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Fuzzy Control with Feedforward Compensator of Superheat in a Variable Speed Refrigeration System

Li Hua* · Dong-Woo Lee** · Seok-Kwon Jeong† · Jung-In Yoon**

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Abstract : In this paper, we suggest fuzzy control with feedforward compensator of superheat to progress both energy saving and coefficient of performance(COP) in a variable speed refrigeration system. The capacity and superheat are controlled simultaneously and independently by an inverter and an electronic expansion valve respectively for saving energy and improving COP in the system. By adopting the fuzzy control, 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 eliminate influence of the interfering loop between capacity and superheat. Some experiments are conducted to design the 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 with inherent strong non-linearity.

Key words : Fuzzy control, Capacity, Superheat, COP, Variable speed refrigeration system, Fuzzy inference, Fuzzy rule base, Feedforward compensator

1. Introduction

According to the 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. The superheat is maintained as a constant value to keep maximum COP, and the capacity is controlled 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 controlling these two parameters. To

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† Corresponding Author(Division of Mechanical Engineering, Pukyong National University), E-mail: skjeong@pknu.ac.kr Tel: 051)620-1507

* Department of Refrigeration and Air-Conditioning Engineering, Graduate School, Pukyong National University

** Pukyong National University

design high-performance and high-precision controller of the refrigeration system, an empirical model that represents dynamic characteristics of the system is necessary at first. As the basic refrigeration system mainly consists 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 complicate 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 engineers in the industrial fields[1],[2].

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 complicate due to interference loops between the capacity and superheat. The control parameters of PID controller are inevitably determined by trial and errors manner based on the tuning method such as Zigler-Nichols[3].

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[4]~[7], little is known about the two control variables at the same time[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 that of PID controller 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 control experimental results show that the proposed fuzzy controller is suitable for the capacity and the superheat control of the variable speed refrigeration system.

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. 2 is schematic diagram of refrigeration control system in this paper. Controlled variables in this system are an indoor 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 thestepping motor to control the opening angle of EEV. The capacity control of the refrigeration system is to adjust refrigerant flow rate by changing compressor speed to cope with thermal load disturbance. On the other hand, the superheat control is to keep up fluctuated superheat as a certain constant value by controlling 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 between reference indoor

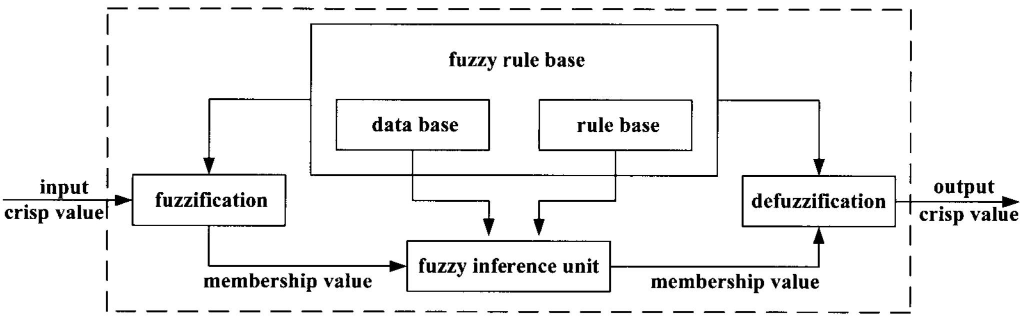


Fig. 1 Basic composition of fuzzy control system

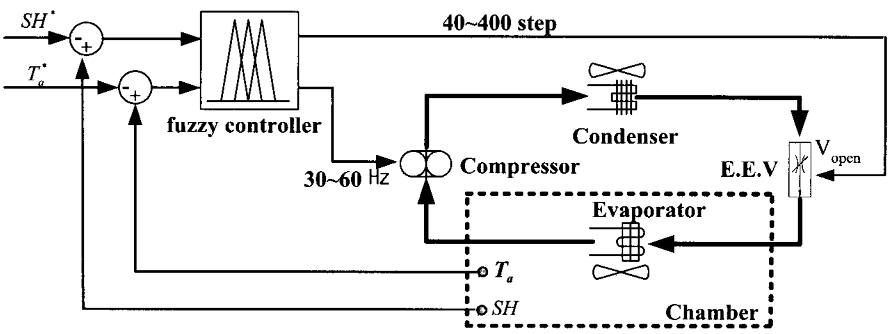


Fig. 2 Schematic diagram of the refrigeration system for experiments

temperature(T_a^*) and measured indoor temperature(T_a), and also 'ee' is the rate of variation of 'e'. Input variables for superheat control are also made up 'e' and 'ee'. The output variables are compressor frequency(f) in the case of capacity control and the opening angle of EEV(VO) in the case of the superheat control.

