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Research Paper

Inherent operational characteristics and operational stability of a variable speed direct expansion air conditioning system

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HIGHLIGHTS

- VS DX A/C system's inherent operational characteristics considering stability studied.
- Speed combinations, DS settings and inlet air states influenced operational stability.
- Evaporator superheat nonlinearity can be used to explain instability.

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ABSTRACT

Previous studies on the inherent operational characteristics of a variable speed (VS) direct expansion (DX) air conditioning (A/C) system at a fixed degree of refrigerant superheat (DS) setting without considering its operational stability have been conducted. Therefore, a follow-up study on the inherent operational characteristics of a VS DX A/C system considering its operational stability has been carried out and the study results are reported. Using an experimental VS DX A/C system, the inherent correlations between its output total cooling capacity (TCC) and equipment sensible heat ratio (E SHR) at different combinations of compressor speed and supply fan speed were studied and the unstable operating points of speed combinations under different DS settings and inlet air states identified. The experimental results suggested while different DS settings may not significantly influence the inherent correlations between TCC and E SHR, but did impact the operational stability. A lower DS setting would result in a larger unstable operating region. Furthermore, VS operation and different inlet air states to the DX evaporator also influenced the operational stability. A higher compressor speed or a lower supply fan speed, and a lower inlet air temperature or relative humidity would lead to a higher chance to instability.

1. Introduction

A direct expansion (DX) air conditioning (A/C) system cools air directly by the expansion of refrigerant inside its DX evaporator or cooling coil. DX A/C systems are hence simpler in configuration, more energy efficient and generally cost less to own and maintain. Therefore, DX A/C systems are widely used in different types of buildings. With the introduction of variable speed (VS) technology to DX A/C systems, both compressor and supply air fan in a DX A/C unit can be simultaneously varied, paving the way to simultaneously control indoor air temperature and humidity by varying simultaneously compressor and supply fan speeds. Over the years, various studies on developing advanced controllers to simultaneously control indoor air temperature and humidity using VS DX A/C systems have been carried out [1–5].

The simultaneous control of both indoor air temperature and relative humidity (RH) using a VS DX A/C system requires the match between not only the total output cooling capacity (TCC) of an A/C system and the total cooling load in a space served by the A/C system, but also Equipment SHR (E SHR), which is defined as the ratio of sensible heat (load) to the total heat (load), of the A/C system and Application SHR (A SHR) of the space [6]. When a VS DX A/C system is used, continuously varying the speeds of both compressor and supply fan would vary E SHR and TCC of the VS DX A/C system so as to match the varying space cooling load to maintain the desired indoor air temperature and humidity. Therefore, to correctly understand the operational characteristics of a VS DX A/C system expressed in terms of its E SHR and TCC at different compressor and fan speed combinations is fundamental to developing control algorithms for simultaneous control over indoor air

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Nomenclature

C	percentage of the maximum compressor speed (%)
F	percentage of the maximum supply air fan speed (%)
M_a	mass flow rate of air through the evaporator (kg/s)
C_{pa}	specific heat (kJ/(kg K))
h_a	air enthalpy (kJ/kg)
Q_s	sensible cooling capacity (kW)
K_e	evaporator gain (°C h/kg)
T_e	evaporating temperature (°C)
T_{db}	air dry-bulb temperature (°C)
T_{wb}	air wet-bulb temperature (°C)

Subscripts

i	inlet
o	outlet
s	sensible

Abbreviations

TCC	total cooling capacity
A SHR	application sensible heat ratio
E SHR	equipment sensible heat ratio
RH	relative humidity
VS	variable speed
DX	direct expansion
A/C	air conditioning
DS	degree of refrigerant superheat
MSS	minimal stable signal
TEV	thermostatic expansion valve
EEV	electronic expansion valve
LGU	load generating unit
RTD	resistance temperature device
FOPDT	first-order plus dead time
IC	inherent correlation
IC_os	inherent correlation considering the operational stability

temperature and humidity using a DX A/C system. For a VS DX A/C system, the inherent correlations (ICs) between its output TCC and E SHR at different combinations of compressor and supply fan speeds were firstly studied by Xu et al. [6]. The study clearly revealed that the output TCC and output E SHR of a VS DX A/C system under VS operation were strongly coupled and mutually constrained within a trapezoid if the two parameters are presented in the same diagram. Li et al. [7] further studied the operational characteristics for the same experimental VS DX A/C system, but at different inlet air states. The study results illustrated that both of the inlet air temperature and relative humidity (RH) level would influence the ICs of the VS DX A/C system.

