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Increasing energy efficiency of displacement ventilation integrated with an evaporative-cooled ceiling for operation in hot humid climate

Mariam Itani, Kamel Ghali, Nesreen Ghaddar*

Mechanical Engineering Department, American University of Beirut, P.O. Box 11-0236, Beirut 1107-2020, Lebanon

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ABSTRACT

The study investigates the optimized and enhanced performance of combined displacement ventilation (DV) and evaporative-cooled ceiling (ECC) using Maisotsenko cycle (M-cycle). The DV/ECC system efficiency is expected to improve by dehumidifying the supply air using solid desiccant (SD) dehumidification system regenerated by parabolic solar concentrator thermal source. Predictive mathematical models of the conditioned space, SD and DV/ECC are integrated to study the performance of the proposed system while utilizing an optimized control strategy for typical offices in moderate humid climate. The developed model was validated with experiments in a climatic chamber at certain supply conditions and fixed load. Good agreement was found between measured and predicted temperatures and loads removed, with a maximum percentage error less than 6%.

A control strategy is adopted to determine optimal values of supply air flow rate and temperature and SD regeneration temperature while meeting space load, indoor air quality, and thermal comfort. The system performance is optimized to get minimal energy cost for a typical office case study in Beirut climate and compared to the cost of using chilled ceiling displacement ventilation (CC/DV) system. The use of the proposed system attained 28.1% savings in operational cost and electric power consumption over the cooling season.

1. Introduction

People nowadays spend about 90% of their time in indoor spaces [1]. This means that, unless indoor air is treated and fresh air is supplied, people are subject to an unhealthy and uncomfortable environment for prolonged periods. With increased demand of fresh air, energy consumption increases in order to condition this required fresh air. Under the fact that 60% of world-wide energy produced is spent in residential buildings [2], the major concern in buildings aims toward reducing energy consumption while maintaining comfort and good air quality.

Although conventional air conditioning systems rely on mixing fresh and return air, these systems may not maintain a healthy and comfortable indoor environment when high concentrations of pollutants are internally generated without enough supply of fresh air. One of the air conditioning systems known for providing both thermal comfort and air quality at relatively low energy consumption is the displacement ventilation (DV) system [3,4]. The DV system provides the supply fresh air at low level and relies on buoyancy to drive the contaminants toward the ceiling level to be exhausted [5]. By that, the space is divided into two regions; lower occupied fresh and cool air region and an upper contaminated region above the breathing level of occupants [6,7]. The two zones separated are separated at stratification height, which is the level at which the rate of air entrained by the buoyancy plumes equals the supply flow rate. To ensure thermal comfort and prevent thermal drafts at the occupied level, DV air conditioning systems supply air at temperatures not less than 18 °C and velocities not more than 0.2 m/s [8]. These two restrictions impose a limitation on the ability of the DV system to remove sensible loads higher than 40 W/m^2. Such limitations have encouraged researchers to consider using chilled ceilings (CC) that aid the DV system in increasing the load removal capacity to 100 W/m^2 [9–11]. However, a CC/DV system consumes considerable energy to cool the ceiling and has the risk of condensation taking place on the ceiling when adjacent air dew point temperature is higher than the ceiling temperature [12,13]. This leads to the suggestion of a passive way to cool the ceiling without additional energy consumption by using a novel evaporative-cooled ceiling [14].

A study by Miyazaki et al. [15] investigated the thermal performance of a passive cooling device represented by a dew point evaporative cooler, which uses the concept of the Maisotsenko

* Corresponding author.
E-mail address: farah@aub.edu.lb (N. Ghaddar).

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Nomenclature

Symbols

CC	chilled ceiling
C_p	specific heat (J/kg K)
COP	coefficient of performance
DV	displacement ventilation
ECC	evaporative-cooled ceiling
$E_{chiller}$	chiller thermal energy (kW)
gt_{max}	maximum temperature gradient (°C/m)
h_{fg}	latent heat of water (J/kg)
h_m	mass transfer coefficient (m/s)
h	convective heat transfer coefficient (W/m^2 K)
H_{min}	minimum stratification height (m)
I	objective cost function ($)
J	operational cost ($)
K_1	effective thermal conductivity of the heat transfer plate (W/m K)
K_2	effective thermal conductivity of the ceiling (W/m K)
P_{fan}	fan power (kWh)
$P_{chiller}$	chiller power (kWh)
PPD_{max}	maximum percent people dissatisfied (%)
Q	fan volumetric flow rate (m^3/s)
$\dot{q}$	radiative heat load (W/m^2)
SD	solid desiccant
T	temperature (°C)
U	velocity (m/s)
W	humidity ratio (kg/kg)
w^*	humidity ratio of saturated air (kg/kg)
X	position (m)

