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Development of a superheat controller for mitigating hunting in a direct expansion air conditioning system

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Abstract

This paper reports a development of a new degree of superheat (DS) controller which can slow down the rate of DS signal transfer in a direct expansion (DX) air conditioning (A/C) system for help mitigate operational instability. Through analyzing the heat transfer occurred at the outlet of an evaporator where the DS was evaluated, the dynamics of the DS signal transfer could be simply characterized by a first-order transfer function model (FOM). The new DS controller was thus developed by incorporating a FOM into a conventional proportional-integral (PI) controlled EEV-evaporator control loop, so that the rate of DS signal transfer could be regulated through varying the time constant of the FOM. Using an experimental DX A/C system, controllability tests for the new DS controller were carried out. Experimental results showed that the new DS controller would help mitigate possible system hunting when the experimental DX A/C system was unstably operated. The developed control strategy provides an alternative way to regulate the DS with an emphasis on operational stability.

Keywords: degree of superheat, hunting, direct expansion, operational stability

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Nomenclature

C_p	: specific heat at constant pressure, kJ/(kg·K)	V	: volume, m^3
R	: thermal resistance, K/kW	K_p	: proportioanl gain, -
DS	: degree of superheat, K	T_i	: integral time, s
T	: temperature, K	Subscript	
t	: time, s	a	: air
τ	: time constant, s	re	: refrigerant
m	: mass flow rate, kg/h	se	: sensor

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), refrigerant mass flow rate and evaporating pressure. Hunting has been noticed in not only the refrigeration systems controlled by thermostatic expansion valves (TEVs) (1-5), but also those controlled by electronic expansion valves (EEVs) (6-9). On the other hand, direct expansion (DX) air conditioning (A/C) systems are widely used in residential buildings. The application of variable frequent technology in A/C has made the simultaneous control of both compressor and fan speed possible, paving ways to achieve better indoor thermal environment (10-14). However, hunting was observed in DX A/C systems, especially when its compressor and supply fan speeds were variable speed operated (7, 15-17). Hunting leads to a lower operational safety and a higher energy consumption (18), and therefore, should be avoided as far as possible for the safe and energy efficient operation of a refrigeration system.

Two-phase flow instability in evaporation process and operating characteristics of an expansion valve-evaporator control loop are generally considered as the two main causes for hunting. As the nature of evaporation, two-phase flow instability can not be avoided. However, the hunting caused by the operating characteristics of an EV-evaporator control loop could be mitigated using certain control strategies (17). For the TEV-controlled refrigeration system, the thermal resistance between TEV's sensing bulb and the tube wall would impact system's operational stability, as it directly affected the time for the DS signal propagate through the TEV-evaporator control loop to adjust the refrigerant mass flow rate required, which was considered as the fundamental reason for hunting. It was previously showed that increasing the thermal resistance between TEV's sensing bulb and the tube wall or increasing the time constant of the TEV's sensing bulb would help reduce the hunting (19-21). Similar to those TEV-controlled refrigeration systems, the time constant of EEV's temperature sensor used for evaluating the DS also affected the operational stability of EEV-controlled refrigeration systems and increasing the time constant of EEV's temperature sensor would benefit the operational stability (22).Therefore, it can be concluded that slowing down the rate of DS signal transfer should be an effective approach to mitigate instability problem encountered in a refrigeration system. However, no related DS controllers as guided by this approach has been developed.

Therefore, through slowing down the rate of DS signal transfer in an EEV-evaporator control loop, a new DS controller for mitigate hunting has been developed and the development results are reported in this paper.

2. Development of the new DS controller

As mentioned in Introduction, the rate of DS signal transfer in an EEV-evaporator control loop would impact its stability. In an EEV-controlled refrigeration system, the rate of DS signal transfer is directly influenced by the heat transfer between EEV's temperature sensor and refrigerant inside the evaporator pipeline. Therefore, a brief analysis on the heat transfer occurred at the evaporator exit where DS is detected is given as follows.

Fig. 1 shows the schematic diagram of a conventional proportional-integral (PI) controlled EEV-evaporator control loop which was made of the EEV, evaporator, EEV's temperature sensor and PI controller. As shown, the DS at evaporator exit, as a feedback control signal to the EEV for modulating its opening, can be evaluated by measuring the refrigerant temperature and evaporating pressure at evaporator exit using a temperature sensor and a pressure transducer. Considering the heat transfer between the temperature sensor which was usually attached to the outer surface of the refrigerant pipe at evaporator exit, and the vapor refrigerant inside the pipe, it would take some time for EEV's temperature sensor to detect the refrigerant temperature which fluctuates all the time, consequently influence the rate of DS signal transfer in the PI controlled EEV-evaporator control loop.

