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FUZZY-PID METHODS FOR CONTROLLING EVAPORATOR SUPERHEAT

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ABSTRACT

A new method is proposed to control the evaporator's superheat with an electronic-expansion-valve (EEV). The conventional PID control with invariable parameters can not receive sound performance because of the variation of evaporators' characteristic parameter under disturbances. To solve this problem, fuzzy algorithm is utilized to adjust parameters of PID control on line, two practical methods are given and both are performed in experiments. It is found that fuzzy-PID greatly reduced the time to reach steady state, the error(± 0.3℃) is much smaller than that of conventional PID, which is ± 1℃.The hardware and software of fuzzy-PID are no more complex than those of conventional PID. By use of fuzzy-PID, the control performance is improved, but the cost does not increase.

INTRODUCTION

Control of the degree of evaporator superheat is an important aspect in refrigeration system control, because it affects efficiency and safety of system directly. The performance of a controller depends on the matching of controller's characteristic to the object.To get good control effect, it is necessary to be acquainted with object's characteristic. Generally, a first-order lag plus time delay model is used to describe an evaporator, it is found that the characteristic parameters in the model alter accordingly with the variation of operating condition. With theoretical analysis and practical experiments, the evaporator's response to variation of refrigerant flow rate and load is observed. Because of its simplicity, robustness and accuracy, PID control is often used for air conditioners and refrigeration machines. But the parameters of conventional PID will not change once they have been defined. At the same time, PID is a linear control method and it can not take satisfactory effects on the highly nonlinear object. Fuzzy control does not need the accurate mathematical model of controlled object and it can also perform very well in multivariable, nonlinear and time-varying systems. But sometimes its accuracy does not meet requirement, it is only a coarse controller. In consideration of individual merits and drawbacks of them, in this paper, these two methods are combined, the fuzzy algorithm is implemented to adjust PID parameters on line in order to improve the applicability of PID.

EVAPORATOR DYNAMIC CHARACTERISTICS

Some researchers think the response of superheat to variation of refrigerant flow in an evaporator is a first-order lag process, $G(s) = \frac{K}{1+Ts}$, K and T change with evaporation temperature and refrigerant flow. Here, the evaporator is treated as a first-order lag plus time delay object, its transfer function can be expressed as:

$$G(s)=\frac{\Delta T}{M}=\frac{K\cdot e^{-\tau s}}{1+T_p s} \tag{1}$$

Where K is the evaporator gain, T_p is the time constant, τ is the delay and s is the Laplace operator. A.OUTTAGARTS observed the variation tendency of these parameters and pointed out that they are function of evaporation temperature T_e and compressor rotation speed N.[1]

In this paper, from evaporator's open-loop response to a step excitation, we can get the characteristic parameters according to Cohn-Coon formula.

$$\begin{cases} K=\Delta(\Delta T)/\Delta M \\ T_p=1.5(t_{0.632}-t_{0.28}) \\ \tau=1.5(t_{0.28}-t_{0.632}/3) \end{cases} \tag{2}$$

Where, ΔM -evaporator flow step excitation;

$\Delta(\Delta T)$ -evaporator superheat response;

$t_{0.28}$ - time for superheat to get 0.28 $\Delta(\Delta T)$ in evaporator's response curve;

$t_{0.632}$ - time for superheat to get 0.632 $\Delta(\Delta T)$ in evaporator's response curve;

Because the degree of opening of the electronic expansion valve driven by stepper motor is nearly linear to refrigerant mass flow , and the motor move rapidly, the evaporator gain can be expressed as the ratio between variation of superheat and pulses imposed to the stepper motor: $K=\frac{\Delta(\Delta T)}{\Delta n}$.

