PI Control with the Smith Predictive Controller for a Variable Speed Refrigeration System

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ABSTRACT: In this paper, we suggest PI control with the Smith predictive controller to improve transient response of a variable speed refrigeration system (VSRS). As the refrigeration system has long dead time inherently, it is difficult to get fast responses of superheat and reference temperature. We incorporated the Smith predictive controller into PI to compensate the effect of the long dead time of the system. At first, we introduced the decoupling model of the system to control capacity and superheat simultaneously and independently. Next, we designed the predictive controller of the superheat based on PI control law. Finally, the control performance by the proposed method was investigated through some numerical simulations and experiments. The results of the simulations and experiments showed that the proposed PI control with the predictive controller could obtain acceptable transient behaviour for the system.

Nomenclature

Δ	: variation
f	: compressor frequency [Hz]
SH	: evaporator superheat [℃]
T_a	: chamber temperature [℃]
T_{ei}	: input temperature of evaporator [℃]
T_{eo}	: output temperature of evaporator [℃]
VO	: opening angle of EEV [%]
E	: error
C_i	: PI controller
G_i	: transfer function
K_p	: proportional gain
K_i	: integral gain
u	: output of PI controller
s	: complex variable

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1. Introduction

Recently inverter-driven refrigeration system, so called "variable speed refrigeration system(VSRS)", is becoming more popular. Therefore, some studies about practical dynamic model and control design methodology of the system for obtaining high control performance and saving energy have been reported.[1-10]

The conventional control schemes of the VSRS have been mainly focused on two representative control variables i.e. the degree of superheat and temperature of chamber. The superheat has been controlled by an expansion device, and it plays an important role to reduce evaporating pressure and to regulate the refrigerant mass flow rate. The superheat is controlled as a certain constant value by adjusting opening angle of an electronic expansion valve (EEV) to improve coefficient of performance (COP) of the system even though thermal load and reference temperature are changed. On the contrary, the temperature of chamber is controlled by adjusting compressor speed, and it is called capacity control. The capacity control is basically conducted to respond to partial loading conditions on the purpose of energy saving.

In the VSRS, the capacity and the superheat could not be controlled independently because of existence of interfering loops between the two control variables.(1-3) The loops made systematical PID controller design very difficult. Furthermore, they are a drawback to get satisfactory transient characteristics in the VSRS which had adjustable control references.

Li et al. suggested the independent control method based on general PI control law and the decoupling model to control the capacity and the superheat simultaneously.(4,5) It aimed at precise control of the two control variables under the assumption that we can get practical model of the system from experiments.

Li et al. also proposed the Fuzzy control with a compensator to cope with difficulty for modeling of the system.(6,7) It could be realized without a complicated dynamic model of the system. Furthermore fairly good control performance comparing to PI were established by it. Therefore, it was possible to choose an appropriate control methodology to meet specific control design requirements.

However, it is difficult to obtain satisfactory quick response of them until now even though we utilize model based the PI due to the inherent long dead time of the variables.(8-10) Hence, in this paper, we will design the Smith predictive controller based on the PI and the decoupling model to overcome this problem. Actually, the proposed controller can be applied to the two control variables in the same way. However, the chamber temperature is negligible

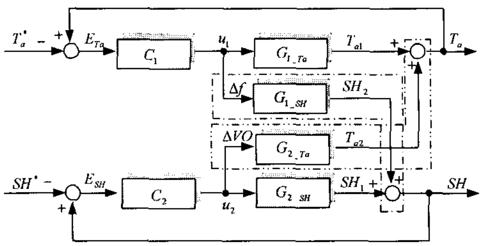


Fig. 1 The control block diagram of VSRS with interfering loops.

