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Effects of superheat nonlinearity on the operational stability of a direct expansion (DX) air conditioning (A/C) system

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Abstract

The paper reports a study on examining the influences of superheat nonlinearity on the operational stability of a direct expansion (DX) air conditioning (A/C) system. Using an experimental DX A/C system, the static nonlinearity of the electronic expansion valve (EEV) and superheat nonlinearity of the evaporator exhibited under different operating conditions were obtained. A first-order plus dead time (FOPDT) model was used to characterize the dynamic responses of the evaporator when the experimental system was operated at different compressor speeds and evaporating temperatures. Using Nyquist stability criterion, the effects of superheat nonlinearity on the system operational stability were theoretically analysed. The study results showed that a higher chance to instability would be resulted in when the system was operated at a smaller EEV's opening, a lower compressor speed or evaporating temperature.

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Keywords: direct expansion; air conditioning system; operational stability; superheat nonlinearity;

1. Introduction

Instability in a refrigeration system, conventionally known as hunting, is the phenomena of the oscillation of certain system operational parameters such as the degree of refrigerant superheat (DS). Hunting has been noticed in not only the refrigeration systems controlled by thermostatic expansion valves (TEVs) [1], but also those controlled by electronic expansion valves (EEVs) [2]. Hunting leads to a lower operational safety and a higher energy

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consumption [3], and therefore, should be avoided as far as possible for the safe and energy efficient operation of a refrigeration system. There have been two different views on the causes of unstable system operation. The first concentrated on the inherent characteristics of an evaporator. The second view tried to explain the cause of hunting based on the influence of the operating characteristics of an expansion valve on system stability. Nonetheless, there has been no verdict of which view would reflect truly what leads to hunting in a refrigeration system.

As a special type of refrigeration system, hunting was also observed in a DX A/C system. With the wide application of variable frequent technology to DX A/C systems, both compressor and supply fan speeds can be varied, making the system operational stability more complicated. While a previous study indicated that the superheat nonlinearity may cause the instability of a DX A/C system when it was variable speed operated [4], no detailed analysis was carried out on investigating the effects of this superheat nonlinearity exhibited at different operating conditions. Therefore, a follow-up study on examining the influences of superheat nonlinearity on the operational stability of a DX A/C system when it was operated at various operating conditions was carried out and the study results are reported in this paper.

2. Experimental set up

2.1. The experimental DX A/C system

The schematic diagram of the experimental DX A/C system shown in Fig. 1. As seen, the experimental DX A/C system was composed of two parts, i.e., a DX refrigeration plant (refrigerant side) and an air distribution sub-system (air side). The major components in the DX refrigeration plant included a variable speed compressor, a PI controlled EEV, a DX evaporator and a condenser. The evaporator was placed inside the supply air duct to work as a DX air cooling coil. The design air face velocity for the DX cooling coil was 1.98 m s^{-1}, and the nominal output cooling capacity from the DX refrigeration plant 7.5 kW. The refrigerant of the plant was R410a, with a total charge of 5.8 kg. The air-distribution sub-system included an air-distribution ductwork with return air dampers, a variable speed centrifugal supply fan, and a conditioned space. Inside the space, there were sensible heat and moisture load generating units (LGUs) for simulating the space cooling load.

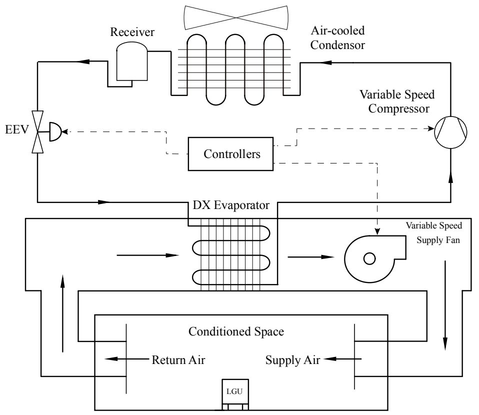
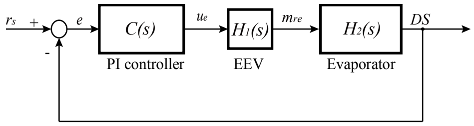


Fig. 1 Schematic diagram of the experimental DX A/C system



$C(s)$ - Transfer function for the PI controller
$H_1(s)$ - Transfer function for the EEV
$H_2(s)$ - Transfer function for the evaporator

Fig. 2 Block diagram of the PI controlled EEV-evaporator control loop

2.2. Experimental conditions and procedures

In order to obtain the nonlinear characteristics for both EEV and evaporator, two sets of experiments were carried out. In the first set of experiments, the flow characteristics of the EEV as expressed in terms of the relationship between EEV's opening and refrigerant mass flow rate passing through it were experimentally obtained through varying EEV's opening from 30% to 60%. On the other hand, for the second set of experiments, in order to examine the nonlinear characteristics of the evaporator exhibited under different compressor speeds and evaporating temperatures, the transient responses for the opening DS at evaporator exit after a sudden change in refrigerant mass flow rate at evaporator inlet under different operating conditions listed in Table 1 were experimentally obtained. Based on the normal operation of the experimental DX A/C system, two groups of operating conditions with different combinations of compressor speed and evaporating temperature were selected to examine the influences of the nonlinear characteristics on the system operational stability, resulting in a total of 6 experimental cases. During experiments, the cooling air flow entering the condenser was maintained constant at 4100 m^3/h, with a fixed condenser cooling air inlet air temperature at 35 ^{o}C.