There are some types of membership function such as triangle form and trapezoidal form etc. The triangle membership function was used to produce a rule base for fuzzy control in this paper. Because the triangle membership function is the most wildly used in the fuzzy control field and it is very easy to design fuzzy controller. The triangle membership function is used for conversion between crisp and membership value. Fig. 3 and Fig. 4 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 -20~20Hz and the range of the superheat control was -9~6%.

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. Table 1 and Table 2 show fuzzy rule bases for controlling the capacity and the superheat. The rule bases were decided from the experience of the controller designer and several experiments.

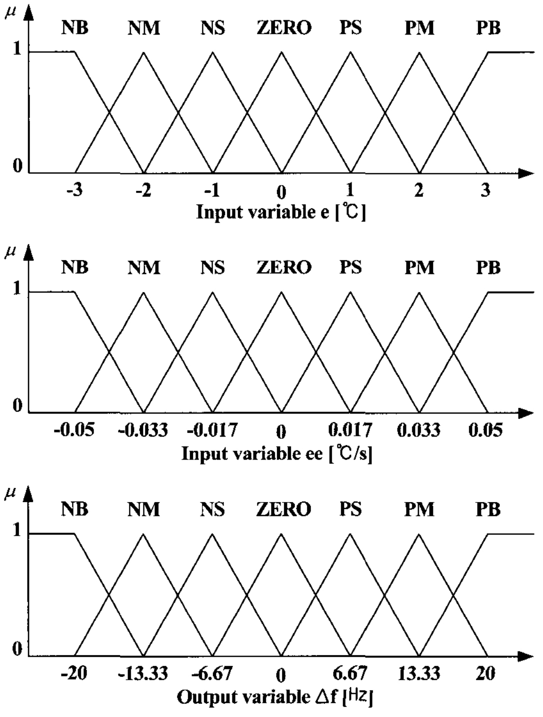


Fig. 3 Membership function for capacity control

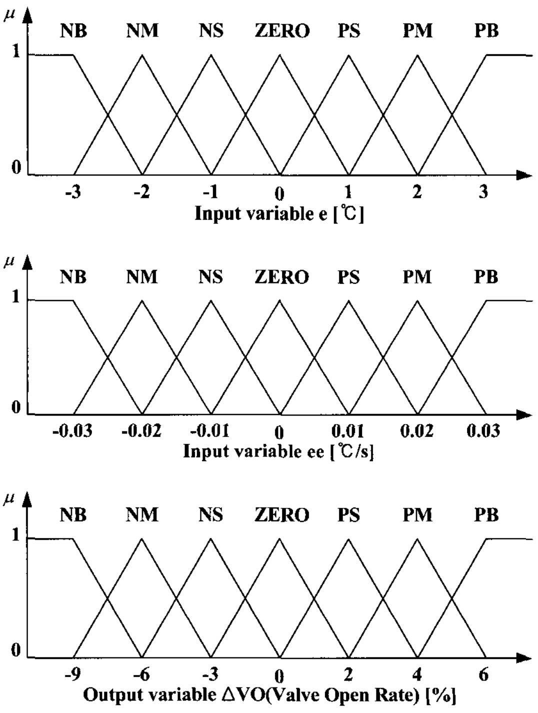


Fig. 4 Membership function for superheat control

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

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 equation (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.

