible is required within the range that keeps the liquid refrigerant from flowing into the compressor [4].

As shown in Figs.14 and 15, superheat and EEV algorithms for both cooling and heating modes were developed and utilized for EEV control.

4.2.1 EEV cooling algorithm

Fig.16 is the minimum superheat according to the compressor signal measured in an experiment under cooling conditions. A superheat cooling setpoint algorithm that uses $S_{\_coc}$ and $S_{\_idfc}$ as input variables and $T_{\_shc,set}$ as output variable was developed by considering efficiency, as shown in Equation (2), to establish a safe superheat.

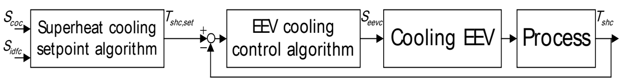

Fig. 14 EEV cooling algorithm

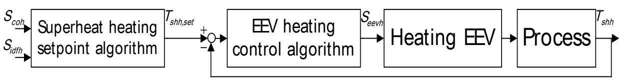

Fig. 15 EEV heating algorithm

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$$T_{\_shc,set} = 7.463 - 0.916S_{\_idfc} - 9.133S_{\_coc} + 0.431S_{\_idfc}S_{\_coc} + 4.729S_{\_coc}^{2} \quad (2)$$

To control superheat to that established by the superheat cooling setpoint algorithm, an EEV cooling control algorithm was developed, which uses superheat difference, $T_{\_shc,d}$, and change in superheat difference, $\Delta T_{\_shc,d}$, as input variables and change in EEV opening amount $\Delta S_{\_eevc}$, as output variable. Figs.17, 18, and 19 show the membership used for the input and output variables, while Table 5 lists the rule base in use.

