Design of Membership Ranges for Fuzzy Logic Control of Refrigeration Cycle Driven by a Variable Speed Compressor

Changho Han, Jaemin Lee, Li Hua, Seokkwon Jeong

Abstract**—**Design of membership function ranges in fuzzy logic control (FLC) is presented for robust control of a variable speed refrigeration system (VSRS). The criterion values of the membership function ranges can be carried out from the static experimental data, and two different values are offered to compare control performance. Some simulations and real experiments for the VSRS were conducted to verify the validity of the designed membership functions. The experimental results showed good agreement with the simulation results, and the error change rate and its sampling time strongly affected the control performance at transient state of the VSRS.

Keywords**—**Variable speed refrigeration system, Fuzzy logic control, membership function range, control performance.

I. Introduction

RECENTLY, control for a VSRS has been attracting high attention because of its ability to save energy. However, the VSRS is a nonlinear system which includes model uncertainty and time delay. Therefore, the robust control is strongly required on the VSRS. So far, many control methods have been applied in order to obtain robust performance on the VSRS. They are largely divided into two groups, model-based control and artificial intelligence (AI) technique without a mathematical model. The PID logic, LQR, and LQG are representative of the model-based control. On the other hand, FLC is a typical method of the AI techniques. In the case of the VSRS, it is not easy to construct the linear model because of its high order and difficulties of parameters identification [1], [2]. Even if the model is built, it includes various model uncertainties. Therefore, it is not enough for the PID control to accomplish the robust control performance on the VSRS. The other control methods, LQR and LQG, are suitable for the MIMO system and possible for obtaining the optimum control performance between input energy and control accuracy. However, it is also hard to maintain the robustness of the control system due to the modeling error of the linearized state equation, and it is not practical because of the model with high-order. In contrast, the FLC of AI technique has been widely applied to various industrial fields as a robust control manner for a nonlinear system including the time delay and model uncertainty [3], [4].

Some researches on the FLC for the VSRS have been studied to cope with the nonlinear characteristics and model uncertainty [5], [6]. However, most of the studies focused mainly on the improvement of transient characteristics and control performance to reduce steady-state error depending on expert's experiences and intuitions [7]-[9]. For this reason, it is not sufficient to systematical consideration on the major design factors of the FLC which are the error, the error change rate in controlled variable and its sampling time. Hence, the influence of the main design factors of the FLC on control performance is analyzed in detail in this paper. At first, the criterion values for the membership function ranges of the error and error change rate are set up from static experimental data for the VSRS [1]. In addition, two different values from the criterion values are prepared to compare control performance through some simulations and experiments. Next, the simulations are conducted to analyze effects on control performance using transfer function models of the VSRS which are deliberately obtained from perturbation experiments. Finally, real experiments for the VSRS were performed and the results were compared with the simulation results. The experimental results showed the same trend with the simulation results, and the error change rate including sampling time strongly affected the control performance of the VSRS.

II. FLC Design of VSRS

A. Control of the VSRS

Fig. 1 shows the schematic diagram of the VSRS control system. The VSRS consists of a variable speed compressor, heat exchangers, and an electronic expansion valve (EEV).

All of the components in the refrigeration cycle are connected each other with many pipes and various valves. For that reason, the whole system has strong inherent nonlinear characteristics in operational ranges. The control system for the VSRS is composed of a Programmable Logic Controller (PLC) including a D/A and A/D converter, an inverter and an EEV drive. In this system, the main control variable is chamber temperature T_a. Other than that, superheat T_s is auxiliary controlled to maintain maximum COP and prevent damages on the compressor due to the liquid back phenomenon. The subscripts 'a' and 's' describe air temperature in the chamber

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and superheat respectively, where the superheat T_s is calculated by a temperature difference between output and input of the evaporator, $T_s = T_o - T_i$. The chamber temperature T_a is precisely controlled by the inverter which regulates the motor rotational speed of the compressor. Meanwhile, the superheat is controlled by a step motor drive which adjusts the opening angle of the EEV. The manipulated variables, control signals, are the frequency (Hz) f_c of the inverter and opening angle (%) V_e of the EEV.

