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Design and Analysis of Fuzzy Control in a Variable Speed Refrigeration System

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ABSTRACT: This paper deals with fuzzy control with a feedforward compensator to progress both energy saving and coefficient of performance (COP) in a variable speed refrigeration system. Both the capacity and superheat are controlled simultaneously and independently in the system. By adopting the fuzzy theory, the controller design for the capacity and superheat is possible without depending on a dynamic model of the system. Moreover, the feedforward compensator of the superheat can reduce influence of the interfering loop between the capacity and superheat. Some experiments are conducted to design appropriate fuzzy controller by an iteration manner. The results show that the proposed fuzzy controller with the compensator can establish good control performances for the complicated refrigeration system in spite of its inherent strong non-linearity. Also, the fuzzy control performances were investigated by comparing to the model based PI control experimental results to evaluate transient behavior under the control.

Nomenclature

Δ	: variation
μ	: output of fuzzy inference
e	: error
ee	: the rate of 'e'
f	: compressor frequency [Hz]
SH	: evaporator superheat [℃]
T_a	: chamber temperature [℃]
VO	: opening angle of EEV [%]
U^{crisp}	: crisp output of fuzzy control
C_i	: PI controller
G_i	: transfer function of system
K_p	: proportional gain
T_i	: integral time [s]
s	: complex variable
t	: time [s]

1. Introduction

According to development of industrial technology and the growing demands for comfort in a residential environment, inverter-driven refrigeration system for energy saving is becoming more popular. Therefore, it is necessary to design high-performance and high-precision controller for obtaining precise temperature and energy saving. It is very well known that the control of capacity and superheat is basic control scheme in the variable speed refrigeration system (VSRS). The superheat is usually maintained as a constant value to keep

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maximum COP, and the capacity control is performed by changing compressor speed to cope with partial thermal load condition. Hence, precise indoor temperature and energy saving can be achieved at the same time by these two controls. To design high-performance and high-precision controller of the VSRS, an empirical model that represents dynamic characteristics of the system is necessary at first. As the basic refrigeration system mainly is consisted of two heat exchangers (evaporator and condenser), an electronic expansion valve (EEV) and a compressor, it is very difficult to get a practical model of the system for the control. Moreover, due to strong inherent non-linearity characteristics of the system and interference loops between chamber temperature and superheat which are control variables, the simple model was hardly obtained without linearization and decoupling of the coupled system. A sophisticated mathematical model from the principle of the energy conservation is suitable for just numerical simulation, but it is a drawback for designing control system systematically due to its high-order differential terms in the model. This is the reason why a simple empirical model is preferred for the engineers in industrial fields.(1-4)

Even though an empirical model obtained from a number of experiments also exists, systematic design of PID (Proportional, Integral, Derivative) controller for precise temperature control is not assured. Because the empirical model strongly depends on transfer functions which were linearized approximately and the model is still complicated due to interference loops between the capacity and superheat. The control gains of PID are inevitably determined by trial and errors manner based on the tuning method such as Zigler-Nichols.(5)

To solve these problems, the applications of the fuzzy control based on the fuzzy inference have been tried widely. Although a large number of studies have been made on the capacity or the superheat control, little is known about the two control variables at the same time.(6-8)

Therefore, fuzzy controller proposed in this paper aimed at simultaneous control of the capacity and superheat without troublesome dynamic model of the system. Hence, the proposed controller enables maximum COP and energy saving at the same time even though the thermal load is varied. If we can get equivalent control performance to PID by using the fuzzy control, it will be very useful design methodology for engineers in the industrial fields.

We investigated important design factors effect on control performance after design of the fuzzy controller. Especially, we found that the fuzzy controller with feedforward compensator of the superheat can obtain good transient response.

Some experimental results show that the proposed fuzzy controller is suitable for the capacity and the superheat control of the variable speed refrigeration system. Also, we compared the control performance of the fuzzy controller to that of model based PI control in this paper. The results of comparison showed that the control performance of fuzzy control are fairly good.

2. Design of fuzzy controller

Fig. 1 shows a basic composition of fuzzy controller. It is basically consisted of fuzzification, fuzzy rule base, fuzzy inference unit, and defuzzification part. In the fuzzification part, the crisp value is converted to a membership value by using fuzzy-set theory. Fuzzy rule base is subdivided into a rule base and a data base. The rule base stores if-then rules, and the data base stores membership values of fuzzy set. The fuzzy inference unit makes inference on fuzzy rule base. The defuzzification part provides a crisp value as final output from membership value of fuzzy inference unit.