On the other hand, the degree of refrigerant superheat (DS) is also a very important operating parameter for a refrigeration system, affecting both its operational stability and energy efficiency. It is commonly acknowledged that a smaller DS would lead to a higher operating efficiency but a poorer operating stability, and vice versa. When the operation of a refrigeration system is unstable, key operating parameters such as refrigerant mass flow rate and evaporating pressure would fluctuate, which is conventionally known as hunting. Hunting has been noticed in not only the refrigeration systems controlled by thermostatic expansion valves (TEVs) [8–12], but also those controlled by electronic expansion valves (EEVs) [13–16]. Hunting leads to a lower operational stability, and a higher energy consumption of the refrigeration system and should be avoided as far as possible. The classical theory of minimal-stable-signal (MSS), defined as a critical minimal DS at which a refrigeration system could exhibit unstable operation, was proposed by Huelle [17]. Huelle [18] later introduced conceptually a so-called MSS line which was a monotone conic curve starting from the original point on a DS (X-axis) – cooling capacity (Y- axis) chart as shown in Fig. 1. As seen, to a specific cooling capacity, there existed a minimal DS to separate a stable region from an unstable region. Therefore, having an appropriate DS setting that can ensure on one hand a higher operating efficiency, and on the other a better operating stability is very important. However, in the previous reported studies on the inherent operational characteristics of the VS DX A/C system [6,7], a constant DS setting of not smaller than 6 °C was used, and hence the issues of operational stability and energy efficiency under different DS settings at various speed combinations of compressor and supply fan were not taken into consideration.

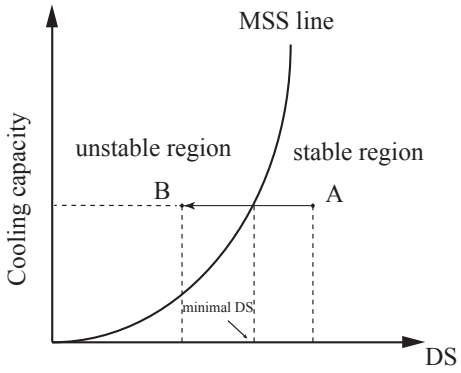

Fig. 1. The MSS line proposed by Huelle [18].

In addition, it was previously shown that the variation of compressor speed impacted the operational stability of an EEV controlled refrigeration system [14], and the water side characteristics for a TEV controlled water chiller also impacted the operational stability [12,19,20]. In fact, in a VS DX A/C system, VS operation or different inlet air states would result in different surface wetness of its DX evaporator, significantly affecting the air side heat transfer, and hence, the overall heat transfer characteristics in the DX evaporator, leading to a potential change in the operating DS at evaporator exit. Consequently, the operational stability of a VS DX A/C system may also be affected due to its VS operation and different inlet air states.

It can be seen, therefore, that while the inherent operational characteristics of a VS DX A/C system in terms of TCC and E SHR under different speed combinations of compressor and supply fan and different inlet air states have been studied in previous studies [6,7], no studies on the influences of operating DS on the inherent operational characteristics may be identified. Furthermore, there were a limited number of studies on the operational stability of a refrigeration system when it was variable compressor speed operated [14,15]. No studies on the influences of varying both compressor speed and supply fan speed at different inlet air states on operational stability may be identified. Therefore, a follow-up study on the inherent operational characteristics of a VS DX A/C system considering its operational stability at