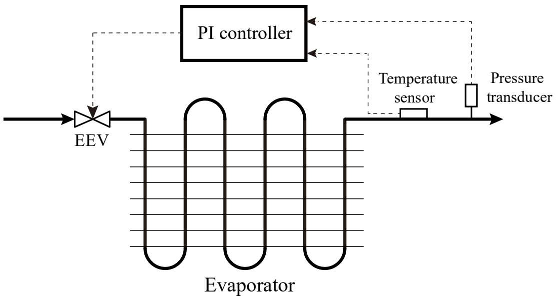

Fig. 1 Schematic diagram of a conventional PI controlled EEV-evaporator control loop

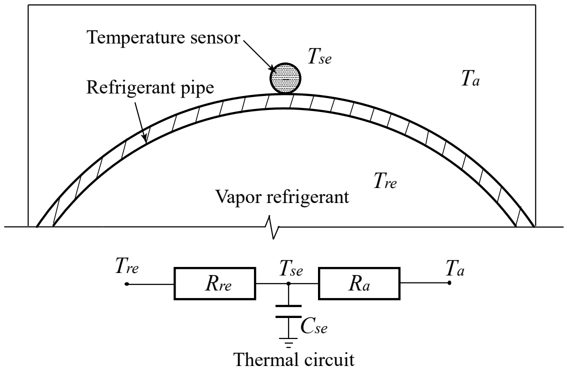

Fig. 2 Schematic diagram of the installation of an EEV temperature sensor attached to the refrigerant pipeline at evaporator exit and its equivalent thermal circuits

Fig. 2 shows the installation details of EEV's temperature sensor attached to the refrigerant pipe at evaporator exit and an equivalent thermal circuit for the heat transfer from refrigerant to the sensor. The heat transfer between the temperature sensor and the refrigerant inside the pipeline yielded:

$$(\rho C_p V)_{se}\frac{dT_{se}(t)}{dt}=\frac{(T_{re}(t)-T_{se}(t))}{R_{re}}+\frac{(T_a(t)-T_{se}(t))}{R_a} \tag{1}$$

where T_{re} is the temperature of vapor refrigerant at evaporator exit, T_a the ambient temperature, T_{se} the temperature measured by the sensor. R_{re} is total thermal resistance between the vapor refrigerant and temperature sensor. R_a is the convective thermal resistance between the sensor and its surroundings.

Generally, in refrigeration systems, EEV's temperature sensors and the refrigerant pipe at evaporator exit are thermally insulated to reduce heat loss. Therefore, the natural convection heat transfer between the sensor and its surroundings can be neglected. Thus, equation (1) can be simplified to:

$$\frac{dT_{se}(t)}{dt}+\frac{1}{\tau_{se}}T_{se}(t)=\frac{1}{\tau_{se}}T_{re}(t) \tag{2}$$

$$\tau_{se}=R_{re}(\rho C_p V)_{se} \tag{3}$$

where τ_{se} is the time constant, which is affected by the thermal resistance between the sensor and vapor refrigerant inside the pipe, as well as the heat capacity of the temperature sensor itself.

Using the Laplace Transform, Eq. (2) can be transformed to:

$$\frac{\Delta T_{se}(s)}{\Delta T_{re}(s)}=\frac{1}{\tau_{se}s+1} \tag{4}$$

As indicated by Eq. (4), due to the heat transfer between the refrigerant inside the pipeline and the temperature sensor the rate of the DS signal transfer was slowed down, which could be simply characterized by a First Order transfer function model (FOM), or a first order low pass filter. Therefore, the new DS controller could be developed by incorporate a FOM into a conventional PI controlled EEV-evaporator control loop as shown in Fig. 3. As seen the FOM was added into the feedback loop, and thus the rate of DS signal was slowed down before it was transferred to the PI controller. According to the previous study [9, 14], when hunting occurred, the operating DS was oscillated at periods ranging from 160s～200s. Therefore, based on the characteristics of low pass filters the time constant, τ_{se}, could be evaluated using Frequency Response Method [14]. In the current study, in order to diminish the oscillation of the operating DS, at the same time maintaining sufficient control sensitivity, the time constant for the FOM was selected as 200s.

3. Controllability tests

Controllability tests were carried out using an experimental DX A/C system with the new DS controller being implemented.

3.1. Descriptions of the experimental DX A/C system

The schematic diagram of the experimental DX A/C system shown in Fig. 4. 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. During the experiments, the compressor and supply fan speeds were fixed at 4680rpm and 2880rpm, respectively. On the other hand, there were an air heater and a water heater in the LGUs. The two heaters were program controlled to match the sensible and latent loads in the conditioned space, so that the air temperature and relative humidity entering the DX evaporator were maintained at 25°C and 50%, respectively. The DS setting was fixed at 8K.