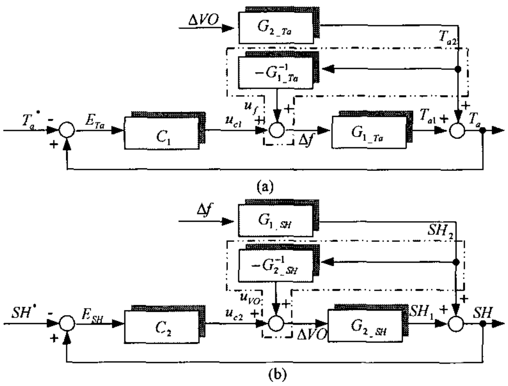


Fig. 2 Block diagram of decoupling control of VSRS.

from compensation because the ratio of dead time to its time constant is considerably small.

2. Superheat control by PI with the Smith predictive controller

Fig. 1 shows a block diagram of the VSRS to control the superheat $SH(= T_{eo} - T_{ei})$ and chamber temperature T_a simultaneously. Here, $C_i(i = 1, 2)$ shows controllers and G_i means transfer function in complex domain. $G_{1\_T_a}$ represents the transfer function between the chamber temperature and the compressor speed, and G_{1_SH} is the transfer function between the superheat and the compressor speed. Also, $G_{2\_T_a}$ represents the transfer function between the chamber temperature and the opening angle of

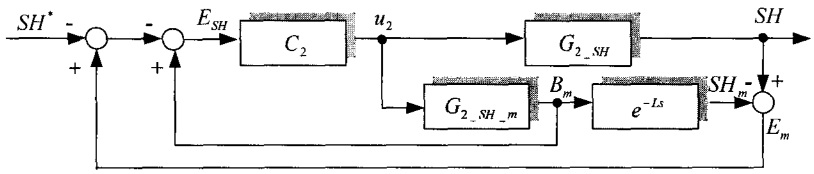


Fig. 3 Block diagram of superheat control with the Smith predictive controller.

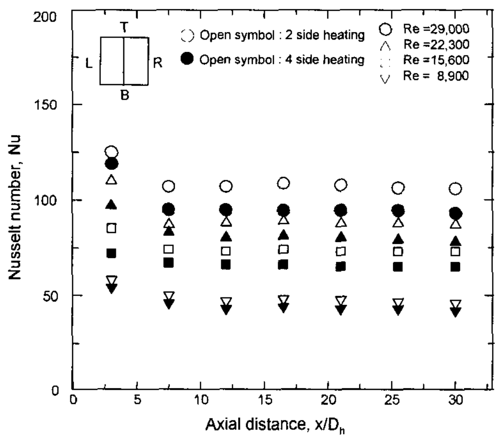


Fig. 4 Local Nusselt numbers.

EEV. G_{2_SH} is the transfer function between the superheat and the opening angle of EEV. The variation of inverter frequency(Δf) to control T_a has an effect on SH and the variation of opening angle of EEV(ΔVO) to control SH also interferes with chamber temperature T_a. Hence, only one of them has been controlled due to the interfering loops illustrated inside the dotted line. Because of the coupling characteristic of the VSRS, the capacity and the superheat were not controlled independently and simultaneously.

Fig. 2 indicates a decoupling model to solve interference problem. It is noted here that Fig. 2 does not have any interfering loops. Also, each influence of operating variables such as the variation of opening angle EEV and the variation of compressor frequency is reflected to their reference input side feedforwardly. The transfer functions of T_a and SH from their references to their responses in Fig. 2 can be given as $T_a/T_a^* = -C_1G_{1\_Ta}/(1-C_1G_{1\_Ta})$ and $SH/SH^* = -C_2G_{2\_SH}/(1-C_2G_{2\_SH})$. It is noted here again that the presented decoupling model does not have the interfering loops as shown in Fig. 1.