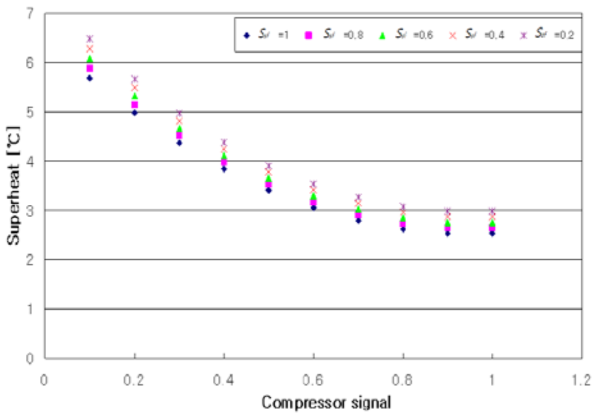

Fig. 16 Minimum super heat

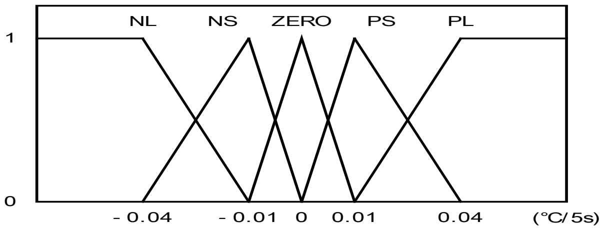

Fig. 17 Membership for $T_{\_shc,d}$

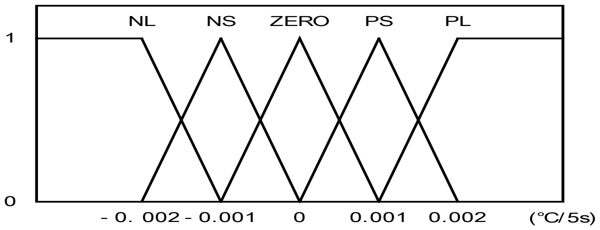

Fig. 18 Membership for $\Delta T_{\_shc,d}$

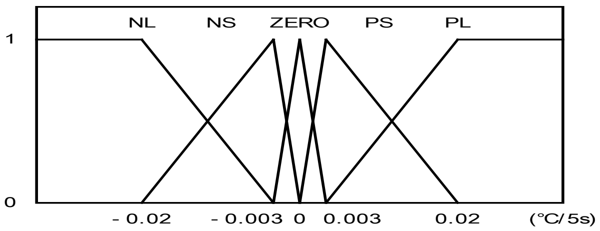

Fig. 19 Membership for $\Delta S_{\_eevc}$

Table 5 Rule base for the cooling EEV control algorithm

$\Delta S_{\_eevc}$		$T_{\_shc,d}$ NL	NS	ZR	PS	PL
$\Delta T_{\_shc,d}$	NL	NL	NL	NL	NL	NL
	NS	NL	NS	NS	NS	PS
	ZR	NL	NS	ZR	PS	PS
	PS	NS	PS	PS	PS	PL
	PL	PL	PL	PL	PL	PL

4.2.2 EEV heating algorithm

Fig. 20 displays the minimum superheat according to the compressor signal measured in the experiment under heating conditions. To establish minimum superheat considering efficiency, a superheat heating setpoint algorithm was developed, which uses $S_{\_coc}$ and $S_{\_idfc}$ as input variables and $T_{\_shc,set}$ as output variable, as shown in Equation (3).

$$T_{\_shh,set} = 8.525 - 1.001S_{\_odfh} - 8.304S_{\_coh} + 0.001S_{\_odfh}S_{\_coh} + 3.610S_{\_coh}^{2} \quad (3)$$

An EEV heating control algorithm using fuzzy logic, which uses superheat difference, $T_{\_shh,d}$, and change in superheat difference, $\Delta T_{\_shh,d}$, as input variables and change in EEV opening rate $\Delta S_{\_eevh}$, as output variable, was developed to control superheat to that established by the superheat heating setpoint algorithm. Figs.21, 22, and 23 show the membership used for input and output variables and Table 6 lists the rule base in use.