The time constant T_p, is related to heat transfer coefficient and thermal inertia of the evaporator, as are the function of thermal resistance R and thermal capacitance C: T_p=RC. Thermal resistance R is the function of heat transfer coefficient outside evaporator α_o and inside the evaporator α_i. α_i is related to refrigerant mass flow rate v_0, heat flow density q_i. α_o is related to cooled fluid Reynolds number Re, Prandtl number Pr, so we can get:[4]

$$R=f(q_i,v_0,\mathrm{Re},\mathrm{Pr}). \tag{3}$$

The thermal capacitance C includes three parts, the evaporator's metal structure C_1, refrigerant C_2 and cooled fluid C_3. C_1 and C_3 are constant after the evaporator has been constructed. C_2 is related to distribution, density, specific enthalpy of refrigerant and inner volume of a evaporator, it will keep constant when the structure of evaporator has been defined. So T_p can be expressed as following:

$$T_p=f(q_i,v_o,\mathrm{Re},\mathrm{Pr}) \tag{4}$$

Time delay τ is the time for refrigerant flowing through the evaporator, it is decided by refrigerant flow rate and length of evaporator. τ comprises the pure delay τ 0 and the volume delay τ c. τ 0 is the delay caused from signal transmission, which relies on the flow rate of refrigerant and the length of evaporator., the lower the flow rate is, the longer the τ 0 is. Volume delay τ c is caused by the volume of evaporator. Because of the metal tube between refrigerant and cooled fluid, the heat transfer between them must first overcome the thermal resistance of metal tube. When the evaporator structure is fixed, τ_c is constant. So, $\tau = f(v_0, l)$.

As stated above, K can be expressed as the ratio of variation between superheat ΔT and flow M. It is related to the refrigerant flow rate. From above analyses, it is shown that there are many factors affecting the evaporator's characteristics T_p, τ and K. First, they are related to system configuration and evaporator structure. Secondly, they are affected by operating condition of system and flowing condition of refrigerant. Because these factors is cha altring continuously in operation, the evaporator's characteristics will vary accordingly.

FUZZY-PID ALGORITHM

PID control

The digital PID control can be implemented by the following:

$$\Delta u(k) = K_p\{e(k) - e(k-1) + \frac{T}{T_i}e(k) + \frac{T_d}{T}[e(k) - 2e(k-1) + e(k-2)]\} \quad (5)$$

$$\Delta u(k) = u(k) - u(k-1) \quad (6)$$

Where, e -the error between the measured value and set value, u -controller output, K_p -proportional constant, T_i -integral constant, T_d -derivative constant, T -sampling time, k -sampling ordinal number.

In practical control, $\Delta u(k)$ corresponds to the pulse imposed to the stepper motor. Coefficients K_p, T_i and T_d are calculated from Ziegler-Nichols formula and they will not vary once have been obtained. It is evident that the conventional PID is not fit for controlling such objects with variable parameters. But because of its robustness, sometimes it can also take good effect in the case of object's being nonlinear. But from theoretical analyses and practical experiments, it is observed that evaporators' dynamic characteristic will change largely due to the variation of operating condition and outside disturbances. In order to obtain sound control performance, the coefficients of PID should be adjusted on line. [2][3]

Adjustment using fuzzy method

Here, tracking error e, the error between the measured superheat and set value, and de which is the rate of change of e are used as input variables. According to the variation of these two inputs, the PID parameters are tuned using fuzzy algorithm. But if these three coefficients are adjusted simultaneously, the inference rules will be very complex and the experience is incomplete. To solve this problem, two methods are proposed.

Method 1

The PID formula is first simplified with Z-N formula or critical proportion method. For example, according to critical proportion method, put the values of control degree being 1.05 into equation (5):

$$\Delta u(k) = K_p[11.029e(k) - 21e(k-1) + 10e(k-2)] \tag{7}$$

Control degree	controller	T	K	Ti	Td
1.05	PI	$0.03Tr$	$0.53Kr$	$0.88Tr$	——
	PID	$0.014Tr$	$0.63Kr$	$0.49Tr$	$0.14Tr$
1.2	PI	$0.05Tr$	$0.49Kr$	$0.91Tr$	——
	PID	$0.043Tr$	$0.47Kr$	$0.47Tr$	$0.16Tr$
1.5	PI	$0.14Tr$	$0.42Kr$	$0.99Tr$	——
	PID	$0.09Tr$	$0.34Kr$	$0.43Tr$	$0.2Tr$
2.0	PI	$0.22Tr$	$0.36Kr$	$0.05Tr$	——
	PID	$0.16Tr$	$0.27Kr$	$0.4Tr$	$0.22Tr$

Table 1 PID parameters according to critical proportion method

Where Tr -ultimate period, Kr -ultimate gain.

