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Experimental study of plate type air cooler performances under four operating modes

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A B S T R A C T

To reduce the chiller energy consumption in a central air-conditioning system, a heat exchanger, acting as an air cooler, can be installed before an air handling unit to pre-cool the fresh air by recovering cooling capacity from exhaust air. However, studies on evaluating the performances of air cooler under condensation condition are limited. Therefore, an experimental study was conducted to evaluate the plate type air cooler performance under four operating modes (dry/wet mode, low/high air humidity). Under dry operating mode, the air cooler serves as a traditional air cooler; while under wet operating mode, it works as an indirect evaporative cooler (IEC). The cooler dynamic performances during different operating mode transition were investigated. The steady performances under different parameter influence were also comparatively studied. The results show that wet operating improves the sensible and latent cooling capacities of air cooler significantly. Condensation takes place under high humidity inlet air, results in decreasing of sensible efficiency but increasing of latent efficiency and total heat transfer rate. The coefficient of performance (COP) of IEC is higher than that of traditional air cooler under the same testing configuration. The highest COP can reach 9.0 and achieved under wet operating mode with condensation.

1. Introduction

The air-conditioning system is well-known for intensive energy consumption, especially in hot regions where cooling is greatly needed [1,2]. It was reported that in Hong Kong the energy consumption for air conditioning in commercial buildings and residential buildings take up as much as 30% and 31% of the total building energy consumption, respectively [3]. To reduce the energy consumption in an air-conditioning system, energy recovery can be adopted by installing a heat exchanger before an air handling unit (AHU) to pre-cool the incoming fresh air using the exhaust air from air-conditioned space. The heat exchanger can be a traditional sensible air-to-air heat exchanger (plate, fin-plate and fin-tube), heat recovery wheel (sensible and enthalpy), indirect evaporative cooler (dry-coil and wet-coil) or any novel heat exchangers.

The traditional sensible air-to-air heat exchanger, acting as an air cooler, is regarded as a reliable and durable heat recovery device in a ventilated air-conditioning system, which is also introduced in ASHRAE Handbook [4]. The modeling of this device has been fundamentally studied. The simple model adopts uniform heat transfer coefficient and one-dimensional analysis [5]. The variations of heat transfer coefficient and air temperature along the fins were taken into consideration in some improved models [6,7]. A three-dimensional model for analyzing the performance of cross-flow fin-tube heat exchangers under dry and dehumidifying conditions was proposed by An and Choi [8]. The simulation results showed that for dehumidifying cases, the sensible heat transfer rate seemed insensitive to the inlet humidity change. Although the modeling of such heat recovery device has been widely reported, limited experimental works had been presented in literatures. Fernandez-Seara et al. [9] experimentally analyzed an air-to-air heat recovery unit equipped with a sensible polymer plate heat exchanger (PHE) in residential buildings, but no condensation case was reported. Gendebien et al. [10] developed a model for an air-to-air heat exchanger dedicated to heat recovery ventilation considering dry (non-condensation) and partially wet regimes (condensation). The experimental tests were conducted but focused on validation of the proposed semi-empirical model.

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Nomenclature

c_{pa}	specific heat of air, J/kg·°C
h_{fg}	latent heat of vaporization of water, J/kg
i	enthalpy of air, J/kg
m	air mass flow rate, kg/s
P	power consumption, W
Greek symbols	
ω	moisture content of air, g/kg
Subscripts	
p	primary/fresh air
s	secondary/exhaust air
out	outlet air
in	inlet air
Q	heat transfer rate, W
s	channel gap, m
t	Celsius temperature, °C
u	air velocity, m/s
η	sensible efficiency
wb	wet-bulb
sen	sensible heat
lat	latent heat
tot	total heat

Indirect evaporative cooler (IEC) is another heat exchanger which can be used for energy recovery in an air-conditioning system. It has been regarded as a promising energy-saving technology for its high efficient, low energy consumption, pollution-free and easy maintenance features [11,12]. Unlike the traditional heat exchanger, the IEC needs to be operated under wet condition and produces cooling air by water evaporation. The most commonly used plate-type IEC consists of a traditional plate-type heat exchanger, a water circulation and a distribution system. The heat exchanger is composed of alternative wet and dry channels which are separated by thin plates. In the wet channels, the spraying water drops form a thin water film on the plate surface and consistently evaporates into the main stream of the secondary air. The primary air in the adjacent dry channels is cooled by the low separating wall [13].