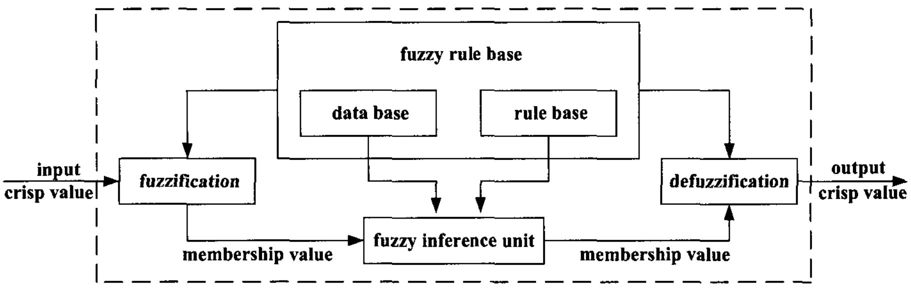


Fig. 1 Basic composition of fuzzy control system.

Controlled variables in this system are chamber temperature T_a and the superheat *SH* which is the difference between the refrigerant temperature at outlet and inlet of an evaporator. The controlled system is the basic refrigeration cycle, and the actuators of the cycle are the induction motor driven by an inverter to control compressor speed and the stepping motor to control the opening angle of EEV.

Two fuzzy controllers for the capacity and the superheat are designed independently. Input variables for the capacity are made up of 'e' and 'ee'. Here, 'e' is the error and 'ee' is the rate of variation of 'e'. Triangle membership function is used for conversion between crisp and membership value. Fig. 2 and Fig. 3 are membership functions for the capacity control and the superheat control respectively. The range of the capacity and superheat of 'e' were -3~3 ℃. The range of 'ee' in the superheat was smaller than the capacity. The control output range of the capacity was -20~20 Hz and the range of the superheat control was -9~6%.

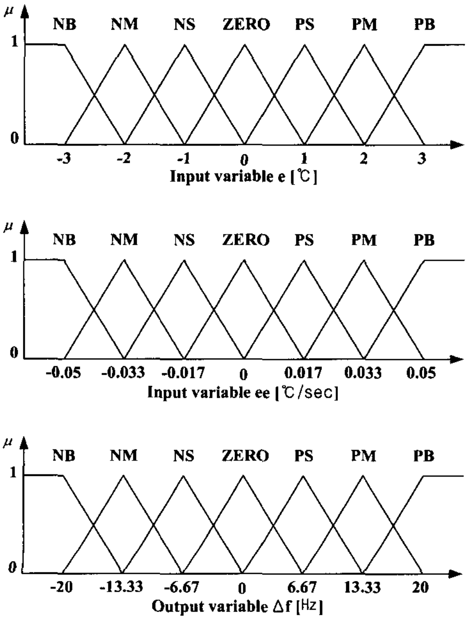


Fig. 2 Membership function for capacity control.

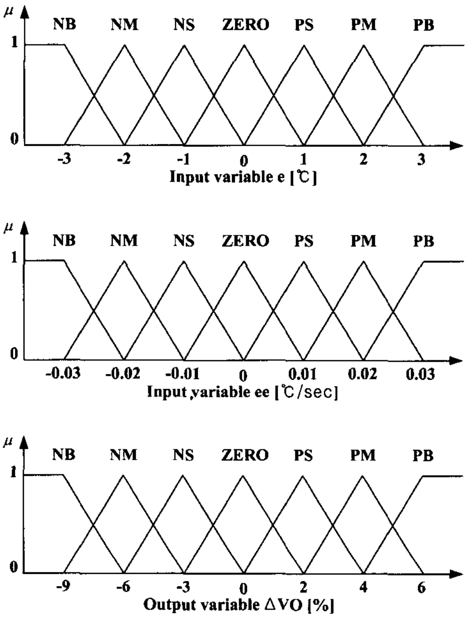


Fig. 3 Membership function for superheat control.

