Energy and Buildings 121 (2016) 22–31

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Applicability and energy efficiency of temperature and humidity independent control systems based on dual cooling sources

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ARTICLE INFO

Article history:
Received 20 October 2015
Received in revised form 1 April 2016
Accepted 1 April 2016
Available online 1 April 2016

Keywords:
THIC
Dual cooling sources
Applicability
Heat moisture ratio
Energy efficiency

ABSTRACT

Temperature and humidity independent control (THIC) systems demonstrate promising energy-saving potential compared with the conventional air conditioning systems. One type of THIC systems is proposed to use dual cooling sources with different temperatures since they could be produced easily by traditional vapor compression refrigeration chillers. This paper investigates the applicable condition of the THIC system based on dual cooling sources (DCSTHIC system). It is found that the DCSTHIC system has limited conditions (such as scopes of the heat moisture ratio and the fresh air rate) when applied, otherwise the indoor air temperature and humidity can't be fulfilled, and further available scope of the heat moisture ratio realized by the DCSTHIC system is disclosed for air conditioned spaces. The minimum realized heat moisture ratio depends on the temperature of low-temperature cooling sources (t_{LCS}). A parametric study is also conducted to analyze effects on the energy efficiency of DCSTHIC systems. These parameters include the heat moisture ratio (ε) and temperatures of dual cooling sources. Results show that DCSTHIC systems show more significant energy-saving potential in the air conditioned spaces with higher ε. The system COP improvement ranges from 3.1% to 17.5% compared with conventional air conditioning systems when the heat moisture ratio changes from 8000 kJ/kg to 15,000 kJ/kg. This study helps to guide the design and optimization of DCSTHIC systems.

1. Introduction

Conventional air conditioning (CA) systems handle sensible and latent loads simultaneously, leading to lower COP of the chiller. This is owing to the fact that air must be cooled at a temperature below the dew point to allow condensation [1,2]. Although CA systems can meet the demand of temperature and humidity adjustment, they suffer from the problem of huge energy consumption. Therefore, many researchers work on the novel air conditioning systems to enhance the energy efficiency [3–8].

Varieties of hybrid systems were constructed and tested to reduce energy consumption, where a combination of different techniques was used. These techniques contained vapor compression refrigeration, adsorption refrigeration, absorption refrigeration, ejection refrigeration, evaporative cooling, liquid desiccant dehumidification and solid desiccant dehumidification [9–12]. Among these hybrid systems, temperature and humidity independent control (THIC) systems are prevalent and have been promoted to be alternatives to CA systems in recent years. These systems separate the latent load from the total load, removing the latent load independently. Thus, evaporators are allowed at a higher temperature to deal with the sensible load and the COP of the chiller is improved [13,14]. Some investigators developed and conducted performance analysis on the THIC systems employing hygroscopic desiccants. Ma et al. [15] investigated a system which consisted of three subsystems namely a vapor compression heat pump system, an adsorbent refrigeration system and a liquid desiccant dehumidification system. The system showed more enhancements in performance under larger latent load ratio. Zhao et al. [16] studied the effectiveness of a THIC system using the liquid desiccant to control humidity in an office building. They found the COP of the entire system driven by heat pump could reach up to 4.0 in Shenzhen. A radiant cooling system integrated with liquid desiccant dehumidification was presented by Quan et al. [17]. In the system, the latent load was removed by a part of dry air derived from desiccant dehumidification and the sensible load was removed by the chilled water produced by the other part dry air through evaporative cooling. Dai et al. [18] presented a system using solid adsorbent to realize refrigeration and dehumidification simultaneously. The system was used

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http://dx.doi.org/10.1016/j.enbuild.2016.04.001
0378-7788/

Nomenclature

d	Humidity ratio, kg/kg
h	Enthalpy of air, kJ/kg
t	Temperature, °C
t_g	Dry-dulb temperature, °C
t_s	Wet-dulb temperature, °C
G	Air flow rate, kg/s
GL	Air rate processed by the LTCS, kg/s
GW	Fresh air rate, kg/s
$COP1$	COP of the LTCS
$COP2$	COP of the HTCS
COP_S	System COP
Q_L	Load processed by the LTCS, kW
Q_H	Load processed by the HTCS, kW
Q_1	Indoor load, kW
W_1	Indoor latent load, kg/s
g	Acceleration of gravity, m/s^2
M	Water flow rate, m^3/s
H	Total head of the pump, m
w	Energy consumption, kW
h_L	Air enthalpy of state L, kJ/kg
Greek	
ε	Heat moisture ratio, kJ/kg
ϕ	Relative humidity, %
ρ	Density of the chilled water, kg/m^3
η	Pump efficiency
Subscripts	
LCS	Low-temperature cooling source
HTS	High-temperature cooling source
m	Mixed
min	Minimum
max	Maximum
N	Indoor air state
W	Fresh air state
tot	Total
P	Pump
F	Fan
CS	Cooling source