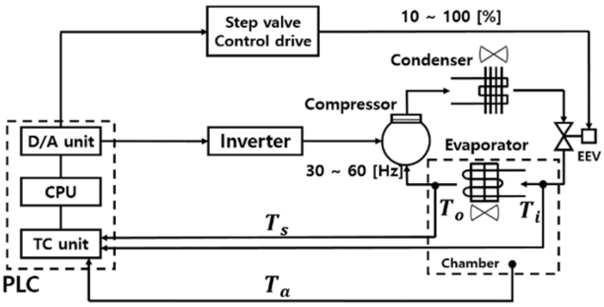


Fig. 1 Schematic diagram of control system for the VSRS

B. Fuzzy Logic Controller Design for the VSRS

The fuzzy controller basically consists of fuzzification, knowledge base, fuzzy inference, and defuzzification unit. The knowledge base is composed of a database and a rule base which is described in if-then form.

Fig. 2 shows the conceptual diagram of FLCs for the VSRS. Two FLCs are independently employed for controlling the chamber temperature T_a and the superheat T_s.

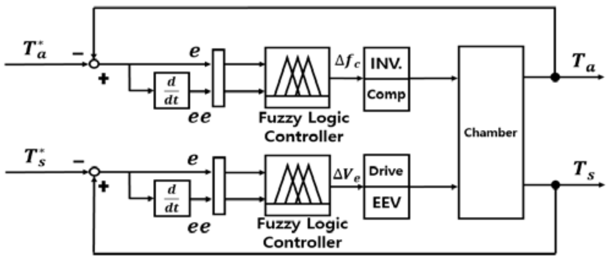


Fig. 2 Conceptual diagram of FLCs for the VSRS

The FLCs have two inputs (e, ee) and single output which is frequency Δf_c and opening angle ΔV_e on each FLC. Thus, three fuzzy sets for each FLC are needed to transform the values between the crisp value and the membership value. Input variables of each FLC are control error e and its error change rate ee. The output variables of each FLC are frequency Δf_c and opening angle ΔV_e for controlling the inverter and the EEV drive respectively. The symbol Δ represents the increment value of each output variable during sampling time. In the FLCs, the membership values are transformed from the crisp values of e and ee. In the inference process, input membership values are inferred to output membership values with the rules that embedded in rule base by a designer. Consequently, the crisp manipulated variables, Δf_c and ΔV_e , are calculated by the centroid of gravity method which explained in (1) at the defuzzification step.

$$U^c = \frac{\sum \mu(i) b_i}{\sum \mu(i)} \quad (1)$$

where U^c is the defuzzified value which means output crisp value of the fuzzy inference. The b_i indicates the center of area of membership functions, and $\mu(i)$ represents output membership value.

Tables I and II are the rule bases for controlling the chamber temperature T_a and superheat T_s. They are usually designed by expert's knowledge and surface diagram analysis. The membership functions of the input and output variables used the evenly-distributed triangles of the general form with seven fuzzy numbers.

TABLE I
RULE BASE FOR COMPRESSOR CONTROL

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

TABLE II
RULE BASE FOR EEV CONTROL

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

C. Main Design Factors of FLC

The error $e(= T^* - T)$ and error change rate $ee(= \Delta e/t_s)$ are investigated as main design factors of the FLC. Since ee is defined as $\Delta e/t_s$, the sampling time t_s is also dealt with a design factor in this paper. The membership range of ee is designed considering Δe variation during specific sampling time.

At the early design stage, the ranges of membership functions for the input and output variables, especially their limit values, should be determined before the next design step. Obviously, those limits inevitably have some influence on control performance. Unfortunately, the decision for the limit values also depends on expert's knowledge and experiences.

In this paper, the upper and the lower limits of the membership functions of the input variables e, ee and the output variables $\Delta f_c, \Delta V_e$ can be empirically selected from static characteristic experimental data. The data offer very useful information between manipulated variables and controlled variables.

Fig. 3 shows the experimental data, and Fig. 4 indicates the membership functions of input and output for controlling the T_a, T_s based on Fig. 3. The output value of the fuzzy controller is calculated by using the membership functions in Fig. 4 and the rule bases in Tables I and II. The Mamdani's min-max method is applied for the inference. Thus, the minimum value is selected for the input fuzzification and the maximum value is chosen for the output fuzzification.