Table 1 Rule base for capacity control

		ee						
		NB	NM	NS	Z	PS	PM	PB
	NB	NB	NB	NB	NB	Z	Z	Z
	NM	NB	NB	NM	NM	Z	Z	Z
	NS	NB	NM	NS	NS	Z	Z	Z
e	Z	NM	NS	Z	Z	Z	Z	Z
	PS	NS	Z	Z	Z	PS	PM	PB
	PM	Z	Z	Z	PS	PM	PB	PB
	PB	Z	Z	Z	PB	PB	PB	PB

Table 2 Rule base for superheat control

		ee						
		NB	NM	NS	Z	PS	PM	PB
	NB	NB	NB	NM	NM	NS	Z	Z
	NM	NB	NM	NS	NS	Z	Z	Z
	NS	NM	NS	NS	Z	Z	Z	Z
e	Z	NM	NS	Z	Z	Z	Z	Z
	PS	NS	Z	Z	Z	PS	PM	PB
	PM	Z	Z	Z	PS	PS	PM	PB
	PB	Z	Z	Z	PS	PM	PB	PB

The membership functions of input and output variable and rule bases must be determined to design fuzzy controller. In this paper, these are decided by a trial and error manner throughout some experiments. It is noted here that we do not depend on any dynamic model of the system to design controller. Table 1 and Table 2 show fuzzy rule bases for controlling the capacity and the superheat.

Output is calculated in a fuzzy inference part using the fuzzy rule bases. This inference is based on the Mamdani min-max arithmetic. In the defuzzification part, membership value is converted to a crisp value as final output by the center of gravity method like Eq. (1).

$$U^{crisp} = \frac{\sum \mu(i)\, b_i}{\sum \mu(i)} \tag{1}$$

Where, U^{crisp} means crisp output of fuzzy inference, b_i indicates center of area of a membership function and $\mu(i)$ is the output of fuzzy inference.

To reduce the effect of the disturbance that the interference of the variation of compressor speed toward superheat, we proposed fuzzy control with feedforward compensator of superheat. Fig. 4 indicates feedforward compensator of superheat. Disturbance d which has an effect on superheat due to the variation of compressor speed Δf can be expressed as Eq. (2).

$$d = \Delta SH = \frac{\Delta SH}{\Delta f}\Delta f \tag{2}$$

To cancel the effect of this disturbance, we designed the compensator such as Eq. (3) by an iteration method.

$$u_f = k\, d = k'\Delta f \tag{3}$$

Where, u_f is compensating quantity of ΔVO, and k' was set as 0.5 in this paper.

In experiments, the control range of Δf and ΔVO were set as 30~60 Hz and 10~100% respectively. Control period was 30 sec for the capacity and superheat.

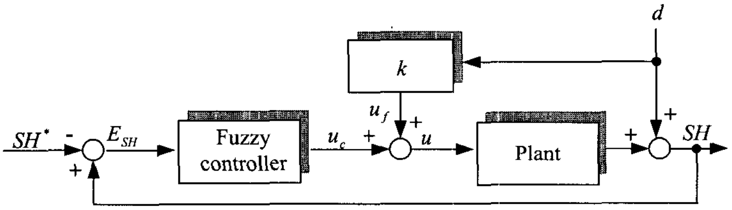
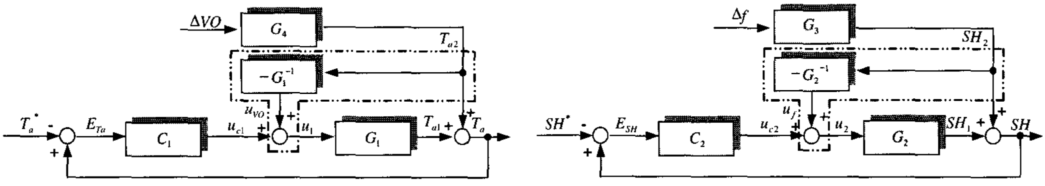


Fig. 4 Feedforward compensator of superheat.



(a) (b)

Fig. 5 Block diagram of decoupling control for VSRS.