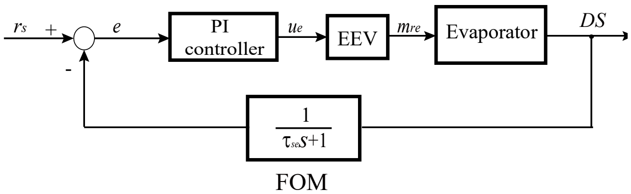

Fig. 3 Block diagram of the new DS controller

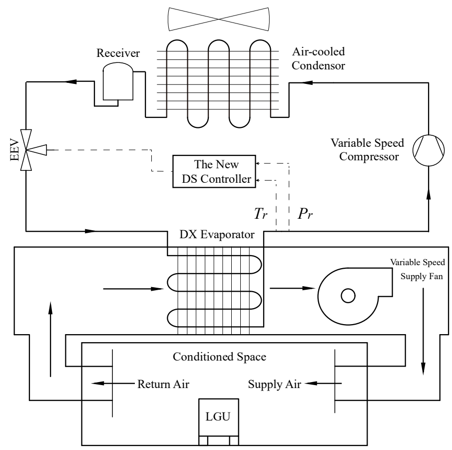

Fig. 4 Schematic diagram of the experimental DX A/C system

3.2. Experimental results

Different PI control settings would affect the operational stability of the PI controlled EEV-evaporator control loop, a larger proportional or integral gain would lead to a higher chance to instability. Therefore, to verify the feasibility of the new DS controller, two sets of experimental conditions with different PI control setting as listed in Table 1 were adopted. According to the previous study (22), the time constant of the FOM was chosen as 200s for slowing down the rate of DS signal transfer. At the beginning of each test, a conventional PI based DS controller was adopted to regulate EEV's opening. At 1200s, the new DS controller was introduced and then EEV's opening was regulated by the new DS controller for the rest of the test.

Table 1 Experimental conditions with two groups of different PI settings

Test No.	Proportional gain, K_p	Integral time, T_i	Time constant in the FOM
I	-1.5	60s	200s
II	-2	80s	200s

Figs 5 and 6 show the experimental results for the test I and II, respectively. As seen in Fig. 5, the measured operating DS were fluctuated and the fluctuation amplitude was over ±2K at the beginning of the test. As the feedback control signal, the fluctuation of the measured operating DS would cause the frequent opening and closing of the EEV, and thus the oscillation of the mass flow rate as shown in Fig. 5(b), consequently resulting in system hunting. However, after introducing the new DS controller at 1200s, the operating DS measured would be settled at its setting of 8K after experiencing some fluctuations. Consequently, the mass flow rate became stable and the hunting was mitigated. The same conclusion was drew from the experimental results for test II showed in Fig. 6. As seen, after introducing the new DS controller, the fluctuation amplitude for the operating DS was diminished, and the oscillation of the mass flow rate was vanished. This was because in the new DS controller the FOM was functioned as a low-pass filter. When hunting occurred, the feedback control signal with a certain fluctuation frequency was attenuated and could not be passed through the FOM, thus the fluctuation amplitude was diminished and hunting mitigated. The controllability test results showed that the new DS controller was able to help mitigate possible hunting for the experimental DX A/C system under different operational conditions, demonstrating the feasibility of the controller proposed.