3. Experimental result

Photo. 1 shows real experimental system. Fuzzy controller for controlling both capacity and superheat is realized by the Programmable Logic Controller(PLC) with specific converter modules D/A and TC(Thermocouple). Table 3 represents the specification of a test unit of the experimental system. The experimental system 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

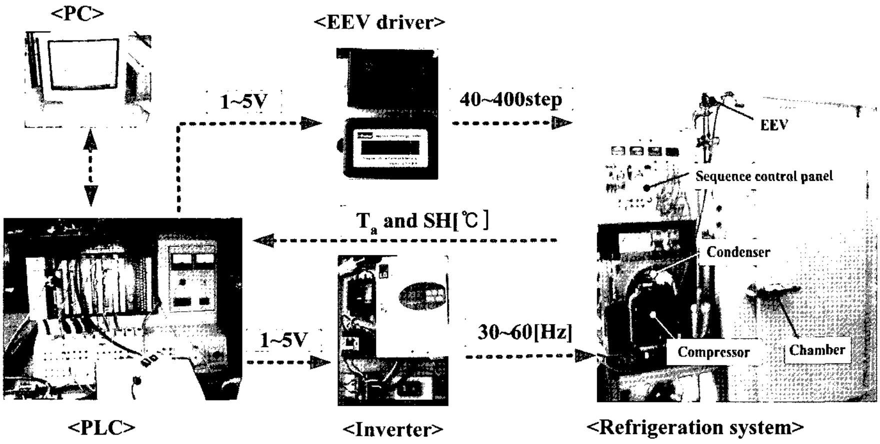
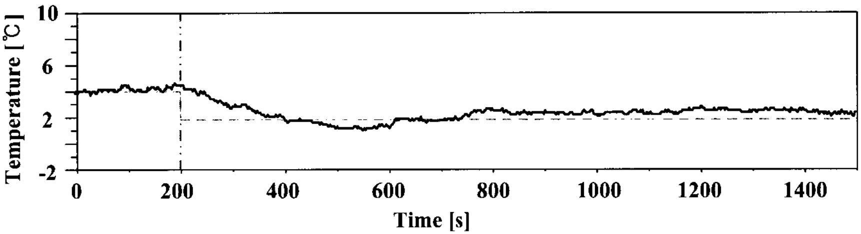


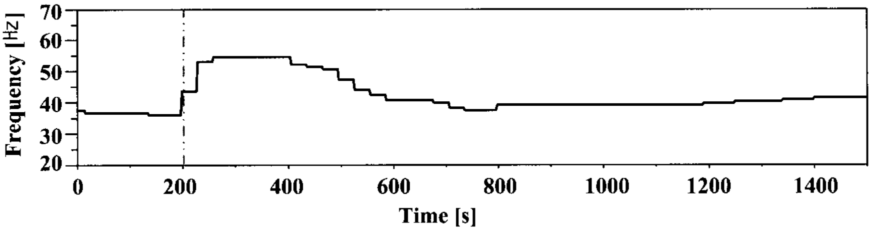
Photo. 1 Experimental system of fuzzy controller for capacity and superheat control

Table 3 Specification of a test unit

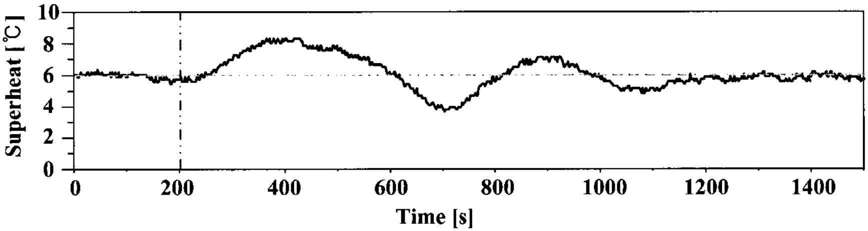
Compressor	Type	Vertical, Reciprocating	Inverter	Type	PWM
	Power	220V, 60㎐, 1.5㎾		HP	2
Condenser	Type	Fan fin type	Step valve control interface	Input voltage	DC 12V
	Capacity	3450 ㎉/h		Input signal	DC 1-5V or 4-20㎃
Evaporator	Type	Fin-tube type		Output	0-400 step
	Capacity	680 ㎉/h	PLC	Relay unit	32 Ch.
Expansion Valve Device	Type	EEV		D/A unit	16 Ch.
	Model	JHEV 14A		TC unit	16 Ch.
	Rated voltage	DC 12V		CPU	GM2
Refrigerant	Type	R22	Chamber	Size	1200x700x1650[㎜]



