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# The Control of Superheat and Capacity for a Variable Speed Refrigeration System Based on PI Control Logic

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**Key words**: Variable speed refrigeration system(VSRS), PI control, Superheat, Capacity control, Coefficient of performance(COP), Decoupling model, Feedforward compensator

**ABSTRACT**: In this paper, we suggest the high efficient control method based on general PI control law for a variable speed refrigeration system. In the variable speed refrigeration system, the capacity and the superheat are mainly controlled by an inverter and an electronic expansion valve, respectively, for saving energy and improving coefficient of performance. Thus, we proposed a decoupling model to eliminate the interfering loop between the capacity and superheat at first. Next, we designed PI controller to control the capacity and superheat independently and simultaneously. Finally, the control performance was investigated through some experiments. The experimental results showed that the proposed PI controller based on the decoupling model can obtain good control performance under the various control references and thermal load.

## Nomenclature

$\Delta$ : 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 [%]
$d$ : disturbance
$E$ : error
$C_i$ : PI controller
$G_i$ : transfer function
$K_p$ : proportional gain
$T_i$ : integral time [s]
$u$ : output of PI controller
$s$ : complex variable
$t$ : time [s]

## 1. Introduction

The applications of inverter refrigeration system for commercial and residential purpose have been increased widely owing to their saving energy and progress in comfort. It is inevitable to design practical controller in order to control the variable speed refrigeration system (VSRS) for the purpose of saving energy and establishing high efficiency. A basic refrigeration cycle is composed of a compressor, heat exchangers and an expansion valve. Components of the cycle are deeply connected with pipes each other and have inherent nonlinearity.(1-3) Hence, it is not easy to design a suitable controller for the

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system.

The conventional control schemes of the VSRS are mainly focused on representative two controlled variables, superheat and capacity. 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 the electronic expansion valve (EEV) to improve coefficient of performance (COP) of the system. The capacity control is basically conducted to respond partial loading conditions on the purpose of energy saving. Usually, refrigeration machines operate under the partial loading conditions, conventional on/off control of a compressor for responding partial load influences to the compressor durability because of frequent switching actions. Therefore, the on/off control system is now gradually replaced by a VSRS with an inverter driven compressor.

In the VSRS, the capacity and superheat can not be controlled independently because of an effect of interfering loops when the compressor speed and EEV opening angle are varied. The loops make systematical PID controller design very difficult. Furthermore, they are a drawback to get good transient characteristics in VSRS which has adjustable control references.

Choi et al.(4) suggested a superheat control method for variable speed heat pump system. The compressor frequency in the method was determined by an empirical equation which was obtained by the regression analysis. Therefore, it is inevitable to have fairly large steady state errors as far as the system is based on the empirical model. Also, they expressed the transfer function from EEV opening angle to superheat as the first-order system with dead time, and designed PI controller with feedforward to control superheat. However, as the capacity control considered only the steady state, the superheat control had very big overshoot and undershoot.

To overcome this problem, we suggest the independent control method based on general PI control law and an decoupling model to control capacity and superheat simultaneously in this paper. Thus, we propose the decoupling model to eliminate the interfering loop at first. Each transfer function in this model is obtained from number of experiments. Next, we design PI controller based on the decoupling model. Finally, we will show some experimental results which can prove good control performance of the proposed control system.

## 2. Decoupling model

Fig. 1 shows a block diagram of a refrigeration system which has interfering loops inside the dash dot and the dash two dot lines. Controlled variables are chamber temperature $T_a$ and the superheat $SH$ which is the temperature difference of refrigerant between outlet and inlet of an evaporator. Here, $C_i(i=1,\ 2)$ means PI controller and $G_i(i=1\sim4)$ represents transfer function of the system. Because of the coupling characteristic of the refrigeration system, the capacity and superheat were not controlled independently.