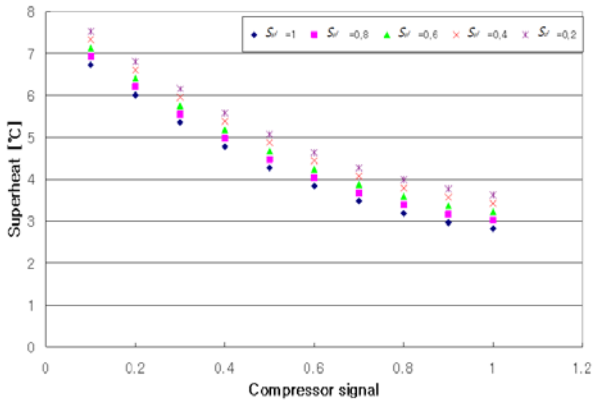

Fig. 20 Minimum super heat

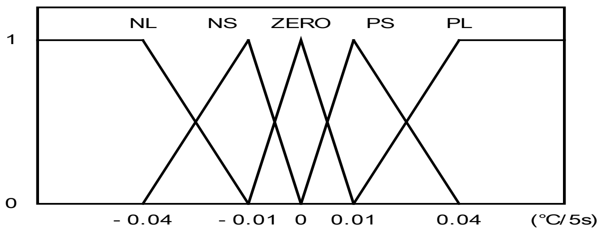

Fig. 21 Membership for $T_{\_shh,d}$

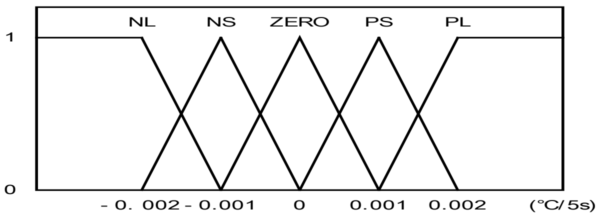

Fig. 22 Membership for $\Delta T_{\_shh,d}$

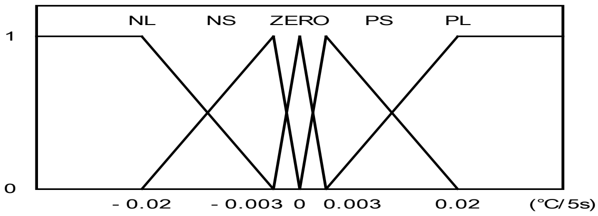

Fig. 23 Membership for $\Delta S_{\_eevh}$

Table 6 Rule base for the heating EEV control algorithm

$\Delta S_{\_eevh}$		$T_{\_shh,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_shh,d}$	NL	NL	NL	NL	NL	NL
	NS	NL	NS	NS	NS	PS
	ZR	NL	NS	ZR	PS	PS
	PS	NS	PS	PS	PS	PL
	PL	PL	PL	PL	PL	PL

4.3 Storage pump algorithm

4.3.1 Storage pump cooling algorithm

A cooling algorithm was developed and utilized, which uses temperature difference in the entry and exit of the heat exchanger between the heat pump and storage, $T_{\_w,hsec,d}$, and its change, $\Delta T_{\_w,hsec,d}$, as input variables and change in storage pump signal, $\Delta S_{\_spc}$, as output variable. Figs.24, 25, and 26 show the membership used for the input and output variables, while Table 7 lists the rule base in use.

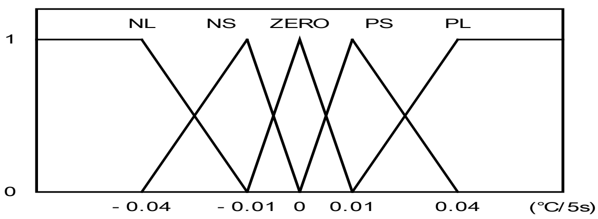

Fig. 24 Membership for $T_{\_w,hsec,d}$

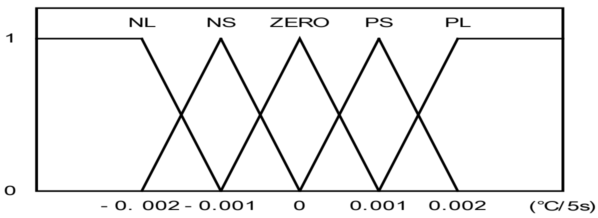

Fig. 25 Membership for $\Delta T_{\_w,hsec,d}$

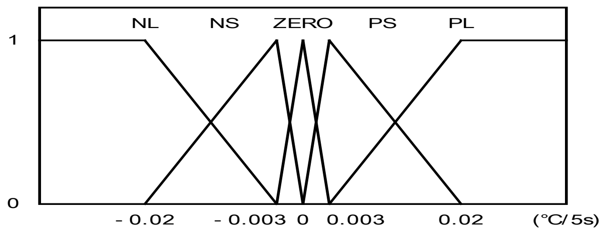

Fig. 26 Membership for $\Delta S_{\_spc}$

Table 7 Rule base for the storage pump cooling control

$\Delta S_{\_spc}$		$T_{\_w,hsec,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_w,hsec,d}$	NL	NL	NL	NL	NL	NL
	NS	NL	NS	NS	NS	PS
	ZR	NL	NS	ZR	PS	PS
	PS	NS	PS	PS	PS	PL
	PL	PL	PL	PL	PL	PL

4.3.2 Storage pump heating algorithm

A heating algorithm was developed and utilized, which uses temperature difference in the entry and exit of the heat exchanger between the heat pump and storage, $T_{\_w,hseh,d}$, and its change, $\Delta T_{\_w,hseh,d}$, as input variables and change in storage pump signal, $\Delta S_{\_sph}$, as output variable. Figs.27, 28, and 29 show the membership used for the input and output variables; Table 8 lists the rule base in use.