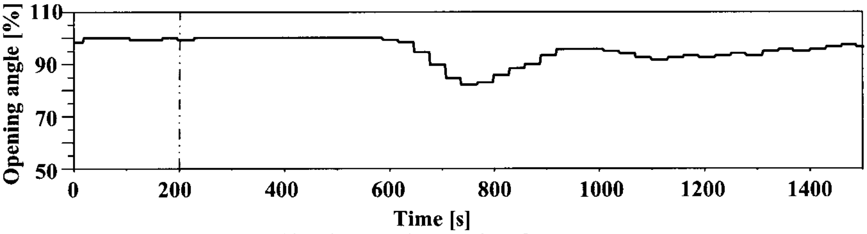
(a) The response of chamber temperature to follow T_a reference



(b) The compressor frequency to follow T_a reference



(c) The response of superheat



(d) The opening angle of EEV

Fig. 5 The responses of chamber temperature and superheat by fuzzy control according to the variation of chamber temperature reference

the PLC. The compressor was driven by the 3 phase induction motor with a general V/f constant type inverter. The stepper motor to drive EEV was operated by a step valve control interface. The input control signals of inverter and step valve control interface were gotten from D/A unit of the PLC. All temperatures were measured by thermocouples(T-type). The temperature information was transmitted to TC unit of the PLC with real time for operating input variables, 'e' and 'ee', in the fuzzy controller. The control sampling time was set at 30 seconds in this study.

Fig. 5 shows control responses of the chamber temperature and the superheat when the chamber temperature reference was abruptly changed from 4℃ to 2℃. The thermal load was 1.5㎾ and the superheat control reference was set at 6℃. From the experimental results, the chamber temperature response was fairly good but the superheat oscillated and settling time was very long. It is desirable to control the capacity and superheat simultaneously in the variable speed refrigeration system. In spite of simultaneous control of them, good control performances can not be obtained because of the effect of interference of the variation of compressor speed toward superheat. The evaporating pressure will be varied when the compressor frequency is varied. Then the superheat of evaporator is also changed due to the variation of evaporating pressure. To overcome this problem, we proposed fuzzy control with feedforward compensator of superheat which can eliminate the influence of the interfering loop between capacity and superheat.

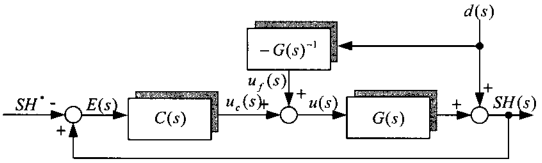


Fig. 6 Feedforward compensator of superheat

Fig. 6 indicates feedforward compensator of superheat. $C(s)$ represents fuzzy controller, and $G(s)$ means transfer function as follows;

$$G(s)=\frac{\Delta SH}{\Delta VO} \tag{2}$$

Disturbance $d(s)$ which have an effect on superheat due to the variation of compressor speed Δf can be expressed as equation (3).

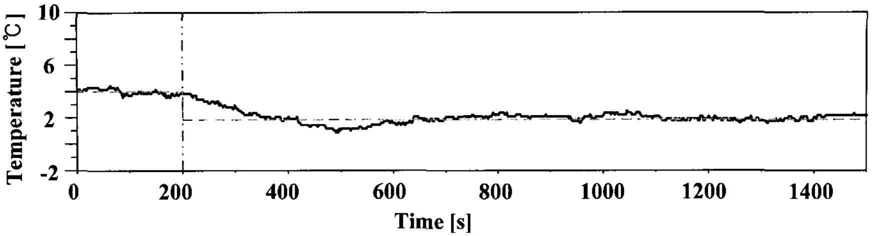
$$d(s)=\frac{\Delta SH}{\Delta f}\Delta f \tag{3}$$

To cancel the effect of this disturbance, we designed the compensator such as equation (4) by iteration method.