Fig. 2 shows a decoupling control model proposed in this paper. It is noted here that Fig. 2 does not have any interfering loops and each influence of operating variations such as varia-

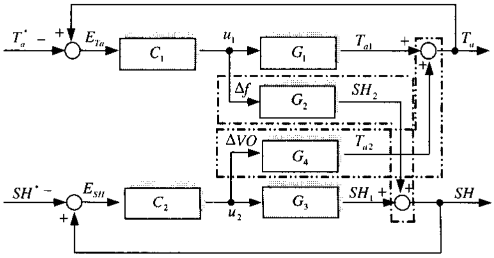
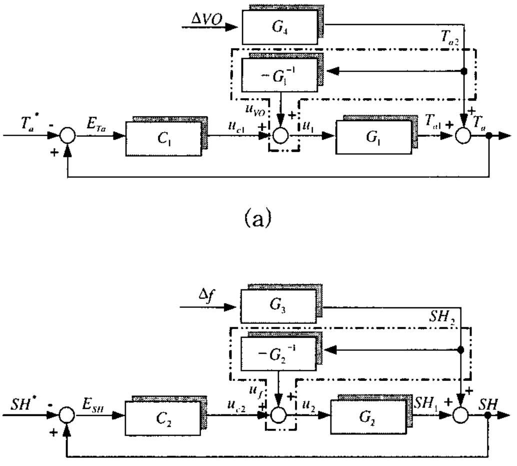


Fig. 1 The control block diagram of VSRS with interfering loop.



(a)

(b)

Fig. 2 Block diagram of decoupling control for VSRS.

tion of EEV opening angle $\Delta VO$ and compressor frequency $\Delta f$ are reflected to their reference input side with feedforward manner.

Outtagarts supposed the transfer function of superheat as the first-order model with dead time.(5) Some researches(6-9) have proved that the variation of room temperature according to the compressor speed and the variation of superheat with respect to the opening angle of EEV could also be expressed as the first-order model with dead time. Hence, the transfer function $G_i$ in Fig. 2 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. (1) ~Eq. (4).

$$G_1 = \frac{\Delta T_a}{\Delta f} = \frac{-0.42}{680s+1} \tag{1}$$

$$G_2 = \frac{\Delta SH}{\Delta f} = \frac{-0.47}{780s+1} - \frac{-0.15}{30s+1}e^{-25s} \tag{2}$$

$$G_3 = \frac{\Delta SH}{\Delta VO} = \frac{-0.38}{57s+1}e^{-16s} \tag{3}$$

$$G_4 = \frac{\Delta T_a}{\Delta VO} \tag{4}$$

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

## 3. Experimental results

Fig. 3 shows a schematic diagram of experimental system, and Table 1 represents the specification of a test unit of the system. The experimental system was composed of basic refrigeration cycle and control system. The main components of control system were an inverter, a step valve control interface and a PLC (Pro-

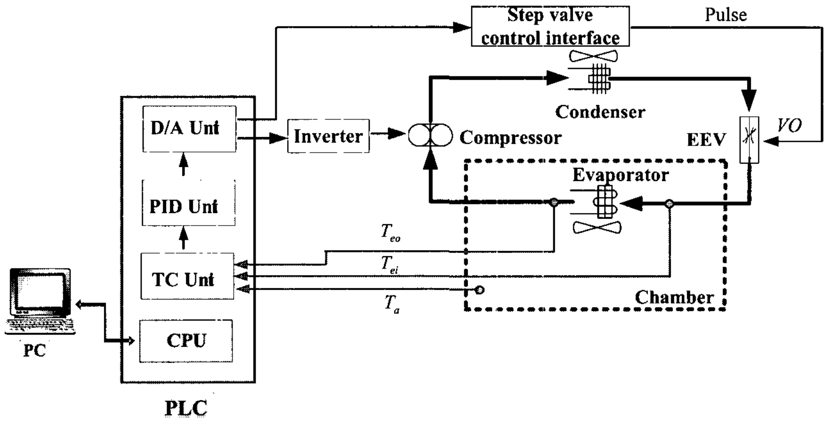


Fig. 3 Schematic diagram of the experimental system.

Table 1 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] |

grammable 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 signals of the inverter and the step valve control interface were gotten 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. The thermal load of the chamber was added by an electrical heater, and its magnitude was varied by adjusting the input voltage of the heater.

The PI controllers based on the 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. (5). The PI gains, proportional gain $K_p$ and integral time $T_i$, were tuned by the Ziegler-Nichols rules.

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^T e(t)dt] \tag{5}$$

It is desirable to control the capacity and superheat simultaneously in the VSRS. In spite of simultaneous control of them based on the conventional coupling model, good control performances such as overshoot, undershoot and settling time could not be obtained because of the effect of interference of the variation of compressor speed toward superheat. To solve this problem, we proposed PI control with a feedforward compensator of the superheat which can eliminate the influence of the interfering loop between the capacity and superheat.