So there is only one parameter K_p in the equation. In real time control, K_p is adjusted continuously on line with fuzzy reasoning. First, e and de must be transformed to E and dE in the universe of discourse. of E and dE are the same, [-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6] According to magnitude and sign, seven subsets are defined on the universes of discourse, {PL,PM,PS,ZO,NS,NM,NL}. Universe of discourse of K_p is, [0,1,2,3,4,5,6,7,8,9,10,11,12,13], four fuzzy subsets are defined, {ZO,PS,PM,PL}.The reasoning rules are worked out as follows:

IF E is NL(PL) and dE is NL or NM(PL or PM), THEN K_p is PL;

IF E is NL(PL) and dE is NS(PS), THEN K_p is PM;

IF E is NL(PL) and dE is ZO or PS(ZO or NS), THEN K_p is PS;

IF E is NM(PM) and dE is NL or NM(PL or PM), THEN K_p is PM;

IF E is NM(PM) and dE is NS(PS), THEN K_p is PS;

IF E is NM(PM) and dE is ZO or PS(ZO or NS), THEN K_p is ZO;

IF E is NS(PS) and dE is NL or NM(PL or PM), THEN K_p is PS;

IF E is NS(PS) and dE is NS(PS), THEN K_p is PS;

IF E is NS(PS) and dE is ZO or PS(ZO or NS), THEN K_p is ZO;

IF E is ZO and dE is NL or PL, THEN K_p is PS.

A fuzzy control table can be established based on these rules. In operation, according to measured E and dE, we can get an optimum K_p by looking up table 2.

K_p		E												
		-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
dE	-6	13	12	10	8	6	5	4	3	2	1	0	0	0
	-5	12	11	9	7	5	4	3	2	1	0	0	0	0
	-4	10	9	7	5	4	3	2	1	0	0	0	0	0
	-3	9	7	5	4	3	2	1	0	0	0	0	0	0
	-2	7	5	4	3	2	1	0	0	0	0	0	0	1
	-1	5	4	3	2	1	0	0	0	0	0	0	1	2
	0	3	2	1	0	0	0	0	0	0	0	1	2	3
	1	2	1	0	0	0	0	0	0	1	2	3	4	5
	2	1	0	0	0	0	0	0	1	2	3	4	5	7
	3	0	0	0	0	0	0	1	2	3	4	5	7	9
	4	0	0	0	0	0	1	2	3	4	5	7	9	10
	5	0	0	0	0	1	2	3	4	5	7	9	11	12
	6	0	0	0	1	2	3	4	5	6	8	10	12	13

Table 2 Fuzzy control table based on method 1

Method 2

In method 1, only proportion coefficient is adjusted. Intending to get better effect, another method is proposed. Because the derivative term has little effect on the thermal control systems[3], derivative coefficient is supposed to be constant.

A correction coefficient, θ, is introduced. K_p, T_i and T_d are expressed as following:[5]

$$K_p = K_{p0} \frac{1}{\gamma\beta} \qquad T_i = T_{i0} \frac{\beta(1+\theta)}{2} \qquad T_d = T_{d0} \tag{8}$$

γ is proportional gain, β is integral gain. θ is obtained from fuzzy reasoning. K_{p0}, T_{i0} and T_{d0} are initial value, which can be got from Z-N formula. According to E and dE, another fuzzy variable, H, is introduced. H reflects the variation tendency of θ in dynamic process. Fuzzy control quantity H must be converted into ordinary quantity h(t), which is used to adjust θ on line, so we can get equation (9):

$$\theta(t) = \theta(t-1) + \eta \cdot h(t) \qquad \theta(t) \in (0,1) \tag{9}$$

η is a positive constant, as used to regulate the rate of change of θ. Here, η=0.1, $\theta(0) = 1$

As method 1, seven subsets are defined for E and dE. The universe of discourse of H is {-2,-1,0,1,2}. According to control table 3, defuzzify H and put it into equation (9). After getting $\theta(t)$, coefficients can be adjusted from equation (8).