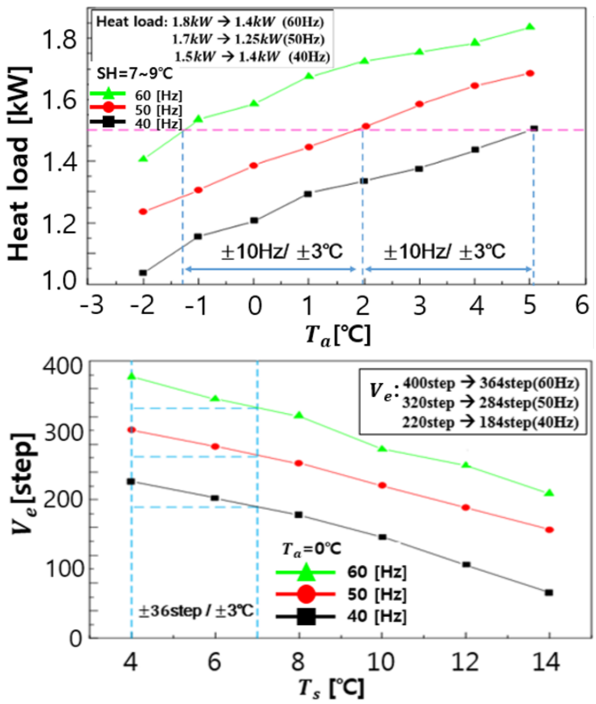
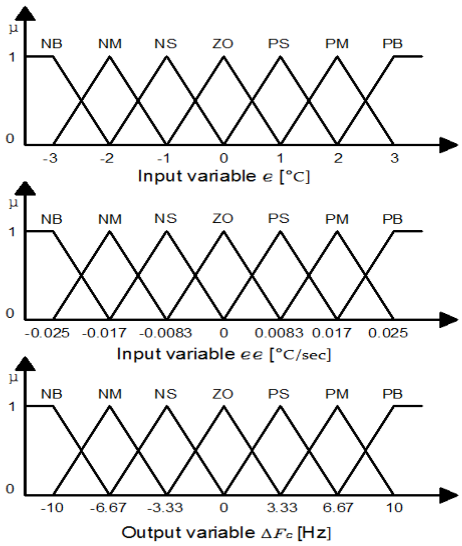
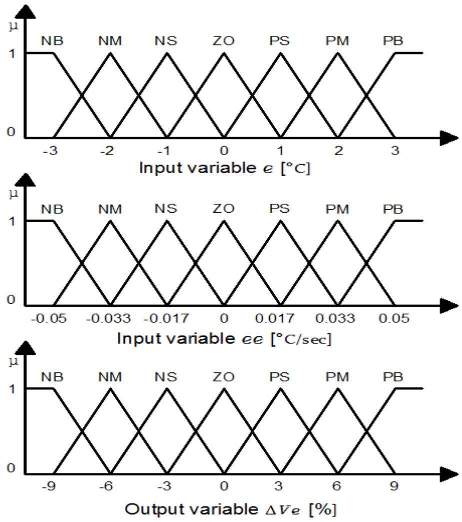


Fig. 3 Static characteristic data by experiments



(a) Compressor



(b) EEV

Fig. 4 Membership functions for the FLC

III. The Results of Simulation and Experiment

Table III shows specifications of the test unit for the VSRS. Figs. 5 and 6 show control block diagrams for the simulations and experiments.