The inside of dash two dot line in Fig. 2(b) indicates the feedforward compensator of the superheat. Disturbance $d(s)$ which has an effect on superheat due to the variation of compressor speed $\Delta f$ can be expressed as Eq. (6).

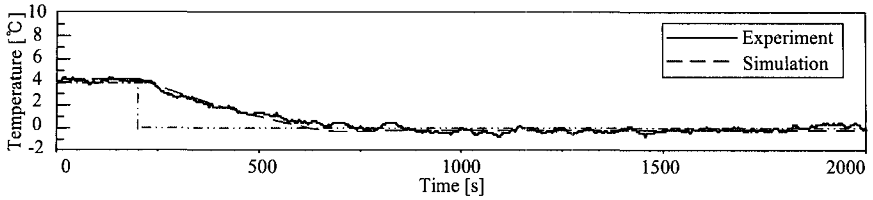
$$d(s) = G_2(s)\Delta f \tag{6}$$

To cancel the effect of this disturbance, we designed the compensator such as Eq. (7).

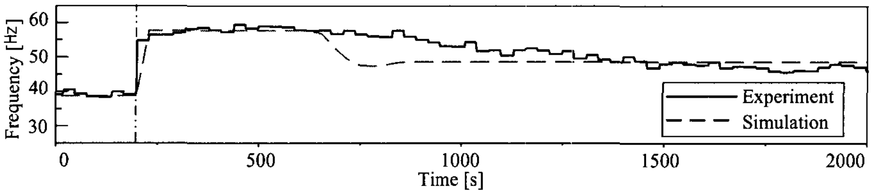
$$u_f(t) = -\mathcal{L}^{-1}[\frac{1}{G_3(s)}d(s)] \tag{7}$$

Where, $u_f$ is compensating quantity of $\Delta VO$ to remove the effect of interference of the variation of compressor speed toward superheat.

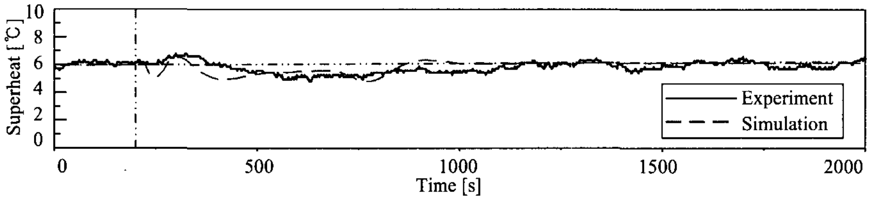
In experiments, the range of $\Delta f$ and $\Delta VO$ were set as 30~60 Hz and 10~100% respectively. Control period was 30sec for capacity and 15sec for the superheat. Also the Pade ap-



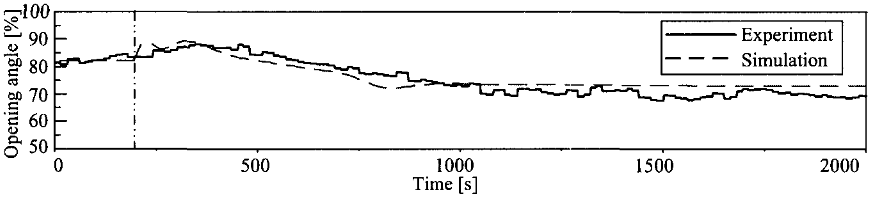
(a) The response of chamber temperature to follow $T_a$ reference



(b) The compressor frequency to follow $T_a$ reference



(c) The response of superheat

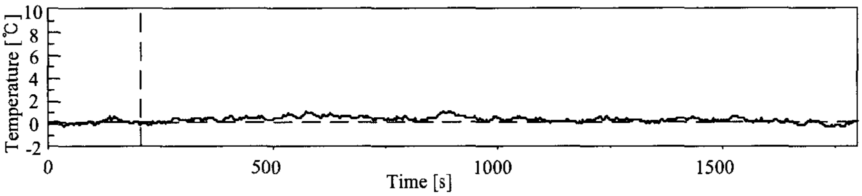


(d) The opening angle of EEV

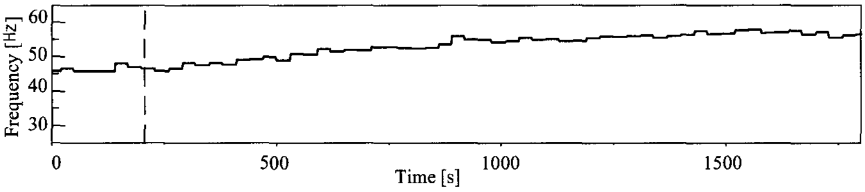
Fig. 4 The responses of chamber temperature and superheat by PI control with feedforward compensator according to the change of chamber temperature reference.

proximation and the Taylor series expansion were used to describe $G_3$ simply.