We supposed the transfer functions in Fig. 2 as first-order model with dead time. And they were obtained by some experiments. A set of Eq. (1)~Eq. (4) shows each transfer function in Fig. 2.

$$G_{1\_T_a} = \frac{\Delta T_a}{\Delta f} = \frac{-0.42}{1+680s} \tag{1}$$

$$G_{1\_SH} = \frac{\Delta SH}{\Delta f} = \frac{-0.47}{1+780s} - \frac{-0.15}{1+30s}e^{-25s} \simeq \frac{-131s^2+7.6s-0.026}{23400s^3+2682s+65.8s+0.08} \tag{2}$$

$$G_{2\_SH} = \frac{\Delta SH}{\Delta VO} = \frac{-0.38}{1+57s}e^{-16s} \tag{3}$$

$$G_{2\_T_a} = \frac{\Delta T_a}{\Delta VO} \simeq 0 \tag{4}$$

In Eq. (3), the transfer function G_{2_SH} has long dead time. Since G_{2_SH} is a main target plant to control SH, we just focused on improvement of transient behaviour of the superheat in Eq. (3).

It is well known that the Smith predictive controller is suitable for controlling the system which has long dead time. It is used to compensate long dead time effectively using modelling techniques. It is needed that the nominal model of the system is to be the same as real plant to apply the controller to the real system. Therefore, we consider the parameter sensitivity of the nominal model in simulation.

In this paper, we prove that the Smith predictive controller makes the transient response of the superheat fast through some numerical simulations and experiments.

Fig. 3 shows block diagram of superheat control with the Smith predictive controller. Here, G_{2_SH} means real plant and $G_{2\_SH\_m}$ is the nominal model described the transfer function without the dead time term e^{-Ls}. In the minor loop, B_m is returned to input side instead of SH. It provides quick compensation without dead time. If the real plant and the nominal plant including dead time are the same, SH will be also the same as SH_m. However, they are usually not the same in a practical system. Hence the difference between SH and SH_m is returned to the input side for compensating control error.

Fig. 4 gives a modified equivalent block diagram to Fig. 3 for numerical simulations and experiments. Here, it is supposed that the nominal plant is equal to the real plant as G_{2_SH}. Superheat SH_{sm} is computed from the opening angle ΔVO (output of PI controller C_2) and G_{sm}. Then, the feedback value $\widetilde{SH}$ is calculated from subtracting system output SH from SH_{sm}. Finally, superheat error value E_{SH} is calculated from subtracting the superheat set value SH^* from $\widetilde{SH}$. E_{SH} is an input value of a PI controller.

Eq. (5) indicates the transfer function of the Smith predictive controller derived from Eq. (3).

$$G_{sm}(s) = \frac{-0.38}{1+57s}e^{-16s} - \frac{-0.38}{1+57s} \tag{5}$$

Eq. (5) can not be applied to the controller in Fig. 2(b) directly. So, it is converted into Eq. (6) by the Pade first-order approximation.

$$G_{sm} \cong \frac{-0.38}{1+57s} \times \frac{1-8s}{1+8s} - \frac{-0.38}{1+57s} \tag{6}$$

Eq. (7) is obtained from the Laplace inverse transform of Eq. (6).

$$g_{sm}(t) = \mathcal{L}^{-1}[G_{sm}(s)] = -0.008844e^{-0.0175t} + 0.01551e^{-0.125t} + 0.006667e^{-0.0175t} \tag{7}$$

Applying the Taylor first-order approximation to Eq. (7), Eq. (8) is derived.

$$g_{sm}(t) \cong 0.0133 - 0.019t \tag{8}$$

Considering that the control including compensation Eq. (8) is realized by digital devices such as programmable logic controller(PLC), the variation of the opening angle can be expressed as Eq. (9) in discrete system.

$$\Delta VO(n) = VO(n) - VO(n-1) \tag{9}$$

When the sampling time is T_s, Eq. (10) can be calculated as predictive value to compensate dead time effect during the sampling time.

$$g_{sm}(T_s) = 0.0133 - 0.0019T_s \tag{10}$$

Hence, we can obtain predictive value SH_{sm} in Fig. 4 from multiplying Eq. (9) by Eq. (10).

3. Numerical simulations and experiments

Fig. 5 shows a schematic diagram of experimental system, and Table 1 represents the specification of a test unit of the system. The experimental system is composed of basic refrigeration cycle and control system. The main components of the control system are the inverter, the step valve control interface and the PLC in the listed on the Table 1.

