Applied Energy 225 (2018) 233–243

Contents lists available at ScienceDirect

Applied Energy

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

Comparative study of on-off control and novel high-low control of regenerative indirect evaporative cooler (RIEC)

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HIGHLIGHTS

- High-low control is proposed for indirect evaporative cooler.
- High-low control and on-off control are comparatively studied.
- Better thermal comfort and air quality can be achieved by high-low control.
- Annual energy consumption is reduced by 11.3% under high-low control.

ARTICLE INFO

Keywords:
Indirect evaporative cooler
Comparative study
Controller
Thermal comfort
Energy efficiency

ABSTRACT

The main characteristic of an indirect evaporative cooler (IEC) is its dependency on ambient air conditions. To ensure stable indoor temperature and provide better thermal comfort for the occupants, proper control strategy is essential. However, very limited studies report the controller used in IEC. Therefore, two control schemes are comparatively studied for regenerative indirect evaporative cooler (RIEC) application, including conventional on-off control and newly proposed high-low (H-L) control. Under on-off control scheme, the fans are either in operation at constant rated speeds or turned off if the indoor temperature is satisfied. While under H-L control scheme, the fans would be switched between high speed and low speed rather than completely turned off. The annual performance of RIEC was simulated under the two control schemes based on the RIEC model and dynamic indoor heat and mass balance model. The results show that the H-L control is superior to on-off control by providing better thermal comfort, better indoor air quality and 11.3% less energy consumption annually. The advantages of H-L control are mainly reflected in transition seasons with smaller indoor temperature variation range, lower switch frequency of the fan speed, smaller predicted mean vote (PMV) variation and longer fresh air guarantee.

1. Introduction

Indirect evaporative cooler (IEC), a sustainable cooling device, has received intensive attentions worldwide in recent decades for its energy efficient, low energy consumption and environmental friendly features [1]. Based on cooling the air by water evaporation, the energy intensive compressor and environmentally harmful Chlorofluorocarbon (CFC) in the conventional mechanical vapor compression refrigeration (MVCR) system are unnecessary. The air passing through an IEC can be sensibly cooled by the walls with the aid of water evaporation in the adjacent channels. Unlike the MVCR system that highly replies on energy-intensive vapor compression process, an IEC equipped with only two air fans and a circulating pump is characterized by low energy consumption. In theory, the lower limit outlet air temperature of an IEC is the wet-bulb temperature of ambient air. However, in recent decade, a more advanced IEC named regenerative IEC (RIEC) was proposed and intensively studied, with the ability to cool the fresh air to its dew-point temperature [2].

The evaporative cooling is proved to have huge energy saving potential in hot and arid regions because of large evaporation driving force [3–5]. However, the main shortcoming of this technology is its high dependency on ambient weather conditions. The supply air temperature is greatly influenced by the variation of outdoor temperature, humidity and internal cooling load from season to season and even from minute to minute [6]. To ensure stable indoor temperature and provide better thermal comfort to the occupants, proper control strategy is

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https://doi.org/10.1016/j.apenergy.2018.05.046
Received 8 March 2018; Received in revised form 5 May 2018; Accepted 9 May 2018

Nomenclature

A	heat and mass transfer area, m^2
H	cooler height, m
Q	cooling load, W
T	time interval
V	volume, m^3
c_{pa}	specific heat of air, J/kg·°C
c_{pw}	specific heat of water, J/kg·°C
h	heat transfer coefficient, W/m^2·°C
h_m	mass transfer coefficient, kg/m^2·s
h_{fg}	latent heat of vaporization of water, J/kg
i	enthalpy of air, J/kg
m	mass flow rate, kg/s
r	extraction air ratio of RIEC
s	channel gap, m
t	Celsius temperature, °C

Greek symbols

ω	moisture content of air, kg/kg
ρ	air density, kg/m^3

Subscripts

H	high speed
L	low speed
N	indoor air
p	primary air
s	secondary air
w	wall/water
ew	evaporation water
in	inlet
out	outlet
sup	supply air
sen	sensible heat
lat	latent heat

Abbreviations

IEC	indirect evaporative cooler
H-L	high-low control
PMV	predicted mean vote
MVCR	mechanical vapor compression refrigeration system
RIEC	regenerative indirect evaporative cooler
HVAC	heating, ventilation and air-conditioning

essential.