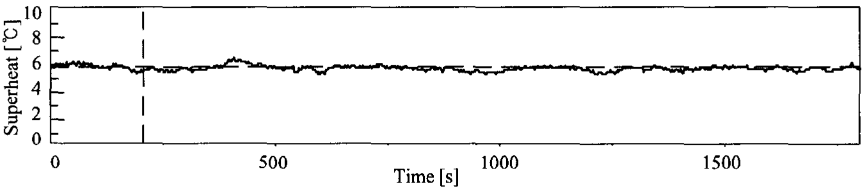
Fig. 4 describes the PI control response of chamber temperature and superheat when the chamber reference temperature was abruptly varied from 4 ℃ to 0 ℃ at 200 second. The thermal load was 1.45 kW and the superheat reference was 6 ℃. Fig. 4(a) shows the PI control response of chamber temperature when the reference was changed. It took about 400 seconds to get close set point value from change of reference. Fig. 4(b) shows the response of compressor frequency to follow the reference of chamber temperature. It can be seen that set point frequency of the compressor for controlling the capacity was very stable. Fig. 4(c) presents the PI control response of superheat according to the change of chamber temperature reference. The superheat must be controlled as a constant value even though the compressor speed and chamber temperature were varied. The percent overshoot of the superheat was about 15%, but the maximum overshoot of it was below 7 ℃. The maximum undershoot of



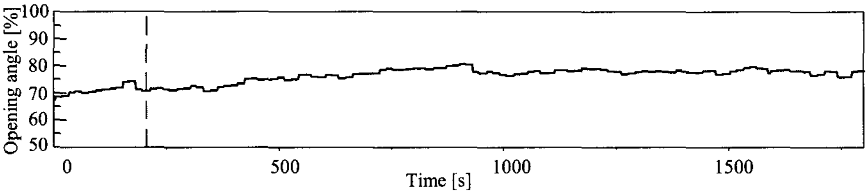
(a) The response of chamber temperature under the change of thermal load



(b) The compressor frequency



(c) The response of superheat under the change of thermal load



(d) The opening angle of EEV

Fig. 5 The responses of chamber temperature and superheat by PI control with feedforward compensator according to the variation of thermal load.

superheat was above 5 ℃. They were acceptable scope of superheat in this system. Fig. 4(d) indicates the opening angle of EEV when the PI controller was operated. The set point value of EEV opening angle was varied stably to maintain the superheat as 6 ℃.

These experimental results presented fairly good control performance and they also coincided with the simulation results which were described with dash line in Fig. 4.

Fig. 5 describes responses of chamber temperature and superheat when thermal load was varied from 1.44 kW to 1.57 kW. The chamber temperature reference was set at 0 ℃ and the superheat reference was 6 ℃. From Fig. 5(a), we found that the chamber temperature was maintained as 0 ℃ even the thermal load was varied. Fig. 5(b) shows that the compressor frequency increased to control the chamber temperature as 0 ℃ because of the increase of thermal load. Fig. 5(c) presents the PI 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. 5(d) shows the opening angle of EEV under the given thermal load. The PI control responses indicated good control performance of the capacity and superheat under various thermal load conditions.

## 4. Conclusions

In this paper, we presented the decoupling control design with PI controller to control the capacity and superheat independently and simultaneously without interfering loops on the purpose of saving energy and progress of COP. The suggested decoupling model was obtained from several experiments under various operating conditions. Then, we designed PI controller based on the decoupling model. Some experimental results show that the designed PI controller with the feedforward compensator was effective to control the VSRS.

(1) The superheat was controlled as 6 ℃ within ±1 ℃ errors when the chamber temperature reference was varied.

(2) The chamber temperature and superheat were controlled as their reference values within ±1 ℃ errors when the thermal load was varied.

It is expected that the suggested decoupling control method can establish not only precise chamber temperature control but also high COP in the VSRS.

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