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Energy Procedia 158 (2019) 2182–2187

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Adaptive control for degree of refrigerant superheat in a direct expansion air conditioning system under variable speed operation

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Abstract

Direct expansion air conditioning systems are widely installed in small-to medium- scale buildings due to their advantages of simple configuration, high energy efficiency and low cost to own and maintain. The two main targets of air conditioning operation include improving the system operational efficiency and energy efficiency. Stable system operational efficiency is directly related with the operation of electronic expansion valves and degree of superheat at the outlet of evaporator. In this paper, an adaptive DS controller is developed to improve the system operational efficiency based the experimental performance of a DX A/C system and reported. The adaptive DS controller is designed to seasonably regulate the degree of superheat when the system is subjected to changes in operating conditions. Experimental controllability test results show that the controller has a very stable behavior, allowing an effective and fast control of the DS setting.

Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.

Keywords: Adaptive control; Air conditioning; Degree of superheat; Variable speed

1. Introduction

Air conditioning (A/C) systems are widely used in buildings for indoor thermal environment control. The energy consumption for A/C takes a large share of the total energy use in buildings. A close look at the US energy consumption shows that approximately 40% of all the energy used in the US was by heating, ventilation and air conditioning (HVAC) and refrigeration systems in 2011 [1]. In small-to medium-scale buildings, direct expansion (DX) A/C systems are commonly used due to their advantages of simple configuration, high energy efficiency and low cost to own and maintain [2, 3]. Therefore, it is very important to improve the operational efficiency of DX A/C systems to contribute to both environmental protection and sustainable development.

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Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.
10.1016/j.egypro.2019.01.618

The operating degree of refrigerant superheat (DS) is a key operating parameter in a DX A/C system, impacting both its operational stability and efficiency. It is commonly acknowledged that a smaller DS would lead to a higher operating efficiency but a poorer operating stability, and vice versa. Therefore, for ensuring a stable and efficient operation, the operating DS should be well regulated with its desired limits. Due to the advantages of rapid response time, nearly zero activating superheat and easy realization of programmed control, the electronic expansion valve (EEV) has been widely used in refrigeration systems, paving tremendous ways to adopt different control algorithms. In an EEV-controlled refrigeration system, proportional and integral (PI) and proportional, integral and derivative (PID) control algorithms are extensively used to regulate the EEV's opening in order to controlling refrigerant mass flow rate in response to DS at evaporator exit [4, 5]. In practice, a PI controller is adequately capable to provide an acceptable control performance, without the need to consider the problems associated with the derivative actions, namely the need of properly filtering out the measurement noise [6]. However, due to the presence of significant nonlinearities in the response for the control input, e.g. EEV's opening, to operating DS, the PI controller with fixed control settings was unable to regulate the operating DS within its desired limits when the operational condition was varied, leading to a slow, oscillatory, or unstable closed-loop response [7, 8]. Therefore, an adaptive DS controller whose control settings could be automatically adjusted in accordance with change of operational condition for a DX A/C system has been developed and the development results are reported in this paper.

2. Controller development

2.1. Descriptions of the experimental system

The schematic diagram of the experimental DX A/C system is shown in Figure 1. As seen, the experimental DX A/C system is 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, an 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.

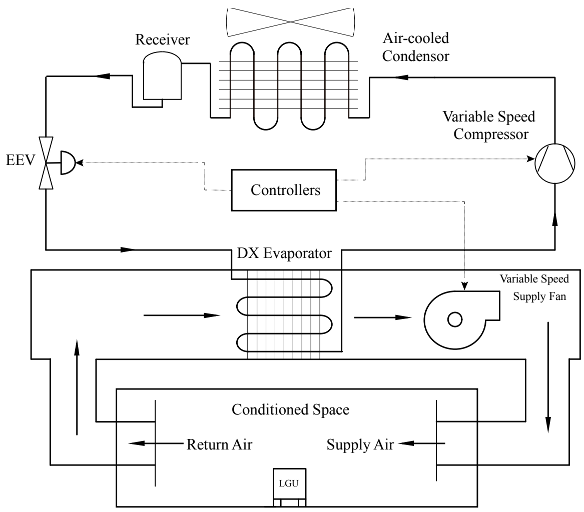

Figure 1 Schematic diagram of the experimental DX A/C system

2.2. Superheat nonlinearity

There exists a significant nonlinearities in the response for the control input, namely, EEV's opening, to operating DS. In the experimental DX A/C system, the transfer function for the EEV, $H_1(s)$, can be written as:

