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A direct expansion based enhanced dehumidification air conditioning system for improved year-round indoor humidity control in hot and humid climates

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ABSTRACT

Once a conventional On-Off controlled single evaporator direct expansion (DX) air conditioning (A/C) system is installed, it has to be operated at different seasonal cooling load situations, and hence would have a hard time in trying to maintain the desired indoor thermal environment at all times, unless complicated and costly supplementary measures to provide variable dehumidification capacity are provided. Therefore, a novel standalone enhanced dehumidification A/C (EDAC) system was proposed based on multi-evaporator air conditioning technology. This paper reports an experimental study on the developments of such an EDAC system and the control strategy for operating the EDAC system for achieving improved year-round indoor humidity level. Firstly, the detailed configurations of the EDAC system and the control strategy are presented. Secondly, a detailed description on the setup of a prototype experimental EDAC system, and on instrumentation and experimental cases is reported. This is followed by presenting the experimental results and related discussions. The experimental results show that the use of the EDAC system and the control strategy was able to achieve year-round improved indoor humidity control, while still maintaining the required indoor air temperature control in hot and humid climates, at a higher energy efficiency, as compared to a conventional On-Off controlled single evaporator DX A/C system.

1. Introduction

In buildings, controlling indoor humidity at an appropriate level is critically important since this directly affects building occupants' thermal comfort, indoor air quality (IAQ) and the operating efficiency of building A/C systems [1–5]. Direct expansion (DX) based A/C systems are widely used for controlling indoor air temperature and humidity in various buildings because they are simpler and more energy efficient, and generally cost less to own and maintain [6].

In hot and humid climates, such as Hong Kong, A/C is usually required for more than 7 months from April to October in a year. At different time period within the 7 months, however, space latent load that directly affects indoor air humidity level can vary significantly. A previous study [7] suggests that in a bedroom in a residential flat in Hong Kong, the share of the latent part in the total space cooling load is at 53%, i.e., at an sensible heat ratio (SHR) value of 0.47 (or 1–53%) in April, but only 28% in October and stays between 30% and 40% in the other months. Therefore, in hot and humid climates in different seasons in a year, different cooling and dehumidification requirements in an air conditioned space will be encountered, as follows:

- In April to early May (Period I), at a low SHR value, with a moderate outdoor air temperature usually lower than 25 °C but a higher moisture content, space air conditioning is dominated by dehumidification;
- From mid-May to mid-September (Period II), both outdoor air temperature and moisture content stay high, and therefore both air cooling and dehumidification are required;
- In mid-September to October (Period III), outdoor air temperature may still be high, but outdoor air is drier and space air conditioning dominated by air cooling, demanding less dehumidification.

If a DX A/C system is used, it will, once installed, then have to be operated at different seasonal space cooling load conditions. However, the current trend in designing a conventional DX A/C system is to have a smaller moisture removal capacity in an attempt to boost its energy

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Nomenclatures

ΔRH	relative humidity control dead-band, %
ΔT	temperature control dead-band, °C
RH_i	indoor air relative humidity, %
$RH_{i,s\ (ADO)}$	indoor air relative humidity set point at ADO mode, %
$RH_{i,s\ (EDAC)}$	indoor air relative humidity set point at EDAC mode, %
T_i	indoor air temperature, °C
$T_{i,s\ (ADO)}$	indoor air temperature set point at ADO mode, °C
$T_{i,s\ (EDAC)}$	indoor air temperature set point at EDAC mode, °C
T_o	outdoor air temperature, °C
$T_{o,\ ac}$	outdoor air temperature above which air conditioning is required, °C
T_S	supply air temperature, °C