The compressor of the basic refrigeration cycle is driven by the induction motor with a

Table 1 Specification of a test unit

Compressor	Type	Vertical, Reciprocating	Inverter	Type	PWM, V/f = const.
	Power	220V, 60Hz, 1.5kW, Φ3		HP	2
Condenser	Type	Fan fin type	Step valve control interface	Input	DC 12V
	Capacity	3450 ㎉/h		Input signal	1~5V DC or 4~20㎃
Evaporator	Type	Fin-tube type		Output	0~400 step
	Capacity	680 ㎉/h	PLC	D/A unit	16 CH.
Expansion valve device	Type	EEV		PID unit	16 Loop
	Range	0~506 pulse		TC unit	16 CH.
	Rated voltage	DC 12V		CPU	GM2
Refrigerant	Type	R22	Chamber	Size	1200 x 700 x 1650[㎣]

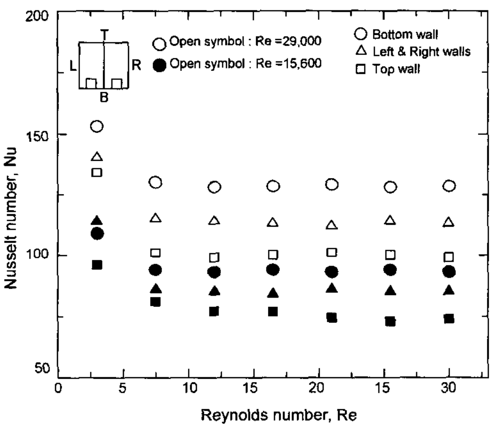


Fig. 5 Local Nusselt numbers in the 4 side heating channel.

general V/f constant control type inverter. The stepper motor to drive EEV was operated by a step valve control interface. The input control signal of inverter and the step valve control interface is obtained from a special D/A unit of the PLC. The PI control is also performed by the PID unit of the PLC. All temperatures were measured by T-type thermocouples. The temperature information is transmitted to a TC (ThermoCouple) unit of the PLC on real time.

Fig. 6 shows one of the numerical simulation results, step response of the superheat, when the proportional and the integral gain are optimum conditions. The PI gain with the predictive controller should be retuned by iteration manner. It can be seen that the significant response differences in settling time between simple PI controller and the PI plus predictive controller is existed. It is clear that the predictive controller can progress the transient behaviour so called an indicial response of the superheat in spite of its inherent long dead time.

Fig. 7 provides simulation results about parameter sensitivity analysis. The three kinds of parameters of the model i.e. the DC gain, the time constant, and the dead time in Eq. (3) were investigated to analyze sensitivity. Each parameter was supposed that it has ±10% errors from its real value. From these analysis, we can estimate that the predict controller can be applied to the real system if the nominal model has errors within ±10% comparing to real plant. Because the maximum overshoot was approximately 10% in Fig. 7(c), and it was considered allowable value. It is noted here that the only one parameter among three parameters was varied from its real value in this sensitivity analysis.

Fig. 8 and Fig. 9 indicate experimental results to verify improvement of transient response of the superheat by the predictive controller.

Fig. 8(a) represents the superheat response according to variation of thermal load in the chamber based on PI. The PI gain was set up 4 and 0.07 respectively. The thermal load was

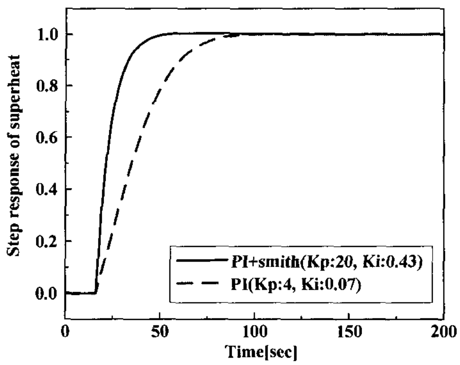
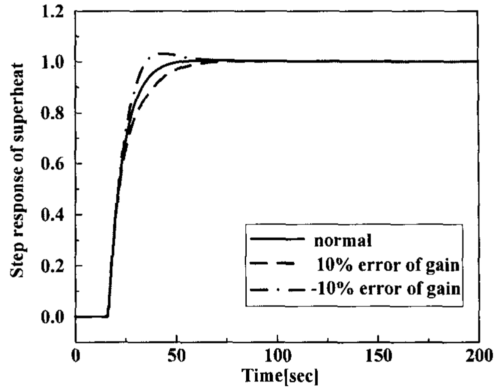