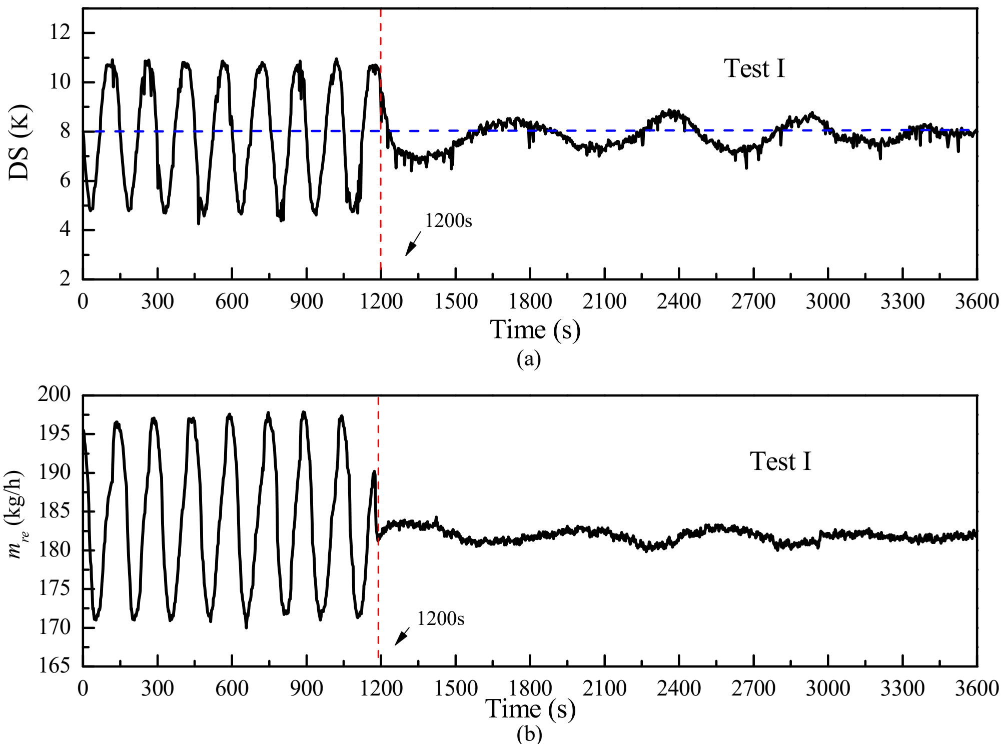

Fig. 5 Experimental results for Test I (a) DS, (b) mass flow rate

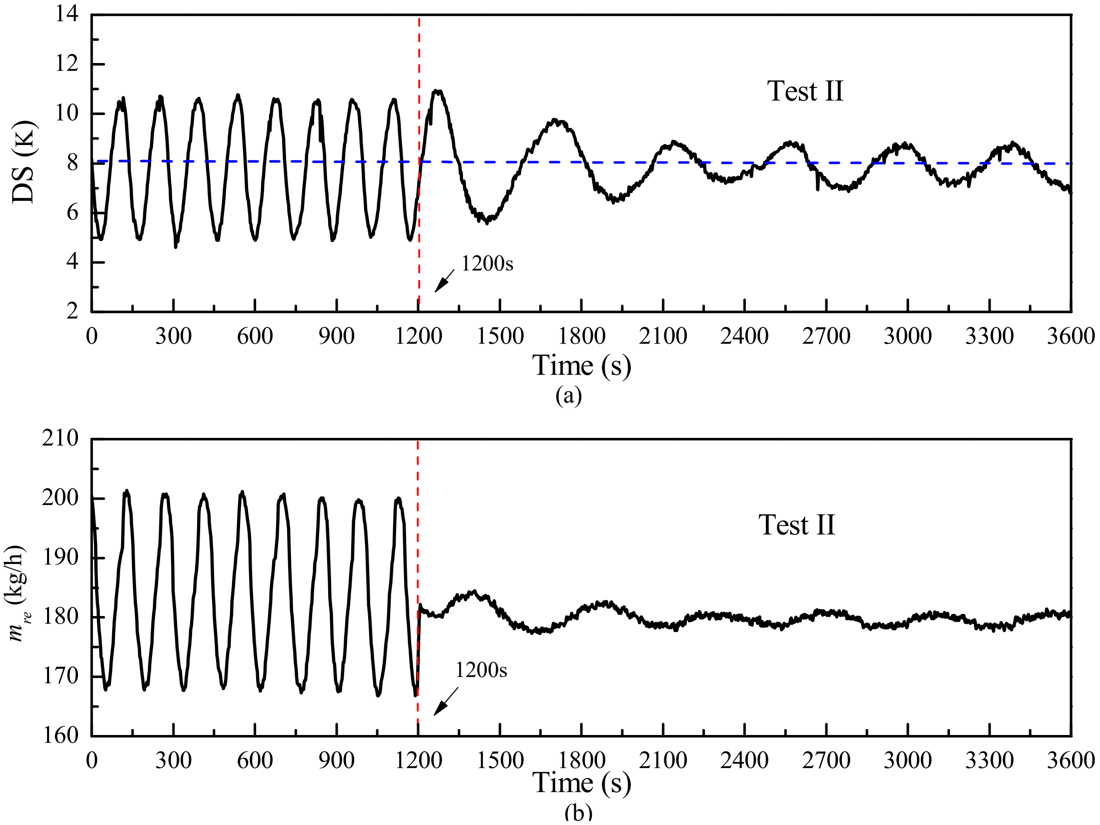

Fig. 6 Experimental results for Test II (a) DS, (b) mass flow rate

4. Conclusions

Through incorporating an FOM into a conventional PI controlled EEV-evaporator control loop to slow down the rate of DS signal transfer, a new DS controller for mitigating possible hunting has been developed and the development results is reported in this paper. Using an experimental DX A/C system, controllability tests were carried out. The experimental results showed that the new DS controlled developed was able to help mitigate system hunting under different operational conditions.

Acknowledgements

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