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Displacement Ventilation System Combined with a Novel Evaporative Cooled Ceiling for a Typical Office in the City of Beirut: Performance Evaluation

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Abstract. Displacement ventilation (DV) system incorporated with a novel evaporative cooled ceiling, Maisotsenko cycle (M-cycle) is a passive technique used to enhance the load removal in spaces. This study examines the performance of the integrated system in increasing the load removal of the DV system beyond the 40 W/m^2 limit with no additional energy consumption for a typical office in Beirut. Mathematical models for the space and the evaporative cooled ceiling will be developed and then validated through experimentation. Simulations are performed under different supply air relative humidity values, were an improvement in sensible load removal of 18.65%, 44.3% and 72.25% at supply air relative humidity of 90%, 50% and 10% respectively. Results showed better cooling performance at lower supply air relative humidity.

Key words

Displacement ventilation, Maisotsenko cycle, indoor air quality, mathematical modelling.

1. Introduction

Indoor air quality has a significant effect on the health of human beings, where it is noticed nowadays that people spend about 90% of their time in indoor spaces [1]. Such behavior will result in an environment that does not meet the criteria for health under long periods of exposure to pollutants, unless indoor air is treated and fresh air is supplied. This means that more energy is consumed to condition the needed fresh air. Under the fact that 60% of world-wide energy produced is spent in residential buildings [2], the major concern in buildings became to ensure good indoor air quality with thermal comfort under minimal energy consumption. One of the popular air conditioning systems considered to be superior in providing both thermal comfort and air quality with low energy consumption is displacement ventilation (DV) [3] and [4]. To ensure thermal comfort, the supply air temperature of a DV system is usually greater than 18^{0}C and the acceptable supply velocity is less than 0.2 m/s to prevent any thermal draft in the occupied zone. These constraints limit the application of the DV system to low cooling loads of less than 40 W/m^2. Researchers introduced a chilled ceiling to the DV system to increase the sensible load removal of the DV system. A study performed by Chakroun et al. in Kuwait [5], included both testing and modeling of a combined chilled ceiling and DV system to ensure good air quality and energy savings in comparison with conventional air conditioning systems. The space was modeled to have multi air layers and to take into account the generated plumes for a typical hot summer day in Kuwait under transient weather conditions. Results of the study showed good agreement between the experiments and the model, where 50% energy savings were achieved in comparison with conventional systems supplying 100% fresh air to the space with a payback period less than 3 years depending on the installation cost. However, the integration of the chilled ceiling with the DV is energy consuming, so an alternative passive way to cool the ceiling is preferred. In this study, the chilled ceiling model incorporates a Maisotsenko cycle (M-cycle) by passing the DV upper air through a novel evaporative channel to lower the temperature of the ceiling and assist in removing additional space sensible load. The M-cycle has no additional power consumption on the DV system as preferred. Many researchers studied the thermal performance of the M-cycle. Miyazaki et al [6] performed a study to develop a passive cooling device represented by a dew point evaporative cooler integrated with the ceiling panel and a solar chimney. The cooler cools air using water that evaporates when heat is absorbed from the air. It was found that 40-50 W/m^2 cooling load can be removed without a significant increase in the ceiling temperature. Riangvilaikul and Kumar [7] performed an experimental study of a novel dew point evaporative cooling system. Different supply air conditions of temperature, humidity and velocity were taken to study the effect on outlet air. The results indicated values of wet bulb effectiveness ranging between 92 and 114% and dew point effectiveness between 58 and 84%.

2. Description of Proposed System

The combined system of displacement ventilation and a novel evaporative cooled ceiling for an office space in Beirut is presented in Fig. 1. Cool supply air enters the space at floor level where it picks the load, and then the air is directed toward the ceiling where it passes through a dry channel followed by another wet channel to lower the ceiling temperature, and finally exhausted to the atmosphere as shown in Fig. 2. The office has an 8.2 m^2 floor area and a height of 2.8 m. It consists of one exposed wall on the south facade. The remaining walls along with the floor are partitioned with conditioned spaces. The internal heat in the office has a sensible load of 40 W/m^2.