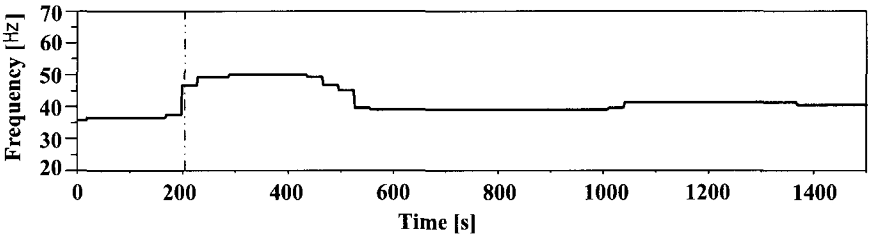
$$u_f(t)=k\Delta f \tag{4}$$

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

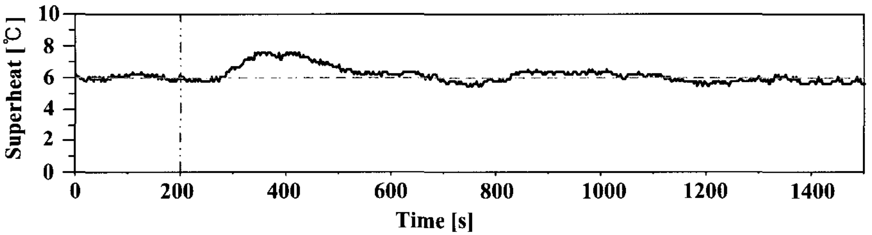
Fig. 7 describes responses of chamber temperature and superheat based on the fuzzy control with the feedforward compensator. The experimental conditions were the same as previous experiment in Fig. 5. Fig. 7(a) shows response of chamber temperature by the fuzzy control with the compensator when the chamber temperature reference was varied abruptly at the time of 200 second. It takes about 400 seconds from reference change to get close set point value. Fig. 7(b) shows the



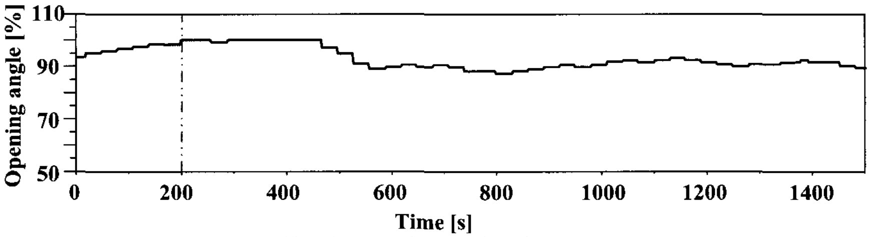
(a) The response of chamber temperature to follow T_a reference



(b) The compressor frequency to follow T_a reference



(c) The response of superheat

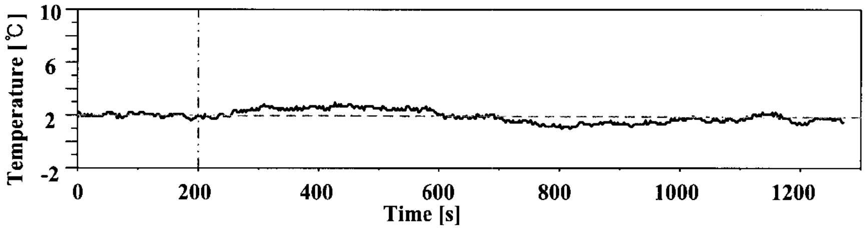


(d) The opening angle of EEV

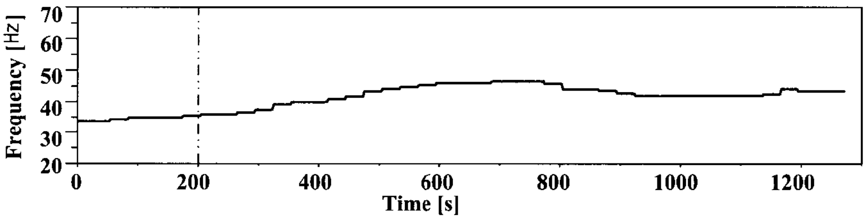
Fig. 7 The responses of chamber temperature and superheat by fuzzy control with feedforward compensator according to the change of chamber temperature reference

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 was very stable. Fig. 7(c) presents the response of superheat control according to the change of chamber temperature reference. The superheat must be controlled as a constant value, 6℃, even the compressor speed and chamber temperature were varied. The percent overshoot is observed 17% approximately in this figure, but the maximum overshoot of the superheat is kept less than 8℃. It is acceptable superheat in this system. Fig. 7(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 provide fairly good control performances of capacity and superheat when the chamber temperature reference was varied.

