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Applying a novel extra-low temperature dedicated outdoor air system in office buildings for energy efficiency and thermal comfort

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ABSTRACT

A novel dedicated outdoor air system consisting of a multi-stage direct expansion coil and a zero-energy heat pipe to generate extra-low temperature outdoor air to avoid moisture-related problems was proposed in this study. The proposed system's performance in achieving the desirable air conditions and better energy efficiency objectives is compared with a conventional direct expansion system for air-conditioning of a typical office building in Hong Kong based on simulation investigations. The simulations were carried out using equipment performance data of a pilot study, and realistic building and system characteristics. It was found that the proposed system, as compared to the conventional system, could reduce the annual indoor discomfort hours by 69.4%. An energy and exergy analysis was also conducted. It was revealed that the proposed system could reduce the annual air-conditioning energy use by 15.6% and the system exergy loss rate by 13.6%. The associated overall exergy efficiency was also found 18.6% higher. The findings of this study confirm that the proposed system is better than the conventional system in terms of both energy and exergy efficiency and the desirable air conditions.

1. Introduction

Recent research advocates the use of dedicated outdoor air systems (DOAS) for space cooling of office environment [1]. A conventional DOAS consists of two parallel systems: a system dedicated to condition outdoor air (OA) that handles latent loads and most of the sensible loads and a terminal system to handle the remaining sensible loads. As such, only sensible cooling is handled at the terminal system to achieve a condensate-free indoor environment and thus avoiding potential moisture-related air quality problems.

For the sensible cooling, previous studies for DOAS focused on the use of chilled ceiling or beam as the terminal system [2]. But the application of such a design may result in insufficient air movement due to the inherent nature of radiant cooling [3]. Another concern is that air naturally dropping from ceiling or beam surface may suppress the stratification boundary of the displacement ventilation to the occupied zone and cause thermal discomfort [4], especially in spaces with total cooling load less than 100 W/m^2 [5].

In view of the above concerns, the authors have recently investigated into the feasible use of dry cooling (DC) air handler to replace chilled ceiling and beams by a series of studies. In the simulation studies, it was found that the combined use of the chilled water-based DOAS and DC air handler in office buildings in hot and humid climates, as compared to conventional systems, could better achieve the desirable thermal comfort conditions and energy efficiency objectives [6], but the condensate-free objective could only be realized under some restricted conditions [7]. In the experimental study, it was found that the associated energy benefits were not evident [8].

Compared to chilled water-based system, direct expansion (DX) coil system is less expensive, less complex, and the dehumidification performance is better. Furthermore, a DX coil system is flexible in installation and in operation, and is considered more energy efficient than the conventional chilled water-based system [9]. Adding the wider use of variable-speed compressor for DX coil systems, their energy efficiency and thermal control performance are further improved [10].

Based on the use of variable compressor DX system, for further energy benefits and better thermal control objectives, a novel DOAS is proposed.

The proposed system consists of an extra-low temperature (XT) DOAS coupled with a zero-energy heat pipe (hereinafter referred to as XT-DOAS system). Energy saving for the XT-DOAS system can be derived from the use of a multi-stage coil system to take advantage of the higher refrigeration efficiency associated with working under higher evaporating temperature and smaller temperature

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Nomenclature

AHU	air handing unit
ARI	Air-conditioning and Refrigeration Institute
c_p	specific heat capacity (kJ/kg K)
COP	coefficient of performance
CV	coefficient of variation
CwR	DX coils equipped with a reheater
DB	dry bulb temperature
DOAS	dedicated outdoor air system
DX	direct expansion
ex	specific mass exergy (kJ/kg)
EER	energy efficiency ratio
EIR	energy input ratio
Ex_{loss}	exergy loss rate (kW)
h	specific enthalpy (kJ/kg)
HPHX	heat pipe heat exchanger
OA	outdoor air
P	pressure (Pa)
PAU	primary air handing unit
R	room design condition state point
R^2	coefficient of determination
RA	return air
RH	relative humidity
RMSE	root-mean-square error
SA	supply air
SHR	sensible heat ratio
T	temperature (K)
x	mass fraction
XT	extra-low temperature

Greek symbol

ε	exergy loss coefficient
η	exergy efficiency

Subscript

o	reference (environment) state
a	moist air
ch	chemical
ci	condenser inlet
co	condenser outlet
da	dry air
ef	effective
ei	DX coil inlet
ent	entering
eo	DX coil outlet
in	input
me	mechanical
out	output
sup	supply
th	thermal
v	water vapor

lifts (between evaporator and condenser) for the early cooling stages. Coupling with the use of heat pipe to reheat the conditioned OA, which has been confirmed effective for application in a hospital ward [11], further reduction in reheating energy can be achieved.

Heat pipe is a heat exchanger that relies on thermosiphon effect to enable heat transfer between two mediums. Based on passive heat transfer, its use has recently been extended to assist thermoelectric generation [12]. Many theoretical and experimental analyses have been done in recent years to enhance and predict the heat transfer mechanism of thermosiphon-based heat exchangers of different designs. Filippeschi investigated its heat and mass transfer characteristics against gravity [13]. Filippeschi and Salvadori developed an experimental method for measuring the transient boiling heat transfer coefficient [14]. Esen and Esen conducted an experimental study on the use of heat pipe to replace water as the heat transfer fluid for a solar water heater [15]. Similar study was conducted by Esen for using heat pipe as the heat transfer fluid for a solar cooker [16]. Because heat pipe can effectively recover waste heat with no additional energy requirements, its development in the Former Soviet Union Countries, USA and Europe has been critically reviewed [17]. Research effort is also made on optimizing its physical characteristics for better heat recovery performance [18].

It can be seen that much research on evaluating the energy performance of the conventional DOAS, DX coil system and heat pipe heat exchanger has been conducted, while nothing is available in extant literature on their integrated use, and the use of a multistage DX coil to treat high temperature OA to an extra-low temperature.

On energy performance evaluation, it is noted that previous studies are often based on the first law of thermodynamics [19], while considering that both energy use and exergy loss are essential characteristics of an energy system [20], an evaluation based on both the first and the second law of thermodynamics is necessary.

This study serves as a preliminary enquiry to the feasible use of the XT-DOAS system in hot and humid subtropical climates. Because the XT-DOAS system adopts an extra-low temperature OA to handle both the latent and sensible loads such that no terminal system is needed to naturally remove the moisture-related problems, the focus of this study is on evaluating its performance in achieving desirable air conditions and better energy efficiency objectives, as compared to a conventional system. The energy efficiency evaluations will be based on energy and exergy analyses.

2. System descriptions

Typical office buildings in Hong Kong, depending on the specific characteristics required in individual air-conditioned space, adopt either constant air volume or variable air volume systems. As DX coil system typically adopts constant speed fan, the use of constant air volume system is assumed for this study. In association, to cater for the difference in sensible heat ratios between the perimeter and interior zones, independent air-conditioning provisions is assumed for the two zones.

Fig. 1a shows the schematic diagram and the psychrometric process of the conventional system and Fig. 1b shows that of the XT-DOAS system. The design conditions, as illustrated, are explained in a later section.

2.1. Conventional system

For a fair comparison, the conventional system is also assumed to have DX coils equipped with a re-heater (abbreviated as CwR system hereafter). As shown in Fig. 1a, the primary air handing unit (PAU) is used to cool and dehumidify OA from State O to State 1. The treated OA is subsequently mixed with the re-circulated air. The mixed air (State 2) is cooled by the air handing unit (AHU) to become the supply air (State 3) for achieving the desired indoor condition (State R). The re-heater is automatically activated when