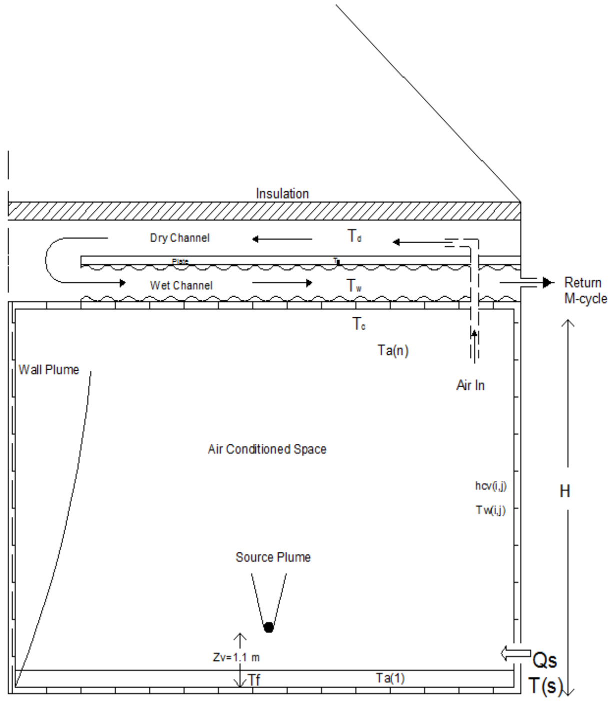

Fig. 1. Schematic of the combined air conditioning system

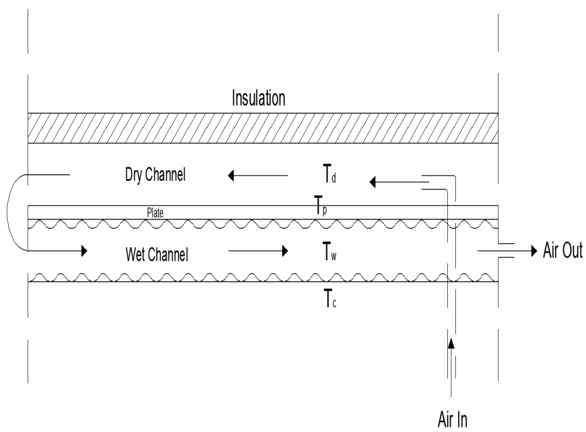

Fig. 2. Schematic of the ceiling M-cycle

3. Mathematical Formulation

Mathematical models for the DV system and M-cycle are developed to solve for the system variables (air supply conditions) that will be selected to meet the constraints for thermal comfort and air quality.

The DV model predicts indoor air temperature for given internal loads and outdoor ambient conditions. The DV plume-multi-layer thermal space model of Ayoub et al. [8] is adopted. To predict the air temperature variation through the ceiling channels and the ceiling temperature, different energy equations are developed using the study of Miyazaki et al. [6] assuming that the heat transfer by conduction within the heat transfer plate, water sheets and ceiling is negligible, as well as that the heat gain through the roof is neglected as the top side of the dry channel is insulated.

A. Energy balance for the air in the dry and wet channels

$$\rho_d C_{pd} u_d a_d \frac{dT_d}{dz} = \alpha_d \left(T_p - T_d\right) \quad (1)$$

$$\rho_w C_{pw} u_w a_w \frac{dT_w}{dz} = \alpha_{w1}\left(T_{s1} - T_w\right) + \alpha_{w2}\left(T_{s2} - T_w\right) \quad (2)$$

The right term of (1) and (2) represent the net convective heat flow in the dry and wet channels. The left hand side of (1) represents the heat exchange in the dry channel. The left hand side of (2) represents the heat exchange with the two sides of the wet channel.