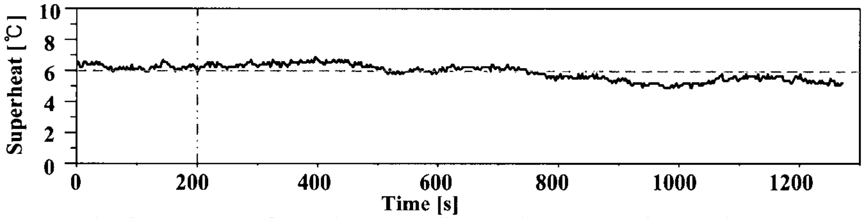
Fig. 8 describes responses of chamber temperature and superheat when thermal load was abruptly varied from 1.35㎾ to 1.57㎾ at 200 second. The chamber temperature reference was set at 2℃ and the superheat reference was 6℃. From Fig. 8(a), we found that the chamber temperature was maintained as 2℃ even the thermal load was varied. Fig. 8(b) shows that the compressor frequency increased to control the chamber



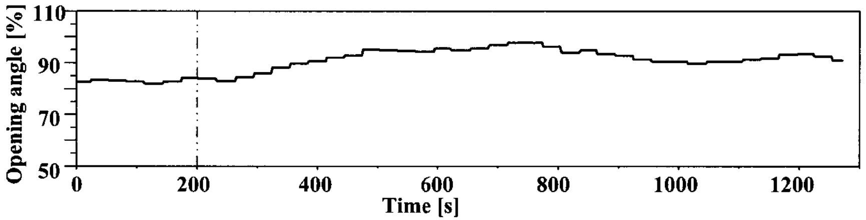
(a) The response of chamber temperature according to the change of thermal load



(b) The compressor frequency



(c) The response of superheat according to the change of thermal load



(d) The opening angle of EEV

Fig. 8 The responses of chamber temperature and superheat by fuzzy control with feedforward compensator according to the variation of thermal load

temperature as 2℃ because of the increase of thermal load. Fig. 8(c) presents the fuzzy control response of superheat according to the change of thermal load. The superheat has been controlled as a constant value, 6℃, to obtain high COP. Fig. 8(d) shows the opening angle of EEV under the given thermal load. The fuzzy control responses indicate good control performance of the capacity and superheat under various thermal load conditions.

4. Conclusion

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 variable speed refrigeration system. The main points are summarized as follows:

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

(2) The superheat response is very sensitive to the variance of compressor speed. Thus, good control performance hardly expected by conventional basic fuzzy controller without compensation of the influence of the compressor speed change.

(3) Fairly good control performances were established by the fuzzy controller with feedforward 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.

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Author Profile

Li Hua

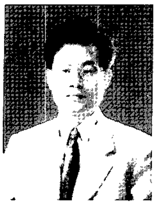
Birth: 1973. 1996: B.Eng., Nanjing Univ. of Science & Technology, China. 2005: M.Eng., Pukyong National Univ., Korea. Current: Ph.D. Student, Pukyong National Univ., Dept. of Refrigeration & Air-conditioning Engg.

Dong-Woo Lee

Birth: 1979. 2005: B.Eng., Pukyong National Univ., 2007: M.Eng., Pukyong National University.

Seok-Kwon Jeong

Birth: 1961. 1983: B.Eng., Pukyong National Univ., Korea. 1995: Eng.Dr., Yokohama National Univ., Dept. of Electrical & Computer Eng., Japan. Current: Professor, Pukyong National Univ., School of Mechanical Engg.



Jung-In Yoon

Birth: 1961. 1988: B.Eng., Pukyong National Univ., Korea. 1995: Ph.D.Eng., Tokyo Univ., of A&T, Japan. Current: Professor, Pukyong National Univ., School of Mechanical Engg.