Subscripts

o	outdoor
i	indoor
S	supply air
s	set

Abbreviations

A/C	air conditioning
A SHR	application sensible heat ratio
ADO	air dehumidification only
COP	coefficient of performance
DX	direct expansion
EEV	electronic expansion valve
EER	energy efficiency rating
EDAC	enhanced dehumidification air conditioning
FRMA	airflow rate measuring apparatus
HX1	the first heat exchanger
HX2	the second heat exchanger
IAQ	indoor air quality
LGU	load generating unit
MEAC	multi-evaporator air conditioning
PID	proportional-integral-derivative
PLR	part load ratio
SEAC	single evaporator air conditioning
SHR	sensible heat ratio
SSLC	separate sensible and latent cooling
SV	solenoid valve
VCD	air volume control damper
VS	variable speed

efficiency ratings (EER) and Coefficient of Performance (COP) [8]. Furthermore, most DX A/C systems are equipped with a single speed compressor and supply fan, relying on On-Off cycling of the compressor as a low cost approach to maintaining only indoor air temperature, whereas indoor air humidity is not controlled directly. Therefore, when a conventional on-off controlled DX AC system is operated during the above three respective periods, different indoor thermal environments may be resulted in and various supplementary measures to ensure correct indoor thermal environmental control employed, as follows:

During Period I, a conventional on-off controlled DX AC system deals with a high indoor latent load and a relatively low sensible load, and space overcooling is therefore common, unless reheating is provided. However, reheating is obviously energy inefficient and is prohibited in many building energy codes. Furthermore, it is difficult to include a re-heater in certain DX AC systems such as a room air conditioner.

To address the problem of space overcooling, an additional standalone dehumidifier, either desiccant based or vapor compression based, may be employed. However, heat generated by a solid desiccant dehumidifier or rejected from the condenser of a vapor compression based dehumidifier can cause thermal discomfort for occupants [9]. On the other hand, a DX AC system may be modified, so that the heat rejected from its condenser which is usually air cooled, or the hot refrigerant gas discharged from its compressor, may be used for reheating air, as described in a number of US patents [10–12]. Recently, an isothermal dehumidifier [13] was proposed, where its DX cooling coil was split into two parts. In the cooling mode, both parts acted as a cooling coil, but in dehumidification mode, one part acted a cooling coil and the other as a refrigerant sub-cooler to heat dehumidified air. The common problems resulting from these modifications, however, included complicated refrigerant circuits and increased air flow resistance due to the addition of a re-heater which is redundant when not in use. In addition, these modifications only address the issue of space overcooling in this particular period of relatively short durations.

During Period II, the demands for both air cooling and dehumidification are high. For a conventional on-off controlled DX A/C system, while it can be operated by On-Off cycling of its compressor to maintain its required indoor temperature setting, indoor air humidity is usually left uncontrolled. Hence, inadequate dehumidification is often encountered due to its smaller moisture removal capacity, leading to a higher equilibrium indoor humidity.

To address the problem of inadequate dehumidification, there can be two major approaches to achieving better indoor humidity control when using DX A/C systems. The first is DX based separate sensible and latent cooling (SSLC) technology to provide supplementary dehumidification capacity. There are reported studies on the development of various SSLC technologies. For example, Ling et al. [14] theoretically studied the pertinent characteristics of a SSLC system using two parallel compression cycles, one for sensible cooling and the other latent cooling. This led to a complicated system configuration and a higher initial cost as two refrigeration cycles were included. In other developments related to SSLC technology, supplementary dehumidification capacity was provided by using desiccant, where the energy used for desiccant regeneration came from either the heat rejected from a condenser in a vapor compression refrigeration cycle [15–18] or solar heat [19–22]. However, it can be also understood that while the use of desiccant can provide sufficient supplementary dehumidification capacity to achieve the desired indoor air temperature and humidity control, such a desiccant assisted SSLC A/C system is inevitably complicated, with higher initial and operational/maintenance costs.

The other major approach is to simultaneously vary the compressor and supply fan speeds in a DX A/C system so as to obtain different system output total cooling capacity and SHR to deal with different space sensible and latent loads. Over the years, there have been extensive detailed studies on the operational characteristics of a DX A/C system under variable speed (VS) operation [23,24] and thus a number of novel capacity controllers [25–32] have been developed. It has been shown that when a VS DX A/C system is operated at a high compressor speed but a low fan speed, a lower evaporating temperature and thus better dehumidification can be achieved, but this is at the expense of running the system at a low efficiency [23,24]. The novel capacity controllers developed, in addition, are usually complicated and need to be supported by suitable mathematical models, involving such advanced complex calculation algorithms as artificial neural network (ANN) [28,29] and fuzzy logic [30,31], thus leading to a high development cost.