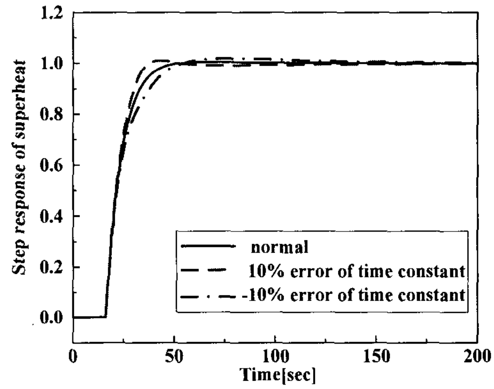
Fig. 6 The comparison of superheat response between PI controller and PI+smith controller.

changed abruptly from 1.57kW to 2.05kW at 100 second point of time signed two dotted line. The superheat was increased during a couple of time and it remained consistent value during a few times. Then, the superheat got close to the reference superheat temperature 6 ℃. Fig. 8(b) indicates the variation trend of opening angle according to the variation of thermal load in Fig. 8(a). After change of thermal load, the opening angle was increased during a couple of time and converged to a certain value i.e. 52. 5%.

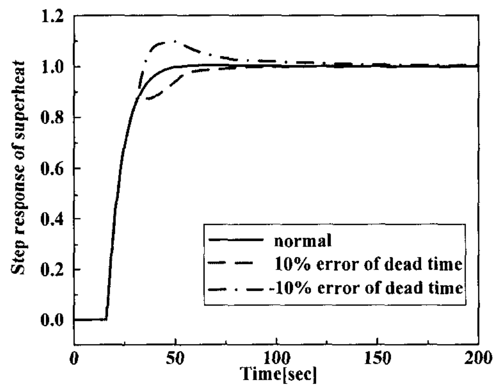
Fig. 9 shows the superheat response based on the PI with the smith predictive when the thermal load was varied. The solid line presents experimental result and the dash line shows simulation result. The experimental result coincided with the simulation result. Fig. 9(a) depicts the superheat response according to the variation of thermal load in the chamber based on the PI with the Smith predictive controller. The PI gain was set up 8 and 0.1 respectively. After change of thermal load, the superheat was increased during a couple of time and it decreased near at 700 second and got close to the reference superheat temperature 6 ℃ near at 1400 second. It was shown that the increasing range of the superheat was smaller than Fig. 8(a). Also, the response quickly converged to the reference input. Fig. 9(b)



(a) sensitivity with regard to DC gain



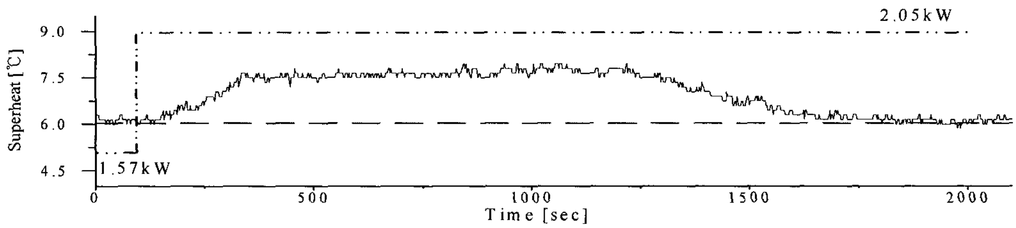
(b) sensitivity with regard to time constant