The experimental procedures were as follows. At a specified compressor speed listed in Table 1, the evaporator inlet air state and supply fan speed were respectively controlled to maintain the required evaporating temperature. After the experimental DX A/C system reached a steady state, a sudden decrease in refrigerant mass flow rate at evaporator inlet was introduced by varying EEV's opening. Finally, through real-time monitoring the variation in the operating DS at evaporator exit, the nonlinear characteristics of the evaporator under different operating conditions listed in Table 1 could be obtained.

Table 1 Two groups of the experimental operating conditions

Group	Case	Compressor speed, f_c (rpm)	Evaporating temperature, T_e (^{o}C)
I	1	4320	3.5
	2	4860	
	3	5400	
II	4	4680	0
	5		3
	6		6

3. Transfer function of the PI-controlled EEV-evaporator control loop

Fig. 2 shows the block diagram of the PI-controlled EEV-evaporator control loop in the experimental DX A/C system shown in Fig. 1. The measured DS at evaporator exit, is directly used as a feedback DS signal to be compared with the reference DS setting, r_s. Based on the error between DS and r_s, or e, the PI controller outputs a corresponding control signal, u_e, to regulate the EEV's opening. Then, the refrigerant mass flow entering the evaporator, m_{re}, will be regulated continuously until e is within its pre-set range.

Consequently, the open-loop transfer function, $G(s)$, for characterizing the transient response for DS to a change in EEV's control signal, u_e, can be expressed as:

$$G(\mathrm{s}) = \frac{\Delta DS(\mathrm{s})}{\Delta u_e(\mathrm{s})} = H_1(s)H_2(s) \tag{1}$$

The closed-loop transfer function for the PI controlled EEV-evaporator control loop, $G_c(s)$, can therefore be expressed as:

$$G_c(\mathrm{s}) = \frac{C(\mathrm{s})G(\mathrm{s})}{1+C(\mathrm{s})G(\mathrm{s})} = \frac{C(\mathrm{s})H_1(s)H_2(s)}{1+C(\mathrm{s})H_1(s)H_2(s)} \tag{2}$$

In Eqs. (1) and (2), $C(s)$ is the transfer function for EEV's PI controller, $H_1(s)$ that for the EEV, $H_2(s)$ that for the evaporator. The open-loop transfer function, $L(s)$, can be expressed as:

$$L(\mathrm{s}) = C(\mathrm{s})H_1(s)H_2(s) \tag{3}$$

For a conventional PI controller, its the transfer function, $C(s)$, can be expressed as:

$$C(s) = K_p + \frac{K_i}{s} \tag{4}$$

The transfer function for the EEV, $H_1(s)$, can be written as:

$$H_1(s) = \frac{\Delta M_{re}(s)}{\Delta u_e(s)} = K_v \tag{5}$$

Normally, the response of the operating DS to a step change in the refrigerant mass flow rate entering an evaporator can be characterized by a first-order plus dead time (FOPDT) process [5-7], and thus the transfer function for the evaporator, $H_2(s)$, can be expressed as

$$H_2(s) = K_e \frac{1}{1+\tau s} e^{-\theta s} \tag{6}$$

where K_e is the evaporator gain, defined as a ratio of the variation of DS from one steady-state to another, ΔDS, to that of the refrigerant mass flow rate supplied, ΔM_{re}. τ is the time constant of the evaporator, θ the delay time between the change of mass flow rate, m_{re}, and that of the DS.

4. Experimental results and analysis

4.1. Static nonlinearity of the EEV

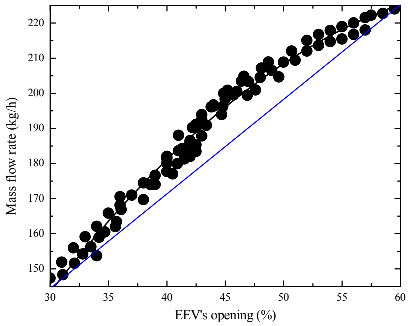


Fig. 3 The flow characteristic of the EEV

Static nonlinearity of a controlled system was a common source of control failure in HVAC or refrigeration systems [8-10]. In the experiments, static nonlinearity of the EEV were also observed which may cause the unstable operation of the experimental system. The flow characteristic of an EEV is the relationship between EEV's opening and refrigerant mass flow rate passing through the valve which is regarded as an inherent operating characteristic for an EEV. Fig. 3 shows the flow characteristic of the EEV used in the experimental system. As seen, the flow characteristic was not a linear curve but a parabolic one within EEV's opening range from 30% ~ 60%, indicating the static nonlinearity of the EEV. Based on the experimental data, the relationship between EEV's opening, u_e, and refrigerant mass flow rate, m_{re}, can be expressed as:

$$m_{re} = -0.0522u_e^2 + 7.43u_e - 32.5 \tag{7}$$

Therefore, the valve gain, K_v, was not constant throughout the range of EEV's opening. For the flow characteristics of the EEV shown in Fig. 3, the valve gain was larger at a lower EEV's opening corresponding to a smaller refrigerant mass flow rate, but smaller at a larger EEV's opening corresponding to a larger refrigerant mass flow rate.