H		*E*												
		-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
dE	-6	2	2	2	2	2	2	0	-1	-1	-1	-1	-2	-2
	-5	2	2	2	2	2	2	0	-1	-1	-1	-1	-2	-2
	-4	2	2	2	2	1	1	0	-1	-1	-1	-1	-2	-2
	-3	2	2	1	1	1	1	1	-1	-1	-1	-1	-2	-2
	-2	1	1	1	1	1	1	0	-1	-1	-1	-1	-2	-2
	-1	1	1	1	1	1	0	0	-1	-1	-1	-1	-2	-2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	-2	-2	-1	-1	-1	-1	0	1	1	1	1	1	1
	2	-2	-2	-1	-1	-1	-1	0	1	1	1	1	1	1
	3	-2	-2	-1	-1	-1	-1	0	1	1	1	1	2	2
	4	-2	-2	-1	-1	-1	0	0	1	1	2	2	2	2
	5	-2	-2	-1	-1	-1	0	0	2	2	2	2	2	2
	6	-2	-2	-1	-1	-1	0	0	2	2	2	2	2	2

Table 3 Fuzzy control table based on method 2

EXPERIMENTAL RESULTS

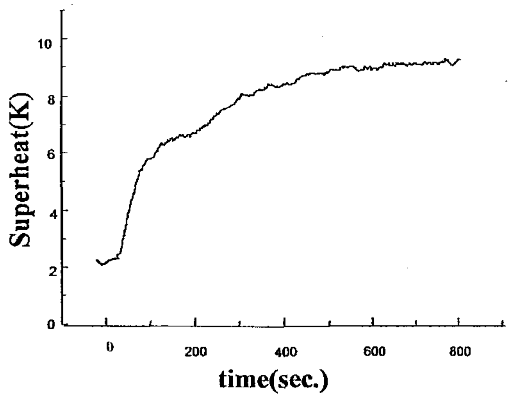

Figure 1 Evaporator's response to a step of opening degree of EEV from 68-48

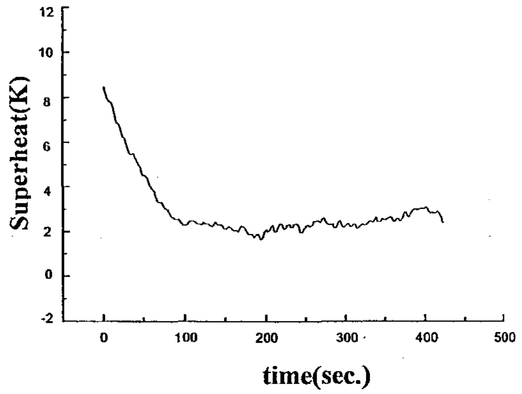

Figure 2 Evaporator's response to a step of opening degree of EEV from 140-180

The characteristics parameters obtained from figure 1 are: T_p=95s, τ=26s, K=0.33. From figure 2, we can get T_p=44s, τ=12s, K=0.048. Comparing these two figures, it is found that T_p, τ and K will decrease when the opening degree of EEV increases. This is because that small oepning degree leads to the low refrigerant flow rate, the heat transfer coefficient become small and the thermal resistance get big. For this reason, the time constant T_p and τ are big. When the flow rate is low, much of heat transfer area is not used, ΔT is sensitive to M, K is big. The increase of flow rate leads to littler sensitivity of ΔT to M, which is because that the increasing proportion of area of evaporator being used will decrease the sensitivity. So it is observed that the gain K will decrease with the increase of flow rate v_0.

In figure 3, an electrical heater is added to increase the heat load of evaporator. It is shown that T_p=59s, τ=12s, K=0.094s.Comparing with figure 2, T_p and K become big.and τ is almost steady. This is because the heater enlarged evaporator's thermal inetia, the thermal resistance and capacity is thus increased. Because refrigerant flow rate didn't vary,thetime delay almost keep constant.

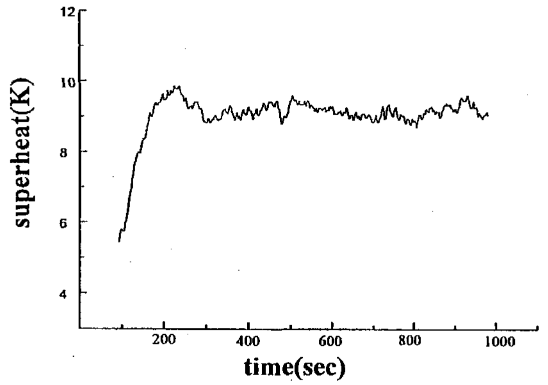

Figure 3 With heater, evaporator's response to a step of opening degree of EEV from 140-180