3. Design of PI controller

Fig. 5 shows a decoupling control model with feedforward compensator. Here, $C_i(i=1, 2)$ means PI controllers and $G_i(i=1\sim4)$ represents each transfer function of the system. It is noted here that Fig. 5 does not have any interfering loops and each influence of operating variation such as variation of EEV opening angle ΔVO and variation of compressor frequency Δf is reflected feedforward to their input side. The transfer function $G_i(i=1\sim4)$ in Fig. 5 was supposed the first-order model with dead time in this paper. They were obtained from several experiments under various operating conditions and shown in Eq. (4)~Eq. (7).

$$G_1=\frac{\Delta T_a}{\Delta f}=\frac{-0.42}{680s+1} \quad (4)$$

$$G_2=\frac{\Delta SH}{\Delta f}=\frac{-0.47}{780s+1}-\frac{-0.15}{30s+1}e^{-25s} \quad (5)$$

$$G_3=\frac{\Delta SH}{\Delta VO}=\frac{-0.38}{57s+1}e^{-16s} \quad (6)$$

$$G_4=\frac{\Delta T_a}{\Delta VO} \quad (7)$$

As the gain of the transfer function G_4 is very small and time constant of it is very large, we ignored the influence of G_4 hereafter.

The PI controllers based on empirical decoupling model were designed to control the capacity and superheat independently. An output of the PI controller, manipulated variable, $u(t)$ is shown as Eq. (8). The PI gains, proportional gain K_p and integral time T_i, were tuned by the Ziegler-Nichols rules.

$$u(t)=K_p[e(t)+\frac{1}{T_i}\int_0^T e(t)dt] \quad (8)$$

From Fig. 5(b), the disturbance $d(s)$ which have an effect on superheat due to the variation of compressor speed Δf can be expressed as Eq. (9).

$$d(s)=G_3(s)\Delta f \quad (9)$$

To cancel the effect of this disturbance, we designed the compensator such as Eq. (10).

$$u_f(t)=-\mathcal{L}^{-1}[\frac{1}{G_3(s)}d(s)] \quad (10)$$

Where, u_f is compensating quantity of ΔVO to remove the effect of interference of the variation of compressor speed toward superheat.

In experiments, the range of Δf and ΔVO were set as 30~60 Hz and 10~100% respectively. Control period was 30sec for capacity and 15sec for the superheat. Also the Pade approximation and the Taylor series expansion were used to describe G_3 simply.

4. Experimental results

Photo. 1 shows a real experimental system, and Table 3 represents the specification of a test unit of the system. The experimental sys-

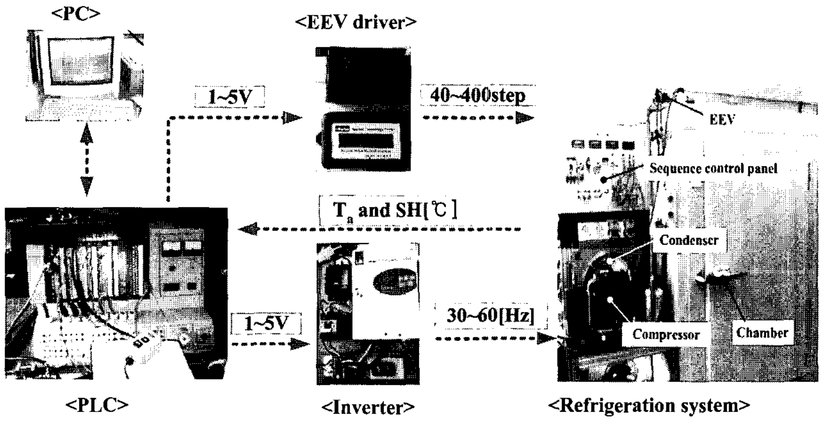


Photo. 1 Experimental system of fuzzy and PI controller for capacity and superheat control.

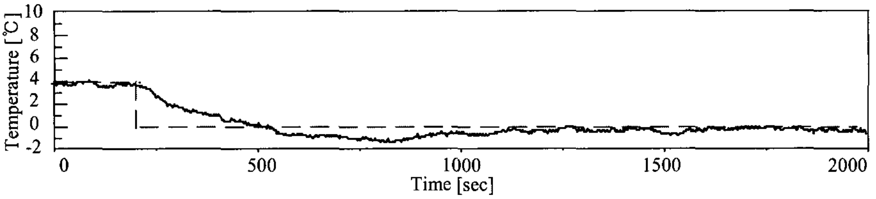
Table 3 Specification of a test unit

Compressor	Type	Vertical, Reciprocating	Inverter	Type	PWM
	Power	220 V, 60 Hz, 1.5 KW		HP	2
Condenser	Type	Fan fin type	Step valve control interface	Input voltage	DC 12 V
	Capacity	3450 kcal/h		Input signal	DC 1~5 V or 4~20 mA
Evaporator	Type	Fin-tube type		Output	0~400 step
	Capacity	680 kcal/h	PLC	CPU	GM2
Expansion Valve Device	Type	EEV		TC unit	16 Ch
	Model	JHEV 14 A		D/A unit	16 Ch
	Rated voltage	DC 12 V		PID unit	16 Loop
Refrigerant	Type	R22	Chamber	Size	1200×700×1650[mm]