However, current research on IEC focuses on heat and mass transfer modeling [7–10], performance evaluation [11,12] and configuration optimization [13–15], very limited research work can be found reporting the control strategy in open literatures. The most simple and widely used control scheme is on-off control, in which the fans are either operated at a constant speed or turned off if indoor temperature is lower than the setting point. The on-off control is simple, stable and easy to implement, but two shortcomings can be identified. Firstly, no ventilation is provided when an IEC is at 'off' state. Satisfactory indoor air quality (IAQ) cannot be guaranteed, leading to building sick syndrome (BSS) or even outbreak of infectious diseases. Secondly, frequently switching on and off of a fan in transition season is inevitable. It will reduce the life span of the fan and increase its maintenance cost. Although on-off control is widely used in current IEC product, its actual performance has not been reported in detail in open literatures.

To overcome the weaknesses of on-off control, the development and availability of variable speed fan could provide an alternative solution. The fan speed is continuously adjustable under different cooling load. Maximum flow rate is provided at peak cooling load and smaller flow rate is supplied under lower cooling load. The variable speed fan and pump have been successfully implemented in many HVAC equipment and water distribution systems with considerable energy saved [16,17]. New standards of variable speed air conditioning system in China have also been issued as GB21455-2013 and CEL 010-2016, providing minimum allowable values and energy efficiency grade for air-cooled condenser, fully enclosed speed-controlled compressor and speed-controllable air conditioner in climate type T1 [18,19]. However, its most significant disadvantages are high cost and complexity in control algorithm [20,21].

The disadvantages of on-off control and variable speed technology motivate us to develop a novel control strategy that balances the control performance and complexity. There are multi-speed fans available in the market to overcome the pricy and complexity of variable speed technology. The high-low (H-L) control is therefore proposed for IEC. The operation states of the fan include high speed, low speed and shutdown. The high speed is designed to meet the peak cooling load and the low speed meet the minimum fresh air demand of the occupants. The fan operates at high speed when the indoor air temperature is higher than the setting value and at low speed if the indoor air temperature is satisfied. The H-L control scheme combines the advantages of on-off control and variable speed fan for the following reasons. Firstly, no ventilation at 'off' state in on-off control is avoided. Secondly, the proposed H-L control can be realized using multi-speed fans without inverter. Therefore, it is much simpler and less costly than variable speed fan. Thirdly, usage of multi-speed fans is expected to provide energy saving potentials under low speed operation based on affinity laws. In sum, the successful carrying out of the novel control scheme of IEC would help achieve improved indoor air quality for occupants and reduced energy consumption.

Actually, the H-L control had been initially proposed by Xu et al. [22] and applied into direct expansion air-conditioning system. Extensive experiment has been conducted to quantitatively compare the performance of H-L control and traditional on-off control in term of energy efficiency and fluctuation of indoor air parameters. The results show that improved humidity level and higher energy efficiency can be achieved by H-L control. Besides, hardware cost is much lower than that of variable speed technology, contributing to more potential market-oriented applications. Yan et al. [23,24] conducted further experimental and theoretical studies on the H-L control by expanding its application to multi-evaporator air conditioning (MEAC) system.

Although H-L control has been theoretical and experimentally investigated in MVCR system, it has not ever been proposed and quantitatively analyzed for IEC. There are huge differences between MVCR system and IEC system. Firstly, the heat and mass transfer process in MVCR system is complex. It involves with refrigerant, metal walls and air in the evaporator, condenser, electronic expansion valve and compressor. However, the heat and mass transfer process in IEC takes place in primary air channel and secondary air channel with water, air and plate wall involved. Secondly, the MVCR system relies on vapor refrigerant compression process, which is greatly influenced by compressor speed and supply air fan speed. However, the IEC, relying on water evaporation process, is mainly influenced by ambient air temperature and humidity. Thirdly, previous H-L control in MVCR system is used for compressor and indoor supply fan. While the H-L control in IEC is used for primary air fan and secondary air fan.

Considering the working principle and operational characteristics of MVCR system are very different from ambient sensitive IEC, a feasible study is needed to investigate whether H-L control is still effective for IEC, a promising alternative to MVCR system in the future. Although it