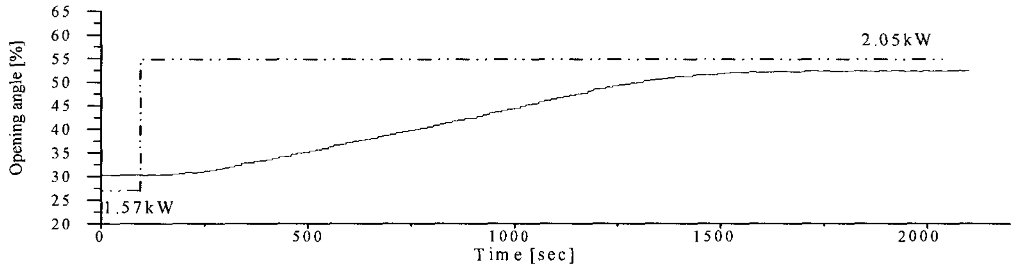
(c) sensitivity with regard to dead time

Fig. 7 Parameter sensitivity analysis.

represents the variation of opening angle according to change of thermal load in Fig. 9(a). The entire trend of Fig. 9(b) is similar to Fig. 8(b). However the increasing rate of the open-

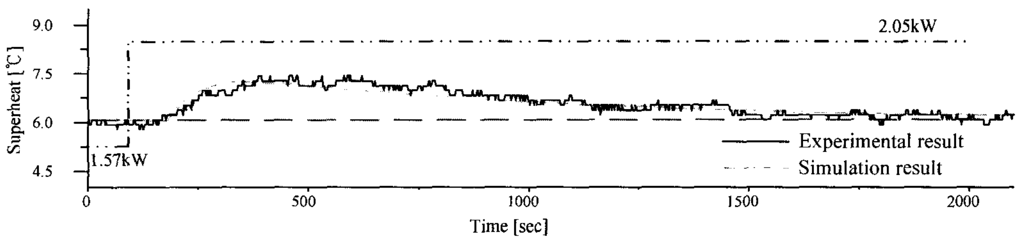


(a) the response of superheat

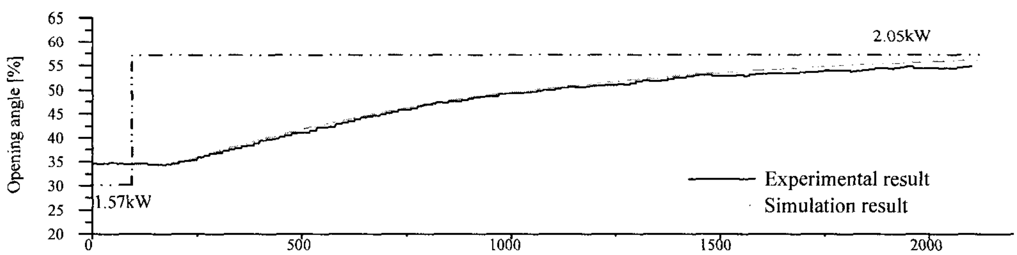


(b) the opening angle of EEV

Fig. 8 The response under the change of thermal load based on PI without the smith predictive controller (K_p : 4, K_i : 0.07).



(a) the response of superheat



(b) the opening angle of EEV

Fig. 9 The response under the change of thermal load based on PI with the smith predictive controller (K_p : 8, K_i : 0.1).

ing angle at right after thermal load change is larger than Fig. 8(b) on account of compensation by the predictive controller. Consequently quick response of the superheat in Fig. 9(a) was obtained.

Comparing Fig. 9(a) to Fig. 8(a), we know that the transient response of the superheat by the PI controller with the Smith predictive controller is better than the one of by general PI controller. Also, from the results of simulations and experiments, we knew that retuning of PI with the smith predictor was necessary.

4. Concluding remarks

In this paper, we suggested a method to improve transient response of the superheat which has inherent long dead time. The Smith predictive controller was incorporated into general PI control based on the decoupling model. Also, we performed parameter sensitivity analysis about the nominal model to investigate application possibility of the controller to real system. From some results of simulations and experiments, the availability of the predictive controller in the VSRS was successfully confirmed. It is expected that the suggested Smith predictive controller can contribute to improve COP of the VSRS.

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