$$H_1(s) = \frac{\Delta M_{re}}{\Delta u_e} = K_v \tag{1}$$

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[9], and thus the transfer function for the evaporator, $H_2(s)$, can be expressed as:

$$H_2(s) = \frac{\Delta \mathrm{DS}}{\Delta Mre} = K_e \frac{1}{1+\tau s} e^{-\theta s} \tag{2}$$

Therefore, the transfer function, $G(s)$, for the EEV-evaporator open loop system can be written as:

$$\mathrm{G}(s) = \frac{\Delta DS}{\Delta u_e} = K_v K_e \frac{1}{1+\tau s} e^{-\theta s} = K_{sys} \frac{1}{1+\tau s} e^{-\theta s} \tag{3}$$

where K_{sys} is the system static gain, defined as a ratio of the variation of DS from one steady-state to another, ΔDS, to that of the EEV's opening, Δu_e. τ is the time constant, θ the time delay. The system static gain was estimated using the relation, ΔDS /Δu_e and the time constant correspond to the time when the DS reached 63% of its final change. Through tracking the dynamic response for the operating DS after the change of EEV's opening, the parameters in transfer function model, G(s), could be identified. In order to obtain the dynamics responses for the operating DS under different operational conditions, two groups of different compressor speeds with each including four cases of different supply fan speeds as shown in Table 1 were set during experimentation.

Table 1 Two groups of different operational conditions

Study Group	Case	Compressor speed (rpm)	Supply fan % of max speed, F	Supply fan Speed (rpm)	Initial DS (°C)
I	I-1	4680	70	2520	6
	I-2		80	2880	
	I-3		90	3240	
	I-4		100	3600	
II	II-1	4860	70	2520	6
	II-2		80	2880	
	II-3		90	3240	
	II-4		100	3600	

The experimental results for study Groups I and II are shown in Figure 2. As seen, the dynamic responses for the operating DS after a corresponding change in EEV's opening, ΔDS /Δu_e, at different supply fan speeds were different as expressed by different system static gains and time constants. There existed a transport time delay before the change of the operating after applying an input of EEV's opening, which was approximately equal to 20s in all study cases. On the other hand, as reflected by the final value of the dynamic response, a larger system static gain, K_{sys}, would be resulted in at a lower supply fan speed. The time constants, τ, became larger at a higher fan speed. However, as shown in, the compressor speeds did not significant impact the dynamic responses for ΔDS /Δu_e, and thus the identified parameters in transfer function model, $G(s)$. Through tracking the dynamic responses for the operating DS, the parameters in the FOPDT model could be evaluated. The relationships between the supply fan speeds and the identified parameters are shown in. Therefore, the system static gain, K_{sys}, and time constant, τ, can be evaluated as a function of supply fan speed, F, by applying Polynomial Regression.

