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Investigating the energy performance of an air treatment incorporated cooling system for hot and humid climate

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ABSTRACT

An air treatment system incorporating an air-purification unit has been proposed to reduce the energy consumption of air-conditioning system and improve indoor air quality. This system employs a lower outdoor-air fraction to realize the acceptable indoor air quality and thermal comfort resulting in marked energy savings due to the reduced cooling load for the outdoor air. The performance of the primary equipment of the air treatment system has been individually investigated. Experimental systems have been constructed to study the air-purification process and to evaluate the chiller's performance. Experimental results have demonstrated that the proposed air-purification unit is able to remove indoor air pollutants such as volatile organic compound. A computational model has concurrently been developed to determine the performance of the air handling cooling coil which is impacted by the outdoor-air fraction and the chilled water temperature. A higher chilled water supply temperature is adopted by reducing the outdoor-air fraction without compromising the supply air cooling capacity. Having a reduced outdoor air cooling load and a better chiller's energy efficiency operating with higher chilled water temperatures, the achievable energy savings of the air-conditioning system has been demonstrated to be up to 36% under a tropical hot and humid climate.

1. Introduction

Outdoor-air ventilation is a common method to maintain a healthy indoor air. Increasing the ventilation rate of the air-conditioning system through greater outdoor air-intake has a positive impact on reducing sick-building syndrome (SBS) symptoms [1,2]. However, increasing the outdoor air fraction more often than not brings about greater energy consumption attributed to a higher cooling load for a higher level of fresh outdoor air, especially in hot and humid climates [3]. Therefore, it is an ongoing research challenge to find alternative cooling and ventilation strategies to reduce energy consumption and improve indoor air quality.

To achieve energy efficient air conditioning systems, researchers have conducted extensive works in terms of designing and engineering novel systems [4–7]. Lin et al. [8] compared year-round energy consumptions of three ventilation methods for typical indoor spaces in Hong Kong. It was observed that the stratum ventilation provided greater energy savings when compared with mixing ventilation and displacement ventilation. Fong et al. [9] further illustrated that the rear-middle-level-exhausted stratum ventilation provided a satisfied thermal comfort condition with least energy consumption. Chua et al. [10] conducted a comparison study on the dehumidification performances of three temperature control strategies, namely, chilled water flow control, bypass air control and the variable air volume control. Theoretical analysis on the cooling coil was developed to investigate the part-load performance. Niu et al. [11] proposed an air-conditioning system that combined chilled-ceiling with desiccant cooling for hot and humid climates. Their results highlighted that the combined system was able to save up to 44% of primary energy consumption compared with a conventional constant volume all-air system. Another low-energy air-conditioning strategy was reported to combine the employment of chilled-ceiling with the use of microencapsulated phase change material slurry storage and evaporative cooling technology to promote energy savings [12]. To curb energy consumption, a number of researchers have proposed combining the conventional air-conditioning system with energy-efficient devices [13–15]. Younis et al. [16] investigated the performance of a displacement ventilation system combined with an evaporative cooled ceiling. Kim et al. [17] employed liquid desiccant dehumidification devices and evaporative coolers to enhance energy

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Nomenclature

A	Area [m^2]
c_p	Specific heat [kJ/(kg °C)]
D	Tube diameter [m]
d_p	Particle mean diameter
G_a	Air flow rate per square meter [kg/(s m^2)]
h	Convection heat transfer coefficient [kW/(m^2 °C)]
h_m	Mass transfer coefficient [kg/(m^2 s)]
i	Enthalpy of air [kJ/kg]
H	Length of the adsorption column [m]
k	Thermal conductivity [W/(m °C)]
Le_f	Lewis factor
m	Mass flow rate [kg/s]
P	Pressure [kPa]
Pr	Prandtl number
Q	Heat transfer rate [kW]
Re	Reynolds number
s	Fin spacing [m]
S_l	Tube spacing in air flow direction [m]
S_t	Tube spacing normal to air flow [m]
T	Temperature [°C]
u	Velocity [m/s]
V	Volume flow rate of air [m^3/s]
W_f	Fan power [kW]
μ	Dynamic viscosity coefficient [Pa s]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]
ϵ	Void fraction
η_s	ω
ω	Humidity ratio [kg/kg]

Subscript

a	Air
dew	Dew-point temperature of air
i	Inner surface
in	Inlet of cooling coil
m	Mean value
o	Outer surface
out	Outlet of cooling coil
s	Surface
w	Water

efficiency. Lee et al. [18] conducted a theoretical study on the decoupling sensible and latent cooling for desirable indoor air conditions. The results indicated that the annual energy consumption could be reduced by 54% over conventional system.