in a grain depot to create the environment suitable for storage. The adsorbent refrigeration system worked in the night and removed the heat gained in the day while the rotary adsorbent dehumidification system worked to carry away moisture produced by grains. Based on modeling in EnergyPlus, Jiang et al. [19] simulated a THIC system, which combined a solid desiccant dehumidification system with a VRF system. They also set up the test rig to verify performance of the system [20]. The proposed system could achieve more comfortable conditions and consume less energy. According to the basic principle of THIC, some investigators also make efforts to find out whether similar efficient systems can be built by the simple cooling dehumidification. Han and Zhang [21] introduced a novel air-conditioner suitable for residential houses. The air-conditioner consisted of two evaporators. One produced chilled water delivered to the radiation panel for temperature control and the other produced dry air for humidity control. Experiments were conducted to investigate effects of outdoor temperature, indoor temperature, indoor humidity, compressor frequency and refrigerant distribution ratio on the unit performance. It was found that this air-conditioner could save about 15.6% of energy consumption. Luo [22,23] simulated the energy consumption of THIC systems using dual cooling sources applied in the offices, hotels, meeting rooms and markets. Results showed that compared with CA systems, these systems using fresh air to control humidity were not energy-saving in hotel buildings. Therefore, Luo suggested that instead of fresh air, the mixture of fresh air and return air should be used to remove the latent load in hotel buildings.

However, literatures on systems using dual cooling sources which are called THIC systems based on dual cooling sources (DCSTHIC systems) are still very limited. The open literature has not given the accurate and explicit answers to following problems: (1) What conditions are the DCSTHIC systems suitable for or which criteria can be used to evaluate the system applicability quantitatively? (2) What is the relative significance of several factors impacting the system performance? In this paper, the heat moisture ratio was proposed to mainly evaluate the system applicability and another limitation of the DCSTHIC system was also discovered, such as maximum fresh air rate which could be applied in such kind of DCSTHIC system. Furthermore, a parametric study was employed to probe effects on the system performance and determine the most important factor.

2. Typical modes of the DCSTHIC system

DCSTHIC systems are usually supported by dual cooling sources including the high-temperature cooling source (HTCS) and the low-temperature cooling source (LTCS). Sensible load in rooms is removed for temperature control due to the sensible cooling of the HTCS. And latent load in rooms is removed for humidity control due to the extremely low temperature of air, which is processed to below dew point by the LTCS. The processed air for temperature control is usually from return air while the processed air for humidity control can be from fresh air or return air. Thus, according to different air handling processes, three typical modes exist in the DCSTHIC systems.

As shown in Fig. 1(a), if the fresh air is not required in the system, the processed air for humidity control consists of the return air. The DCSTHIC system is operated in Mode 1, where one part of the return air is cooled and dehumidified to the machine dew point (state L) for removing the latent load and the other part of the return air is cooled to state C for removing the sensible load (Fig. 2(a)). The mixed state of states L and C is the supplied air state O, which is located on the heat moisture ratio (ε) line of the air conditioned space.

As shown in Fig. 1(b), if the fresh air is required in the system, the processed air for humidity control consists of the mixture of the return air and the fresh air. The DCSTHIC system can be simply operated in Mode 2. In fact, the fresh air demand makes Mode 1 shifts to Mode 2. One part of the return air for humidity control in Mode 1 is replaced by the same quantity of fresh air in Mode 2. As illustrated in Fig. 2(b), the air handling process of Mode 2 is similar to Mode 1.

In Mode 2, plenty of cooling capacity provided by the LTCS is used to process the fresh air. In order to promote the energy efficiency of the system, Mode 3 allows precooling by the HTCS. As illustrated in Fig. 1(c) and Fig. 2(c), the mixed air with state M is firstly precooled to the state L1, and then cooled and dehumidified to the state L by the LTCS. The other air handling process is the same as Mode 2.

3. Applicability and constraint of the DCSTHIC system

3.1. Constraint of the DCSTHIC system for the heat moisture ratio of air conditioned space

In the DCSTHIC systems mentioned in section 2, state N is the indoor air state and state O is the supplied air state located on the heat moisture ratio line. One part of air with state L and the other