4.2. Superheat nonlinearity of the evaporator

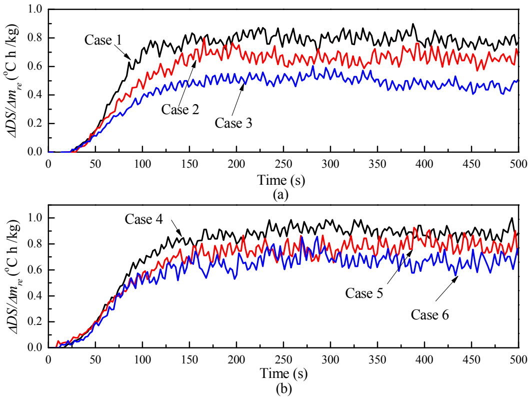


Fig. 4 The dynamic responses of the evaporator at different (a) compressor speeds; (b) evaporating temperatures

As mentioned above, the dynamic responses of the operating DS to a sudden change in refrigerant mass flow rate can be characterized by a FOPDT model. However, due to the superheat nonlinearity exhibited at different operating conditions, the identified parameters in the FOPDT model may be different, consequently impacting the system operational stability. The experimental results of the dynamic responses at different operating conditions listed in Table 1 are shown in Fig. 4. As seen, while different operating conditions would not significantly influence the time delay and time constant, it did have an obvious impact on the evaporator gain as reflected by the final value of the measured response. A larger evaporator gain would be resulted in at a lower compressor speed or a lower evaporating temperature. This variation in evaporator gain at different operating conditions would eventually impact the stability of the PI-controlled EEV-evaporator loop.

4.3. Stability analysis

With the available FOPDT models identified, the operational stability for the EEV-evaporator control loop can be theoretically analyzed through using Frequency Response Method. In using the Frequency Response Method in the classical control theory, Nyquist stability criterion is a graphical technique to determine the stability of a dynamic controlled system and has been widely used for designing and analyzing systems with feedback. The importance of Nyquist stability lies in the fact that it can be used to determine the relative degree of system stability by producing the phase and gain stability margins. With the help of Nyquist stability criterion, the stability of the EEV-evaporator control loop was investigated by analyzing the frequency response of its open-loop transfer function, $L(s)$.

In the current study, a commonly used PI setting, namely, K_p=-0.5 and K_i=-0.0125, was adopted, so that the Nyquist diagrams for $L(s)$ at different operating conditions can be obtained as shown in Fig. 5. As seen in Fig.5(a), as reducing EEV’s opening, contour for the open-loop transfer function $L(s)$, Γ_L, tended to encircle the point (-1, 0), resulting in a lower gain and phase margins. Therefore, the DX A/C system would have a higher chance to instability when it was operated at a lower EEV’s opening. On the other hand, as seen in Figs 5(b) and 5(c), Γ_L for $L(s)$ tended to encircle the point (-1, 0) at a lower compressor speed or a lower evaporating temperature, leading to a lower gain and phase margins of the controlled loop. Therefore, it become clear that a higher possibility to instability of the DX A/C system may result, when it was operated at a lower compressor speed or evaporating temperature. However, in normal operation of a DX A/C system, increasing its compressor speed would cause a corresponding decrease in evaporating temperature. Therefore, increasing compressor speed may also lead to system instability if this increase in compressor speed was unable to compensate the influence of the corresponding decrease in evaporating temperature on operational stability.

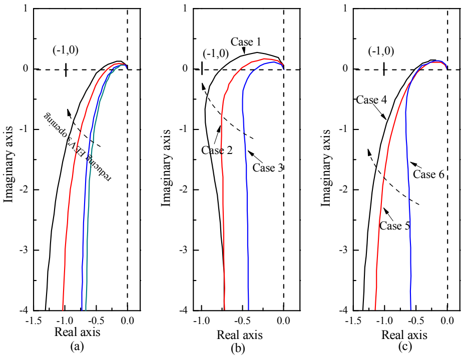


Fig. 5 Nyquist diagrams for *L(s)* at different (a) EEV's openings, (b) compressor speeds, (c) evaporating temperatures

5. Conclusions

In this paper, a study on investigating the effects of superheat nonlinearity on the operational stability of a DX A/C system is reported. The static nonlinearity of the EEV as expressed by its flow characteristic and the superheat nonlinearity of the evaporator as reflected by its dynamic responses were experimentally obtained. Using Frequent Response Method, the influences of superheat nonlinearity on the system operational stability were theoretically analyzed through adopting Nyquist stability criterion. Analysis results showed that a higher chance to instability would be resulted in when the system was operated at a smaller EEV's opening, a lower compressor speed or evaporating temperature.

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Biography

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