TABLE III
Specifications of the Test Unit

Item	Type/Spec.	Value	Unit
Compressor	Vertical	1.5	kW
Condenser	Fin-tube	4	kW
Evaporator	Fin-tube	0.79	kW
Refrigerant	R-22		
Chamber	120×700×1650		mm
Inverter	PWM, V/f=const.	1.5	kW
EEV drive	In/Out voltage/DC	12	V

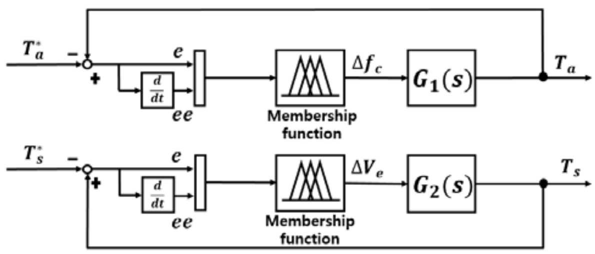


Fig. 5 Control block diagram for simulations

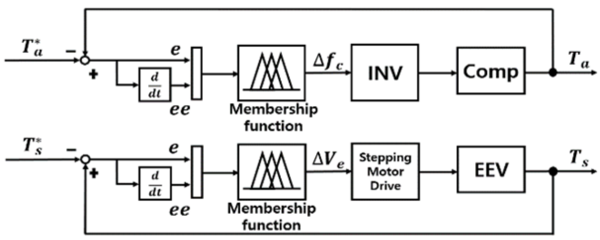


Fig. 6 Control block diagram for experiments

In Fig. 5, $G_i(s)\,(i=1,2)$ is the transfer function of the compressor and EEV achieved by the dynamic characteristics tests. Equations (2) and (3) are the $G_i(s)(i=1,2)$, respectively. In the simulations, (4) which applied the Fade approximation was used instead of (3).

$$G_1(s) = \frac{\Delta T_a}{\Delta f_c} = \frac{-0.42}{680s+1} \tag{2}$$

$$G_2(s) = \frac{\Delta T_s}{\Delta V_e} = \frac{-0.38}{57s+1} e^{-16s} \tag{3}$$

$$G_2(s) \approx \frac{-0.38s-0.0475}{57s^2+8.125s+0.125} \tag{4}$$

Fig. 7 presents the hardware configuration for experiments. The PLC was used as a controller to store each set value and compute the output value from the error information which detected by sensors and fuzzy control logic. The reference value of chamber temperature T_a was set to 4 °C, the superheat T_s was set to 6 °C, and the initial temperature value was set as 28 °C in the simulations and experiments.

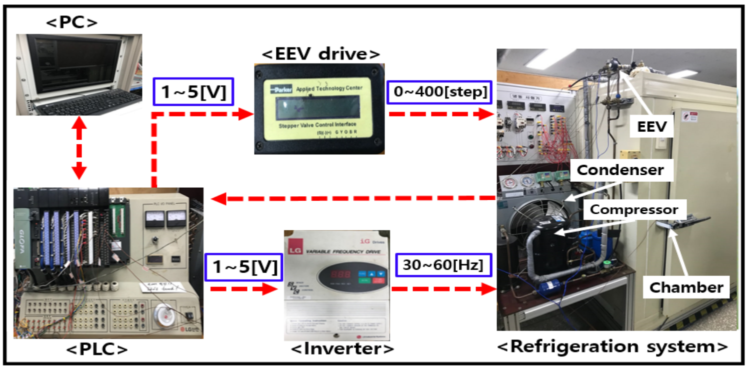


Fig. 7 Hardware configuration for experiments

Table IV shows testing ranges of design factors for simulations and experiments. In the simulations and experiments, the influences of the main design factors e, ee and t_s on the control performance are inspected in detail. The other design factors were fixed to the criterion values when one factor is being tested.

TABLE IV
RANGES OF DESIGN FACTORS FOR SIMULATION & EXPERIMENT

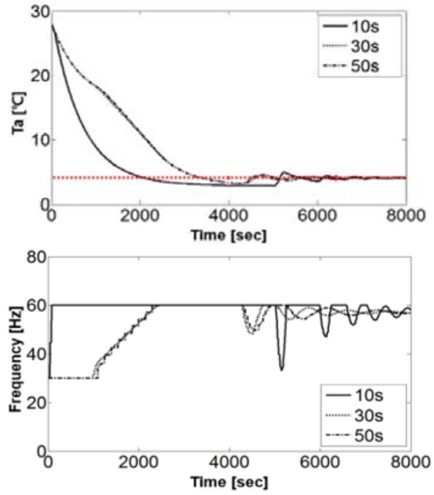
Item	t_s	e	ee	etc.
	10	±1	±0.0125	-
T_a	30	±3	±0.025	criterion
	50	±5	±0.0375	-
	10	±1	±0.025	-
T_s	30	±3	±0.05	criterion
	50	±5	±0.075	-