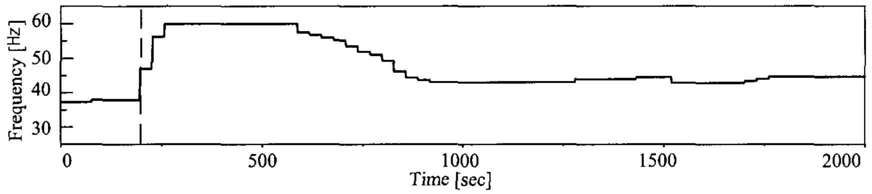
tem was composed of basic refrigeration cycle and control system. The main components of the control system were an inverter, a step valve control interface and a PLC (Programmable Logic Controller).

The compressor of the basic refrigeration cycle was driven by the induction motor with a general V/f constant type inverter. The step motor to drive EEV was operated by a step valve control interface. The input control signal of the inverter and the step valve control interface was obtained from a D/A unit of the PLC. The PI control was performed by a PID unit of the PLC. All temperatures were measured by thermocouples (T-type). The temperature information was transmitted to a TC (Thermocouple) unit of the PLC with real time for operating input variables.

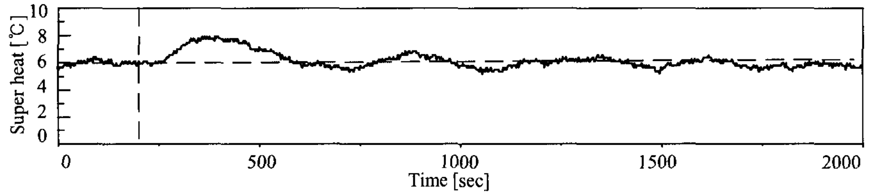
Fig. 6 describes responses of chamber temperature and superheat based on the fuzzy control with the feedforward compensator when the chamber reference temperature was abruptly varied from 4 ℃ to 0 ℃. The thermal load was 1.45 kW and the superheat reference was 6 ℃. Fig. 6(a) shows response of chamber temperature by the fuzzy control with the compensator when the chamber temperature reference was varied abruptly at the time of 200 second. It took about 700 seconds from reference change to get close set point value. Fig. 6(b) shows the response of compressor frequency to follow the reference of chamber temperature. It can be seen that the compressor set point frequency for controlling the capacity



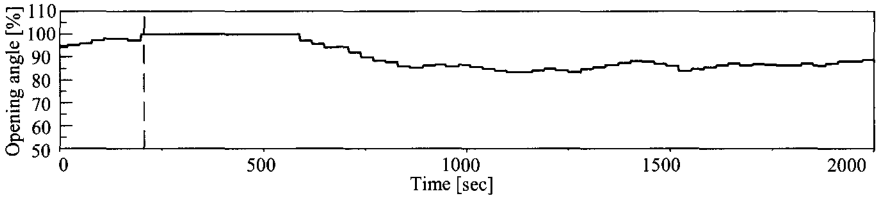
(a) The response of chamber temperature to follow T_a reference



(b) The compressor frequency to follow T_a reference



(c) The response of superheat

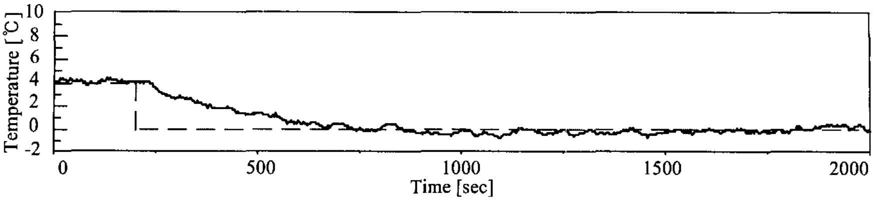


(d) The opening angle of EEV

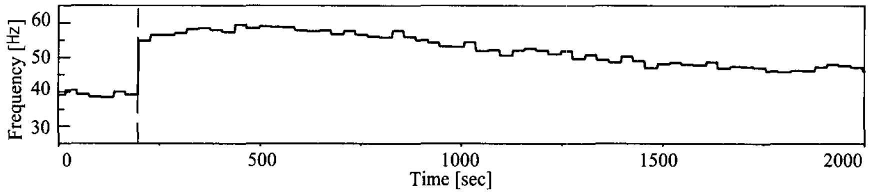
Fig. 6 The responses of chamber temperature and superheat by fuzzy control with feedforward compensator according to the change of chamber temperature reference.