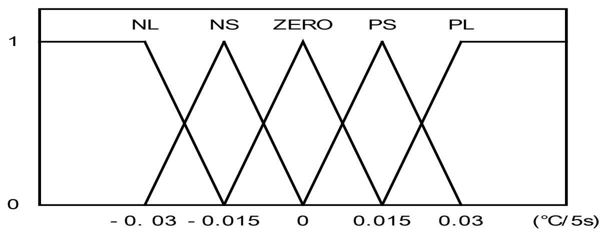

Fig. 27 Membership for $T_{\_w,hseh,d}$

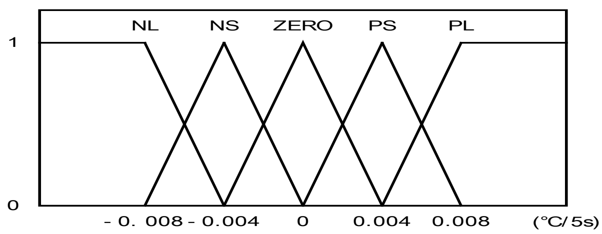

Fig. 28 Membership for $\Delta T_{\_w,hseh,d}$

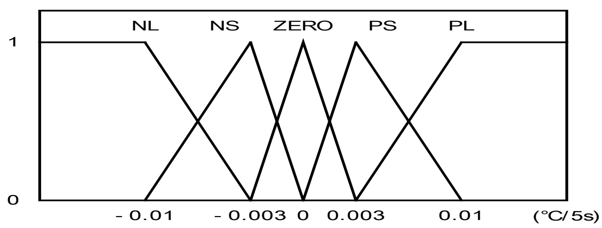

Fig. 29 Membership for $\Delta S_{\_sph}$

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Table 8 Rule base for the storage pump heating control

$\Delta S_{\_sph}$		$T_{\_w,hseh,d}$				
		NL	NS	ZR	PS	PL
$\Delta T_{\_w,hseh,d}$	NL	NL	NL	NL	NL	NL
	NS	NL	NS	NS	NS	PS
	ZR	NL	NS	ZR	PS	PS
	PS	NS	PS	PS	PS	PL

4.4 Outdoor fan algorithm

4.4.1 Storage pump cooling algorithm

The high pressure of the heat pump refrigerant was used as the input variable for controlling the outdoor fan during cooling, and a step speed algorithm with a dead bend of 3 bar and a standard of 30 bar was developed and utilized.

4.4.2 Storage pump heating algorithm

The low pressure of the heat pump refrigerant was used as the input variable for controlling the outdoor fan during heating, and a step speed algorithm with a dead bend of 1 bar and a standard of 8 bar was developed and utilized.

5 Algorithm Control Performance

Performance tests were conducted under standard cooling and heating conditions to validate the performance of the heat pump control algorithm [5]. Figs.30, 31, and 32 show the cooling performance test results of the developed algorithm, while Figs.33, 34, and 35 show those of heating. As shown in the figures, in the cooling test, after indoor temperatures were set by the indoor unit cooling supply temperature, they were adequately controlled through stable compressor control. Cooling superheat was also adequately controlled by stable EEV control according to the preset superheat, and adequate control of the storage pump by storage entry/exit temperature difference was observed. Likewise, heating was adequately controlled by the compressor after the condensing water temperature was established by ambient temperature. Heating superheat was also appropriately controlled by the EEV, and entry/exit temperature differences.