Figs. 8 and 9 present behaviors of T_a and T_s obtained by the simulations and experiments when the sampling time t_s is set as 10s, 30s, and 50s. Both Figs. 8 and 9 showed that the response of T_a, T_s reached the target value within small steady-state error in any case of the sampling time. In addition, the settling time was the shortest in the case of 10 s. However, the other two cases had similar response speed. This is because under the same Δe, the shorter the value of t_s then the value of ee will be larger. Accordingly, the total manipulated variables become a very large value. On the other hand, when the sampling time is larger than a specific value, the effect of the ee is almost negligible because the manipulated variables become very small.

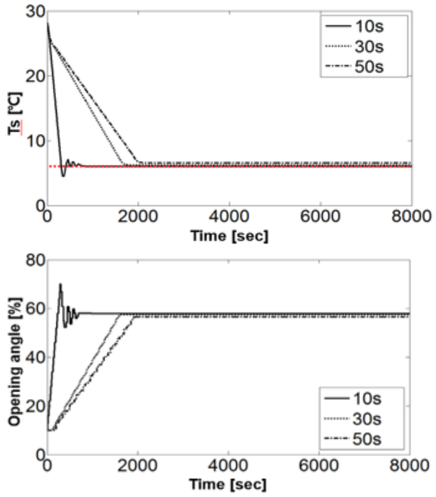
Figs. 10 and 11 represent the responses of T_a, T_s and the variation of manipulated variables according to the change of e range. The convergence rate of T_a and T_s is hardly affected by the range of membership function of e. That is because in all three cases, the difference between the initial value and the target value is very large so that the manipulated variables instantly reach the lower limit and the upper limit. In the vicinity of the steady-state of T_a, the smaller the value of e, then the sensitivity to the error will be greater. However, it can be seen that there is hardly influential on the response of T_a.

Figs. 12 and 13 present the results of simulation and experiment. These two figures indicate the responses of the controlled variables and the behaviors of the manipulated variables according to the change of ee range. It can be seen that the responses of T_a and T_s reach the target value rapidly as the range of ee increases. This is because the manipulated variable increases proportionally to the range of ee increase. The probable reason of a small steady-state error in the responses of T_a and T_s is the design value of the rule base and the evenly-distributed setting of the membership functions. This problem can be solved by applying the unevenly-distributed membership functions around the fuzzy number 'ZO' and fine adjustment of the rule base [1].

All of Figs. 8-13 were simulated and experimented under the same conditions. Comparing the results, responses of the MATLAB simulations and the experiments were almost identical in all three cases. Therefore, simulation results and experimental results were verified to be general and reasonable.

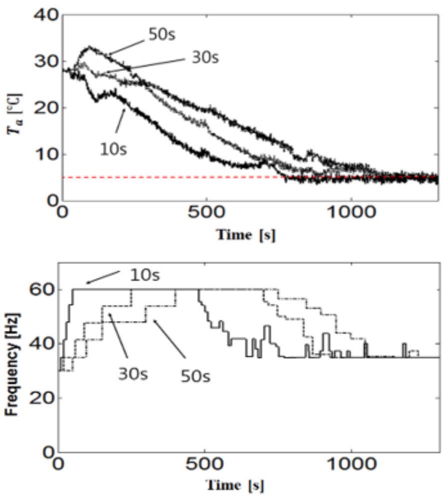


(a) Chamber temperature and its control input



(b) Superheat and its control input

Fig. 8 Effect of sampling time in simulation



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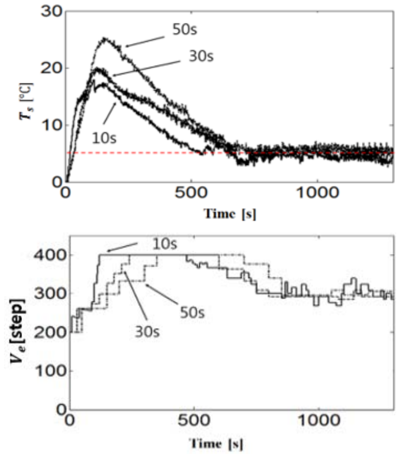