$$K_{sys} = -9.9138 + 0.1639F - 0.0008F^2 \tag{4}$$

$$\tau = 58.993 - 0.0718F + 0.0051F^2 \tag{5}$$

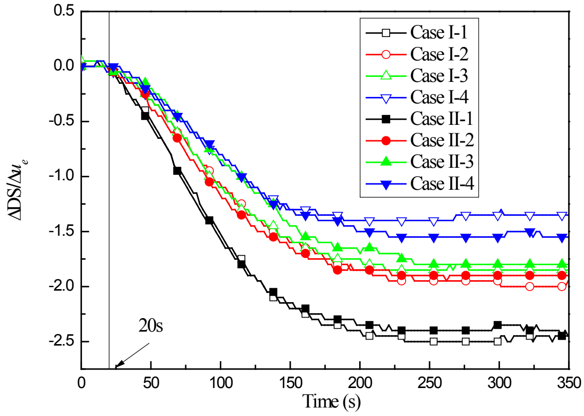

Figure 2 Experimental results for Study Groups I and II

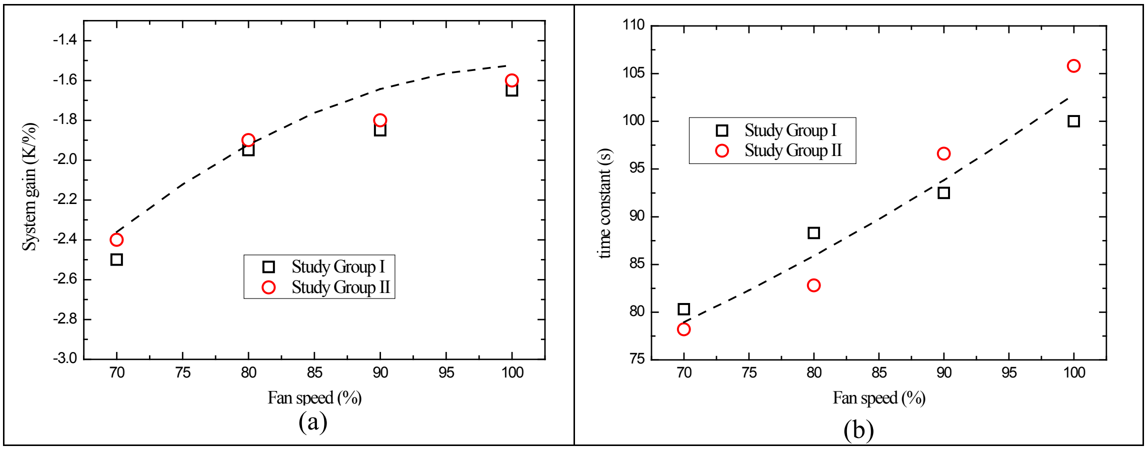

Figure 3 Relationships between the supply fan speeds and the identified parameters (a) static gain, (b) time constant

2.3. Development of the adaptive DS controller

Using the obtained relationships between the identified parameters and the supply fan speeds, the control settings of proportional gain, K_p and integral time, T_i for the PI controller could be evaluated by applying the tuning rule developed by Vilanova [10].

$$T_i = \tau + 0.03\theta\,,\ K_p = \frac{T_i}{2.65K_{sys}\theta} \tag{6 and 7}$$

Consequently, the developed adaptive DS controller could be developed as shown in Figure 4 , and the required control signal of EEV's opening, u_e, can be evaluated as:

$$u_e(k) = K_p \left\{ e(k) + \frac{1}{T_i} \sum_{i=0}^{k} e(i)\Delta t \right\} \quad (8)$$

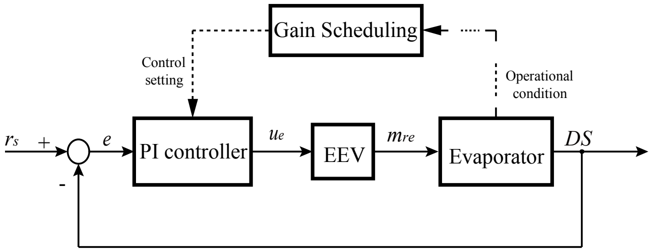

Figure 4 Block diagram of the adaptive DS controller developed

3. Controllability tests

With the developed adaptive DS controller, PI control parameters for EEV, K_p and T_i would be automatically adjusted at different supply fan speeds during the operation of the A/C system. Two controllability tests were carried out the test its control performance and the variations of DS setting with the adaptive controller. At the first step, indoor air temperature and humidity were fixed with the availability of the PID controlled LGU located in the indoor space. Two compressor speeds were adopted in the test, while the supply fan speed was manually adjusted within 60% and 100% of its maximum speed. In both tests, the supply fan speed was initially set as 80%, with 5% increment after 30 minutes' operation. After operated at the maximum speed for 30 minutes, it reduced to 60% and increased to 80% after 1 hour's operation. Detailed test conditions are list in Table 2.