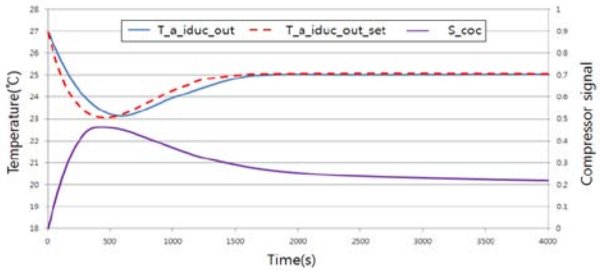

Fig. 30 Supply air temperature control

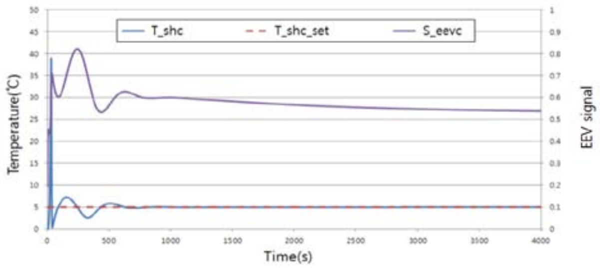

Fig. 31 EEV cooling control

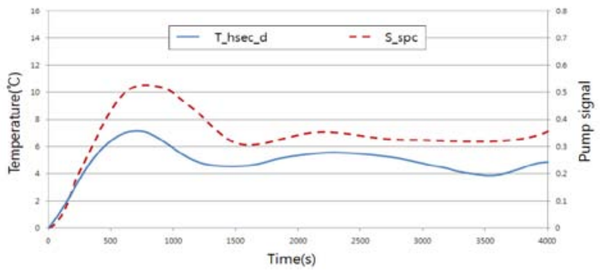

Fig. 32 Storage pump cooling control

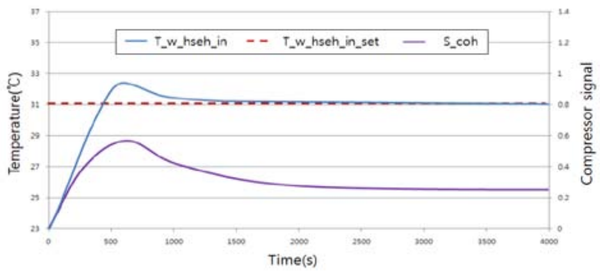

Fig. 33 Condensing water temperature control

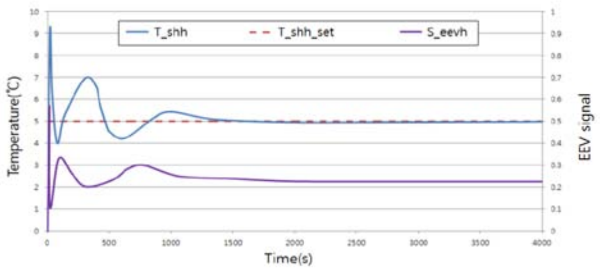

Fig. 34 EEV heating control

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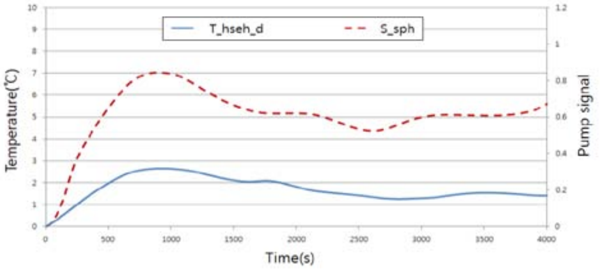

Fig. 35 Storage pump heating control

6 Conclusion

Heat pump control algorithms for cooling and heating were developed to control the heat pump in a heat pump boiler system. This study developed and utilized indoor and outdoor fan cooling, storage pump cooling, and EEV cooling algorithms composed of superheat cooling setpoint and EEV cooling control algorithms, and compressor cooling algorithm composed of indoor unit supply temperature cooling control and compressor cooling control algorithms in cooling mode. The study additionally developed and utilized outdoor fan heating, storage pump heating, and EEV heating algorithms composed of superheat heating setpoint and EEV heating control algorithms, and compressor heating algorithm composed of condensing water supply temperature heating control and compressor heating control algorithms in heating mode.

To validate the control performance of the developed algorithms, performance tests were conducted under standard cooling and heating conditions, which showed that the supply temperature and superheat were appropriately established by the setpoint algorithm and controlled adequately at the set value through stable control.

Hence, the present study concludes that the developed heat pump control algorithm can be appropriately utilized for heat pump boiler system control.

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ISBN: 978-1-61804-268-2