(b) Superheat and its control input

Fig. 9 Effect of sampling time in experiment

IV. Conclusion

In this paper, the influences of the main design factors which are the ranges of the membership functions and sampling time on control performance were examined in detail for the systematic design of the fuzzy controller for VSRS which is the typical nonlinear system. The criterion value and two different values on each membership function range were tested in simulation and experiment. The results showed that the upper and the lower limit values of the membership function can be designed from the data obtained by the static characteristics experiment. The main results achieved from the simulation and experiment are summarized as follows.

(1) The shorter the sampling time t_s causes the abrupt increment of the manipulated variables, the response of the T_a and T_s quickly reaches the target value. However, there was almost little change in response in the case of long sampling time. In addition, it did not affect the steady-state response.

(2) The range of the error e did not significantly affect the transient response of the T_a and T_s due to the rapid saturation of the manipulated variables. However, the smaller the range of e, then the sensitivity to the error will be greater. Therefore, it results in a slight oscillation of the manipulated variables near the steady-state.

(3) The convergence rate of the controlled variables T_a, T_s became faster because the larger the range of ee, then the magnitude of the manipulated variables will be larger. As a result, the transient characteristics were improved. However, Δe is extremely small in the steady-state, so it did not affect the response-characteristics.

(4) The simulation results and experimental results showed a very consistent tendency. Therefore, the effect analysis of fuzzy logic controller design factors discussed in this paper is reasonable.

The results of this study are expected to be very useful for the systematic membership functions determination in fuzzy logic controller design.

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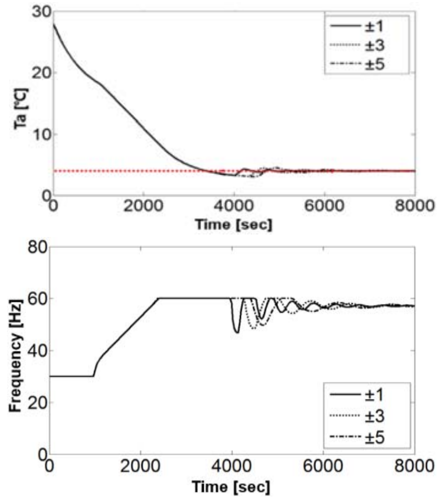
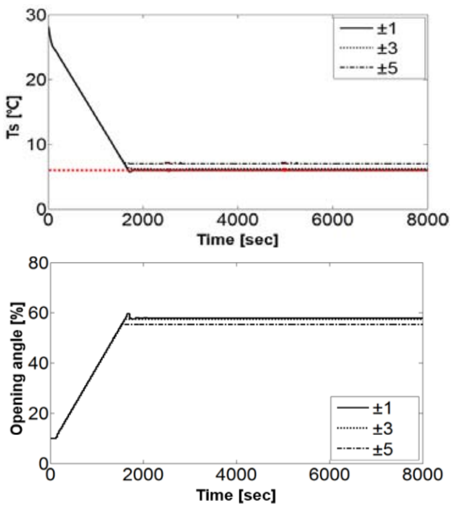
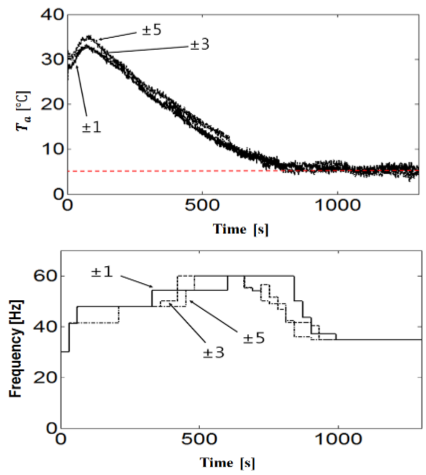