Table 2 Controllability test conditions

Test	Air temperature setting (°C) Dry-bulb	Wet-bulb	Compressor speed (rpm)	Supply fan % of max speed, F	DS setting (°C)
1	24	17.2	4860	80%-85%-90%-95%-	6
2	25	18.5	4680	100%-60%-80%	6

Figure 5 shows the system responses of Test 1 with the adaptive controller regulating EEV opening when the fan speed is changed. As seen, with the adaptive controller, instead of fixed PI control parameters for EEV, K_p and T_i can be automatically adjusted at different fan speeds. K_p and T_i were obtained based on the performance of the DX A/C system as detailed in Section 2. Both K_p and T_i were reduced with the increment of supply fan speeds, and vice versa.

EEV opening was regulated by the developed adaptive DS controller in real time. Therefore, it could be continuously changed to maintain a stable DS value, which is intended to set at 6 °C. In the first 2.5 hours, the supply fan speed is altered with 5% increment each 0.5 hour. Good DS set point tracking at the exit of evaporator was observed, with 93% of the measured DS within ±0.6 °C of the set point during the period. When fan speed was manually increased from 80% to 85% at 1800 s into the test, DS setting was slightly increased. To avoid it deviate from 6 °C, K_p and T_i were reduced immediately. Therefore, EEV opening was responded to increase and DS setting was observed to return to the setting in short time.

At 9000 s into the test, a step change of supply fan speed was made from 100% to 60%. Due to the sudden disturbance, a significant reduction of DS was measured. The adaptive DS controller was immediately responded by simultaneously increasing K_p and T_i, resulting a decreasing EEV opening. The measured DS value reached its new set point in about 1000 s, and after that, the DS value can be steadily controlled.

At 12600 s into the test, the supply fan speed was changed back to 80%. Small variations of DS value could be observed. In the remaining of the testing period, the DX A/C system was operated at constant supply fan speed, with DS and EEV openings steadily maintained.

In Test 2, the DX A/C system were operated at different compressor speed and indoor air status from Test 1. The

experimental results were similar as Test 1.
The two disturbance rejection test results clearly demonstrated that the adaptive DS controller could well control the DS setting at. Despite the variability of fan speeds, the controller shows a very stable behavior, allowing an effective and fast control of the DS setting.

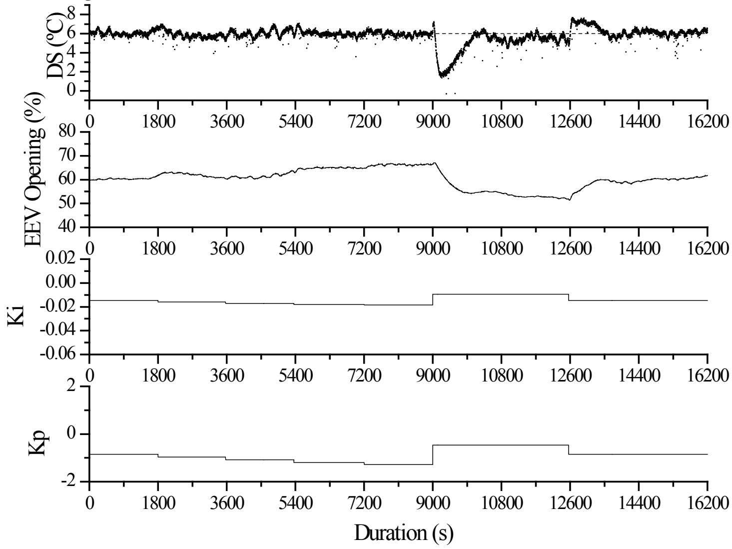

Figure 5 Variation profiles of DS, EEV opening and PI control parameters in the DX A/C system (Test 1)

4. Conclusions

Fixed PID control parameter were usually used in previous EEV controllers, resulting in unstable operating conditions in A/C system. Within this context, an adaptive DS controller is developed and reported in this paper. Based the experimental performance of a DX A/C system, the adaptive DS controller is designed to seasonably regulate the degree of superheating at the evaporator outlet. Experimental controllability test results show that the controller has a very stable behavior, allowing an effective and fast control of the DS setting.

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