was very stable. Fig. 6(c) presents the response of superheat control according to the change of chamber temperature reference. The superheat must be controlled at a constant value, 6 ℃, even the compressor speed and chamber temperature were varied. The percent overshoot was observed 30% approximately in this figure, but the maximum overshoot of the superheat was kept within 8 ℃. It was acceptable superheat in this system. Fig. 6(d) indicates the opening angle of EEV when the fuzzy controller was operated. The opening angle of EEV was adjusted with stable to maintain the superheat as 6℃. These experimental results provided fairly good control performances of capacity and superheat when the chamber temperature reference was varied.

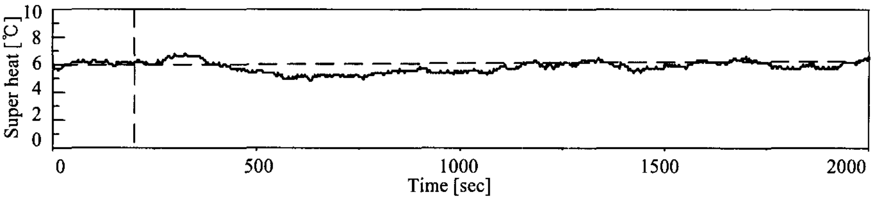
Fig. 7 describes the PI control response of chamber temperature and superheat. The experimental conditions were the same as the previous experiments in Fig. 6., Fig. 7(a) shows the PI control response of chamber temperature when the reference was changed. It took about 400 seconds to get close set point value from change reference. Fig. 7(b) shows the response of compressor frequency to follow the refer-



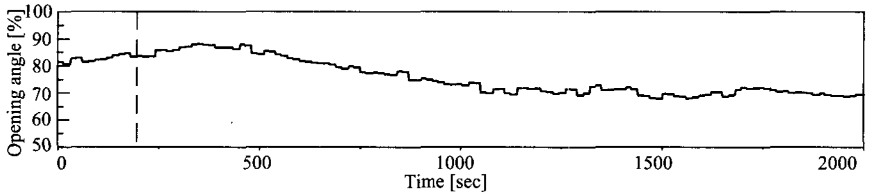
(a) The response of chamber temperature to follow T_a reference



(b) The compressor frequency to follow T_a reference



(c) The response of superheat



(d) The opening angle of EEV

Fig. 7 The responses of chamber temperature and superheat by PI control with feedforward compensator according to the change of chamber temperature reference.

ence of chamber temperature. Fig. 7(c) presents the PI control response of superheat according to the change of chamber temperature reference. Percent overshoot of the superheat was observed about 15%, but the maximum overshoot of it was below 7 ℃. And the maximum undershoot of superheat was above 5℃. They were acceptable scope of superheat in this system. Fig. 7(d) indicates the opening angle of the EEV when the PI controller was operated. The set point value of EEV opening angle was varied stably to maintain the superheat as 6 ℃.

5. Conclusions

In this paper, we presented the fuzzy control with feedforward compensator for the capacity and superheat on the purpose of saving energy and progress of COP in the VSRS. From the experimental results, we can compare the control performance of fuzzy control to that of the model based PI control. The main conclusions are summarized as follows:

(1) The input parameter 'ee' was very important design factor as well as 'e' to get good control performance in the capacity and super-

heat control design.

(2) Fairly good control performances were established by the fuzzy controller with feed-forward compensator of the superheat. The simultaneous control of chamber temperature and superheat based on the suggested controller had good transient responses even though the references and thermal load were varied.

(3) The control performance of PI controller was better than that of fuzzy controller based on feedforward control method. Thus, if we get a dynamic model of the system easily, the PI control is more suitable for precise control and systematical design of the controller for the superheat and capacity.

(4) When we hardly obtain the dynamic model of the system, the fuzzy controller can be used and fairly good control performance is expected.

Acknowledgement

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