(a) Chamber temperature and its control input

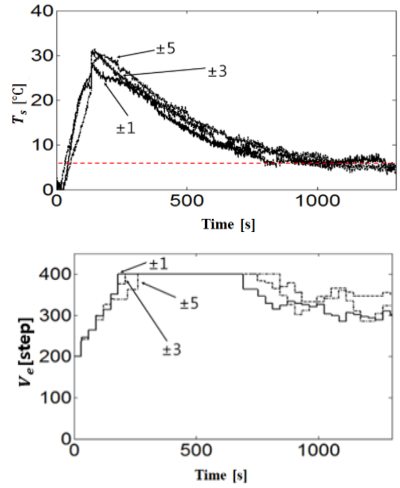


(b) Superheat and its control input

Fig. 10 Effect of e in simulation

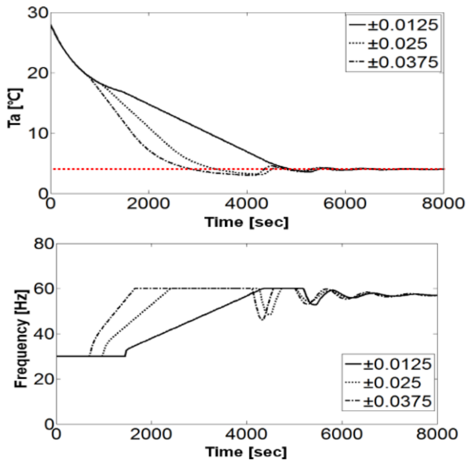


(a) Chamber temperature and its control input

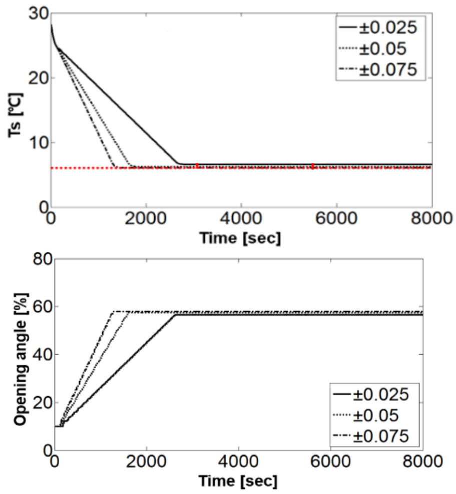


(b) Superheat and its control input

Fig. 11 Effect of e in experiment

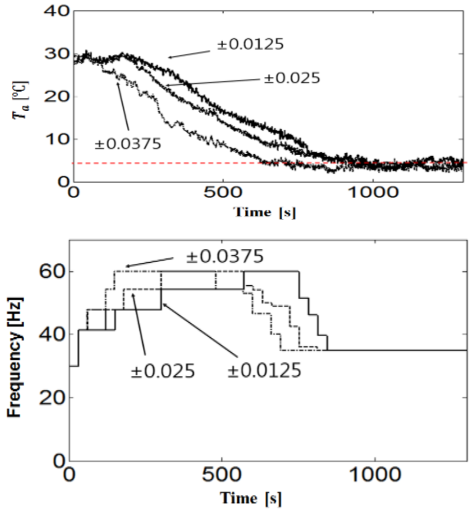


(a) Chamber temperature and its control input

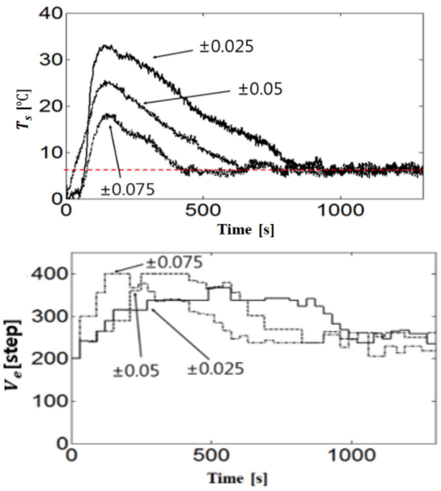


(b) Superheat and its control input

Fig. 12 Effect of ee in simulation



(a) Chamber temperature and its control input



(b) Superheat and its control input

Fig. 13 Effect of ee in experiment

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