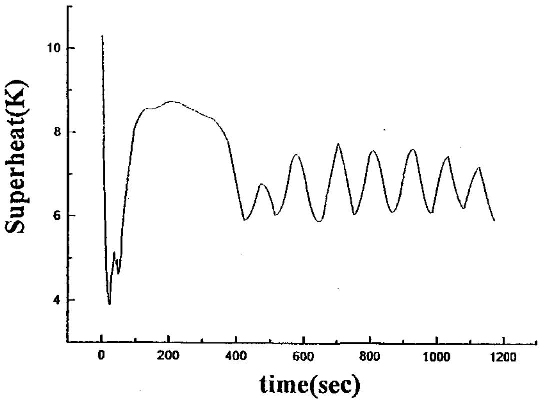

Figure 4 Superheat control using PID algorithm

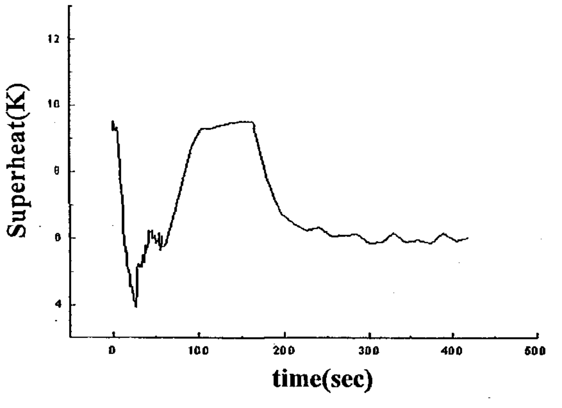

Figure 5 Superheat control using fuzzy algorithm, method1

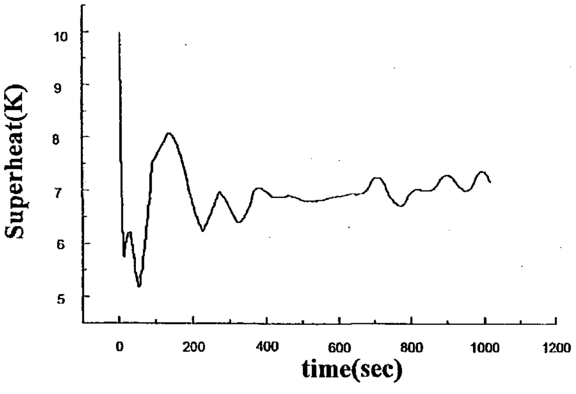

Figure 6 Superheat control using fuzzy algorithm, method2

Figure 4 expresses the control performance of PID. It is apparent that the superheat is also oscillating around the set value, the control is unsteady. Figure 5, 6 show the performance using above mentioned two fuzzy methods. The overshoot is not reduced because no special algorithm is used but the opening of EEV in a set value during start-up and the overshoot is even bigger using method 1. Comparing with the conventional PID, time to reach the steady state is reduced from 400 seconds to 200 seconds, the static superheat is reduced from ± 1 ℃ to ± 0.3 ℃ and the control is pretty steadier than conventional PID. As a summary, it is evident that fuzzy-PID can take better effects.

CONCLUSION

From the response curve obtained in experiments, it is verified that a evaporator can be regarded as a first-order lag plus time delay object. But due to the strong coupling of parameters, which will lead to the high nonlinearity of an evaporator, the characteristic parameters in the mathematical model is much variable. Besides operating condition, the refrigerant flow and heat load can affect them strongly. The characteristic parameters T_p, K, τ will decrease with the increase of refrigerant flow and the heat load will increase T_p, K.

Using fuzzy algorithm to adjust PID parameters is feasible. This method is suited to the evaporator's characteristic. In fact it nonlinearize the conventional PID, so fuzzy-PID can receive good performance in controlling the object with high nonlinearity such as evaporators. Only a fuzzy subroutine is added to the conventional PID, as is easy to achieve. Experiments show although the opening of EEV is invariable during start-up, the time to reach steady state and error are reduced greatly.

Because derivative term has little effect on control, it is feasible to keep an invariable derivative coefficient when adjusting PID coefficients. Sometimes the control can receive good performance only by adjusting the proportional coefficient, this is because the proportional action is the most important in control and the integral and derivative action is also adjusted at the same time.

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