The IEC is widely used for cooling in hot and dry regions because larger cooling capacity can be achieved with low humidity fresh air [14–18]. The cooled primary air is supplied to the interior directly in these regions. In hot and humid regions, the supplied primary air temperature is limited to the high wet-bulb temperature of ambient air, so it is used as an energy recovery device installed before an AHU or cooling coil in an air-conditioning system [19]. The exhausted air with lower wet-bulb temperature from air-conditioned space is used as secondary air to pre-cool the primary air (fresh air). This hybrid cooling system consisted of IEC and mechanical cooling receives great attention in recent years for its high energy saving potential [20–22].

The heat and mass transfer process of IEC has been fundamentally studied by analytical models and numerical models considering different factors, such as evaporation water loss, water film temperature variation, heat conduction of wall, variable Lewis factor and condensation from primary air [23–28]. The experimental study and filed measurement have also been conducted to various kinds of IEC, aiming at: 1. testing the operational characteristics under the controlled laboratory and real building conditions; 2. verifying the established models. Tulsidasani et al. [29] experimentally tested the COP for a tube type IEC at India summer operation condition. It was found that the maximum COP reached 22. Qiu [30] tested a small scale IEC prototype and the poor wetting of plate surface was suspected from the results. Velasco Gómez [31] investigated a polycarbonate-made IEC under two operational modes: with spray water and without spray water. Experimental results proved the spraying water could enhance the cooling performance. Except the traditional tube type and plate type IEC, some novel IEC, such as two stage direct/indirect system, Regenerative IEC (RIEC), M-cycle, desiccant/IEC system with higher efficiency had also been tested and investigated. Jain [32] developed a two-stage evaporative cooler in order to enhance the effectiveness of IEC under high humidity condition. Kulkarni and Rajput [33] tested the performance of a two stage IEC and optimized the system by using different shapes and cooling media in the direct stage. Similar two-stage system had been tested by El-Dessouky et al. [34], Heidarinejad G et al. [35] and Jain [36]. Recently, Duan et al. [37] experimentally investigated the operational performance (EER, wet-bulb efficiency, cooling capacity) and impact factors of a counter-flow RIEC. Cross flow and counter flow M-cycle IEC have also been experimentally tested for parameter study, optimization of geometry and operating conditions [38–41]. However, all the experimental work focuses on evaluating the sensible cooling ability of IEC. No experimental study can be found on evaluating both the sensible and latent cooling performance of IEC with condensation from primary air. It can be a research gap for IEC energy recovery technology applied in humid regions.

In sum, the intensive experimental study on evaluating the performances of both traditional air cooler and IEC with condensation is lacking. Under the high humidity condition, the primary air is not only sensibly cooled but also dehumidified. The simultaneous sensible and latent heat transfer process on the primary air side would make the cooling performance different from that of traditional dry cases. However, to the authors' best knowledge, the detailed sensible and latent cooling performances of the two kinds of air coolers have not been experimentally investigated.

To build the research gap, an experimental study was conducted to evaluate the plate type air cooler performance under four operating modes, including dry operating mode with low humidity air, dry operating mode with high humidity air, wet operating mode with low humidity air and wet operating mode with high humidity air. Under dry operating mode, the air cooler serves as a traditional air cooler; while under wet operating mode, it works as an IEC. So comparisons can be made between traditional air cooler and IEC under either non-condensation or condensation conditions. The cooler dynamic performances during different operating mode transition and steady performances under different parameter influence were investigated as well.

2. Description of test rig

The schematic diagram and photograph of the test rig are shown in Figs. 1 and 2, respectively. A cross-flow plate type heat exchanger was designed and fabricated as the core component of the test rig. The heat exchanger is stacked with alternative primary air and secondary air channels which is separated by the thin aluminum plates. Both the channels are supported by the plastic corrugated sheets and the aluminum plates are hydrophilic-coated to improve its wettability. The geometric parameters of the experimental heat exchanger module are listed in Table 1. This heat exchanger can be used as a traditional air cooler, which uses the cool exhausted air from air-conditioned room to pre-cool the hot fresh air in an air-conditioning system for energy conversation.

An indirect evaporative cooler consisted of the above heat exchanger, a water circulation and distribution system has been