In general, the energy-efficient systems reviewed relied on fresh outdoor air to maintain a desired indoor air quality. However, it may be undesirable to sustain a constant level of outdoor air intake if the outdoor air quality is poor. When such a situation occurs, the use of an air purification process is imperative to continue to sustain good indoor air quality without penalizing the energy efficiency of the air-conditioning system.

In modern buildings, volatile organic compound (VOC) is known as one of the primary indoor airborne pollutants [19]. It has been reported that some of VOCs may cause potential adverse health issues [20,21]. Several studies have proposed possible strategies for removing VOCs. Mo et al. [22] developed a general model for analyzing VOC removal performance of photocatalytic oxidation reactors. Cheng et al. [23] compared several building materials in terms of their VOC emissions. Building materials with mineral content obtained generated the least byproducts after the reaction with ozone. Waring and Wells [24] studied the impact of using ozone, hydroxyl radical, and the nitrate radical on indoor residential VOC conversion. They indicated that the total VOC conversion was dominated by ozonolysis and the hydroxyl radical reactions. Sidheswaran et al. [25] investigated the air cleaning performance of using activated carbon fiber (ACF) filters in air-conditioning systems. The ACF media was able to adsorb VOCs from indoor air. During the regeneration process, VOCs can be desorbed from the ACF media so that it can be used in the next cycle of air cleaning.

Thus far, existing works have yet to adequately evaluate the energy performance of an air-conditioning system equipped with an air-purification unit for minimizing the outdoor air fraction in hot and humid climate. In addition, in recent years, Singapore has been suffering from severe smoke haze regularly due to the numerous forest fires in Southeast Asian. The haze effect is particularly prominent during the Southwest Monsoon Season [26]. This situation further spurs us to developing innovative methods to improve energy efficiency of existing air-conditioning systems while reducing the polluted outdoor air intake and maintaining an acceptable indoor air quality.

To address these issues, the present work proposes an air treatment system with an air-purification unit for reduced cooling load and improved air quality in hot and humid climate like Singapore. The key objectives of this work are to (1) investigate the performance of individual primary equipment of an innovative air treatment system that employs ozone, and (2) evaluate the energy performance of the air-conditioning system with regulated outdoor air flow rate. We will first introduce the air-treatment system design. Thereafter, a mathematical modelling of the air conditioning system's chilled water cooling coil will be developed, followed by the description of experimental setup that incorporates key components. Based on the performance of the air handling unit and the incorporated ozone air purifier, we further illustrate varying levels of reducing energy consumption of the air-conditioning system.

2. Description of the air treatment system

Fig. 1 presents the schematic of the proposed ozone-based air treatment system to improve air quality and to reduce energy consumption. The return air is first filtered and purified in an ozone-based oxidation device. The ozone is produced from the generator using oxygen which is generated by the combined electrolysis and photocatalysis processes. The oxygen can be used to enrich the supply air as well. Thereafter, the CO_2 scrubber, filled with activated carbon filter, reduces the CO_2 concentration and further purifies the supply air. Finally, the air is cooled and dehumidified in air handling unit using chilled water. Due to the air-purification and oxygen enrichment processes, this system is able to employ a lower outdoor-air fraction resulting in a significant saving on energy consumption of the air conditioning system.

3. Mathematical formulation

3.1. Cooling coil of air handling unit

The chilled water coil of air handling unit is an important part of the overall cooling system to maintain the comfortable indoor thermal condition. The supplied air is cooled and dehumidified by passing it through the cooling coil. To precisely determine the performance of the cooling coil, a mathematical model is developed and judiciously described in this section.

The calculation is carried out using the "row-by-row method" [27,28]. The computational domain is discretized into N segments for each row of the cooling coil. Fig. 2 illustrates the computa-