Energy and exergy analyses of advanced decentralized ventilation system compared with centralized cooling and air ventilation systems in the hot and humid climate

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ABSTRACT

This research presents energy and exergy analyses of a new decentralized ventilation system to adapt to the hot and humid climate compared to general centralized ventilation systems. A zone model of an office building was applied for a heat pump cooling system in Singapore. The cooling load capacity of the zone model was simulated using the building energy simulation software "TRNSYS" and energy and exergy analyses of the new ventilation system were carried out through numerical calculations based on the measured cooling load capacity. An effective energy solution for buildings was to increase cooling and ventilation efficiency. The energy and exergy analyses evaluated the performance of the various cooling systems. The research revealed that the new decentralized ventilation system adapted to the hot and humid climate had better performance compared to a centralized all-air system and to a chilled ceiling with centralized air handling unit system.

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1. Introduction

Buildings account for 40% of the global primary energy consumption and are responsible for about one third of global CO_2 emissions [1–3]. The majority of energy consumption of buildings is caused by the operation of heating, cooling and air ventilation systems. In order to reduce fossil energy consumption and global CO_2 emissions, the LowEx research group at the Chair of Building Systems at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) has developed LowEX technologies through an exergetic approach (*e.g.* geothermal heat pump, hybrid solar panel, decentralized heat pump, advanced decentralized ventilation system, *etc.*). Recently, we designed a new decentralized ventilation system to adapt to the hot and humid climate. The major benefits of decentralized ventilation systems are lower pressure losses due to the shorter transportation distances, space savings due to reduced duct volume, lower construction costs [4], the possibility of users influencing the room climate by simple zoning control [5], and flexibility combining natural ventilation with active ventilation system. This new system includes three heat exchange stages, which have free reheating load. The LowEx group newly

designed and successfully launched this novel decentralized ventilation system with free reheating to be adapted to a hot and humid climate in Future Cities Laboratory at National University Singapore (NUS). Generally decentralized ventilation systems are limited to use in the hot and humid climate due to complexity to install a reheating source and exergy consumption in the process; however the LowEx group finally achieved a novel decentralized ventilation system with free reheating adapted to the hot and humid climate. One of the authors' previous study [6] showed that this novel decentralized ventilation system was successfully launched in the hot and humid climate for an efficient building system and presented the possibility that the novel strategy could overcome the current challenge in building environmental controls.

Every energy system analysis, including analyses of air ventilation, heating, cooling, lighting and surface insulation in built environments, is based on energy balances stemming from the first law of thermodynamics; however the energy balance method did not account for energy quality [7,8]. Therefore, exergy analysis was additionally suggested because it includes both the first and the second laws of thermodynamics, thus allowing the assessment of both energy quantity and quality. Exergy is defined as the maximum theoretical work obtainable from the interaction of a system with its surrounding environment until equilibrium is reached [7]. Consequently, exergy is the potential of a given energy flow to

Nomenclature

C_p	specific heat capacity at constant pressure (J/kg K)
Ex	exergy (kJ/h)
F_q	quality factor
h	enthalpy (kJ/kg)
m	mass flow rate (kg/h)
Q	cooling load (kJ/h)
R	Specific ideal gas constant (J/kg K)
S_g	entropy generation rate (W/m^2 K)
T	temperature (K)
w	humidity ratio (%)
η	fan (pump) efficiency
ϕ	relative humidity (%)
ψ	Rational exergy efficiency (%)
v	Specific volume (m^3/kg)

Subscripts

a(ir)	air
all$_{air}$	all–air system
AHU	air handling unit
c	cooling
c.c.	actual cooling capacity
cc	cooling coil
cceiling	chilled ceiling
CCR	actual cooling capacity ratio
ceilingreturn	ceiling return
ceilingsupply	ceiling supply
coolsupy	cooling supply
coolre	cooling return
ch	chemical
chill	chilled ceiling panel
decen	decentralized ventilation system
e.c.	energy consumption
hc	heating coil
hotsuply	hot water supply
hotre	hot water return
in	inlet
indoor	indoor
mix.air	mixed air
out	outlet
p	pressure
phys	physical
rat	rational
reheat	reheated air
rec.	re-circulated
room	room
simple	simple
supply	supply
ven	ventilation system
w	water

Table 1
Boundary conditions of the office unit.

Volume [m^3]	42.772
Net floor area [m^2]	14.77
Indoor temperature [°C]	25
Infiltration ACH	0.1
Person [watt] × [number]	150 × 2
Computer [watt] × [number]	2 × 2
Artificial lighting [watt/m^2] × [number]	1 × 2

U-values [W/m^2 K]		
Structure	Normal insulation	Good insulation
Ceiling	0.378	0.135
Long walls	0.383	0.136
Short walls	0.383	0.136
Ground	0.039	0.039
Window	2.89	1.00

heating or high temperature cooling building systems [8–10]. The major benefit of the low exergy design concept is decreasing the exergy demand in the built environment. Increasing exergy efficiency entails a reduction in potential damaging impacts on the surrounding environment [11]. Based on the exergy principle, the CO_2 emissions from using fossil fuels in built environments are substantially reduced as a result of the use of more efficient energy conversion processes [10]. Regarding studies conducted on LowEx systems, Shukuya [11] described the exergetic approach for a better understanding of the built environment [12]. One of Schmidt's researches reported combining energy and exergy analyses were required in the calculations to achieve thermal loss [13]. Thus, analyzing energy and exergy is an important approach to determine not only the quantity of energy to be saved, but also to improve the quality of the energy consumed by designing more efficient systems.

In this paper, we present energy and exergy analyses of a new decentralized ventilation system and compare it to a centralized all-air system and to a system composed of a chilled ceiling panel with a centralized air handing unit. Consequently, the performance of each system was compared and validated using energetic and exergetic approaches.

2. System description

2.1. Building characteristics

This study selected one office building, which adopted a heat pump system for cooling and dehumidifying processes. The building is located in Singapore and an office unit is designed as a test bed to calculate the cooling and dehumidification capacity of a decentralized system. The building materials were chosen and applied for two cases: one was equipped with a normal insulation and the other was highly insulated, *such as* low *U*-value. Table 1 illustrates the boundary conditions of the office, whose long wall faces south. The thermal calculation was simulated by TRNSYS modeling. Based on ASHRAE 62.1-2010 [14], a minimum supply air rate of 33.4 m^3/h was selected for a sample office space with 14.3 m^2 floor area and 2 occupants.

Fig. 1 presents the annual hourly weather data for Singapore. The temperature and humidity ratio was constantly high throughout the year due to the physical location of Singapore closed to the Equator. Therefore, there is no heating load generated in Singapore, but building systems need high cooling and dehumidification capacity due to its hot and humid climate.

be transformed into high quality energy [8]. Carnot and Kelvin's study showed that a certain amount of energy should flow to a cold storage for work to be extracted from a thermodynamic cycle. The maximal amount of work that can be extracted is then directly linked to the temperature gradient between the system and its cold storage. Based on this principle, one of Bejan's researches described how exergy could be used as a tool to evaluate the value inherent in heat fluxes occurring across different temperature gradients [9]. Hence, for small temperature differences, the exergetic value of the heat flux can be minimized with respect to the energetic value. For this reason, it has been of interest to look for sources with low exergetic value to provide heat to our relatively low temperature