Greek symbols

α	weighing factor
δ	channel height (m)
δ_1	effective thickness of the heat transfer plate (m)
δ_2	effective thickness of the ceiling (m)
ΔT	temperature difference of air in the room and ceiling
ΔP	pressure rise in the fan (kPa)
ρ	density (kg/m^3)

Subscripts

a	air
c	ceiling
d	air in dry channel
gt	temperature gradient
H	stratification height
P	heat transfer plate
PPD	percent people dissatisfied
r	room
w	working air in wet channel
1, 2	water absorbing sheets

cycle, integrated with a ceiling panel and a solar chimney. This cooler takes the air from the room and then cools down due to water evaporation after absorbing the heat from the air. Cooling air under the Maisotsenko cycle results in having an air temperature that approaches the dew point temperature, rather than approaching the wet bulb temperature which is higher for non-saturated air [16,17]. Results of the study by Miyazaki et al. [15] stated that the ceiling can remove 40–50 W/m^2 of radiative cooling load without having a considerable increase in its temperature. The performance of the novel evaporative-cooled ceiling depends on different parameters, mainly on the humidity level in the air and the velocity of air passing through the ceiling [18–20]. Thus, in order to make the use of evaporative-cooled ceiling a viable option, dehumidification of the supply air is needed. Desiccant wheel dehumidification is used, where it utilizes the available solar energy to regenerate the desiccant [21,22].

In contrary to conventional systems that rely on varying one parameter to meet space loads, the presence of several parameters that affect the performance of the proposed system (the humidity level in the supply air, the DV flow rate and temperature) gives reason to search for optimal values of these parameters that enhance the system performance and minimize energy consumption. In the study of Mossolly et al. [7], energy savings up to 15% were attained when the optimized control strategy of varying all system parameters was applied instead of varying the chilled ceiling temperature only. Optimal values of the different parameters can be found by performing an optimization for the integrated system model that gives the minimum energy cost of the system while maintaining thermal comfort and air quality in the space.

In this study, the different systems including the DV/ECC and the solid desiccant dehumidification system that is regenerated through solar collectors utilizing the renewable solar energy will be integrated. The combined DV/ECC is validated through experiments conducted at certain DV supply conditions and space load. The integrated model is optimized to provide comfort and good air quality in the occupied zone at minimal energy cost for an office space in the city of Beirut. The energy consumed by the optimized proposed system is compared to that consumed under a CC/DV air conditioning system.

2. System description

The proposed integrated system applied in a hot and humid climate for space cooling is represented by a schematic in Fig. 1(a) and the process was described on a psychrometric chart, showing the different states that supply and return air pass through, in Fig. 1(b). The hybrid air conditioning system is composed of a desiccant wheel, a sensible wheel, a cooling coil, a regenerative coil, supply and exhaust fans, parabolic solar collectors, an auxiliary heater and an evaporative-cooled ceiling as shown in Fig. 1(a). Basically, the fresh air fan draws outside air at point 1 and passes it through a desiccant dehumidification wheel for dehumidification which will result in an increase in the air temperature to reach point 2 as shown in Fig. 1(b). Then, the air stream is cooled by exchanging heat with the exhaust air through the use of a sensible wheel, as represented by the straight line of constant humidity ratio reaching point 3, in Fig. 1(b). After that, the air is further cooled by the cooling coil to the desired supply temperature at point 4 and supplied to the space. Cool supply air enters the space at floor level and removes the load from the space as it rises toward the ceiling due to buoyancy forces as shown in Fig. 1(a). Consequently, the bottom occupied zone contains the fresh cool air while the heated air due to internal and external loads present rises to the ceiling level and reaches state 5. Before leaving the space, the return air will pass through a ceiling dry channel where the air gets cooled sensibly reaching state 6 and then it passes through a wet channel to evaporatively lower the temperature of the ceiling, and by that gaining humidity and heat to reach state 7 as shown in Fig. 1(b). The return air is then used after heating it to state 8 by the sensible wheel and then to state 9 by the regeneration coil for regenerating the desiccant. Finally, the humid air is exhausted to the atmosphere at state 10. The heat input needs of the regeneration coil for the SD dehumidification are provided partly by parabolic solar concentrators and by an auxiliary heater. The integration of the ECC with the DV system limits the range of the supply temperature; i.e., point 4 on the psychrometric chart in Fig. 1(b), between 18 °C and 24 °C. The