B. Mass balance of the air in the wet channel

$$\rho_{DA} u_w a_w \frac{dX_w}{dz} = \rho_{DA}\left(\alpha_{m1} + \alpha_{m2}\right)\left(X_w^* - X_w\right) \quad (3)$$

The right hand side represents the net convective flow of moisture in the wet channel and the left hand side represents the moisture exchanges with the two water sheets of the wet channel.

C. Energy Balance of the two water sheets

$$\frac{K_{e1}}{a_{e1}}\left(T_p - T_{s1}\right) + \alpha_{w1}\left(T_w - T_{s1}\right) + \rho_{DA}\alpha_{m1}h_{fg}\left(X_w - X_w^*\right) = 0 \quad (4)$$

$$\frac{K_{e2}}{a_{e2}}\left(T_c - T_{s2}\right) + \alpha_{w2}\left(T_w - T_{s2}\right) + \rho_{DA}\alpha_{m2}h_{fg}\left(X_w - X_w^*\right) = 0 \quad (5)$$

The upper water sheet in (4) exchanges heat with the plate and exchanges sensible and latent heat transfer with the flowing air. Similarly, in (5) the lower water sheet exchanges conduction heat transfer with the ceiling plate and sensible and latent heat with the flowing air.

D. Energy Balance of the ceiling and the plate separating the wet and dry channels

$$\frac{K_{e2}}{a_{e2}}\left(T_{s2}-T_c\right)+\alpha_r\left(T_r-T_c\right)+\dot{q}_R=0 \quad (6)$$

$$\alpha_d\left(T_d-T_p\right)+\frac{K_{e1}}{a_{e1}}\left(T_{s1}-T_d\right)=0 \quad (7)$$

The ceiling exchanges heat with the water sheet of the wet channel in (6) as well as convective and radiative heat transfer with the space. The first left term in (7) represents the heat transfer with the dry air and the second term represents the conductive heat flow with the water sheet.

4. Flowchart and Integrated Model Sequence of Operation

A flowchart showing the algorithm of different steps of the model is presented in Fig. 3.

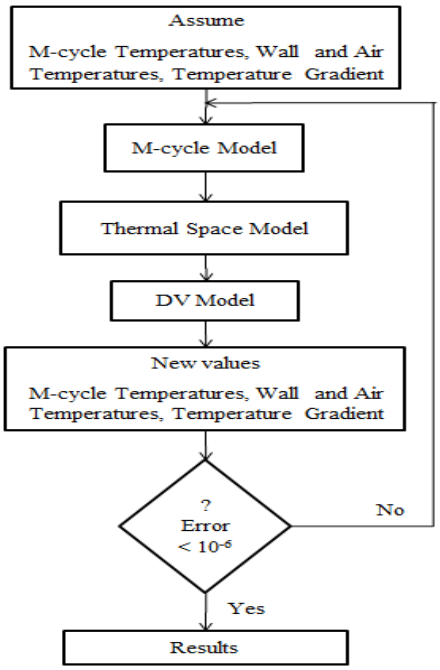

Fig. 3. Flowchart showing the sequence of operation

5. Experimental Work and Validation

Although every component model of the integrated system has been validated in literature, it is important to validate the integrated system model different variables like occupants thermal comfort as well as the ceiling temperature and the improvement in sensible load removal, for different supply air flow rates and temperatures. The validation of the model is done experimentally using a climatic chamber equipped with displacement ventilation coupled with M-cycle cooling system. A chiller is used to provide the necessary cooled water that passes through a cooling coil and cools the supply air. The chamber has a floor area of 9 m^2 and one external wall facing south. The load to be removed by the integrated system is mainly due to internal heat sources. The air is supplied at a flow rate of the value 0.118 m^3/s and the supply air temperature is controlled by changing the chilled water temperature.

Inside the room, the supply air temperature and relative humidity as well as those of the exhaust air, are measured using OM-EL-USB-2 sensors with an accuracy of ±0.5 °C in temperature and ±3 % in relative humidity. Room air temperatures and relative humidity at the occupied height of 1.1 m and at the inlet to the M-cycle setup at the height of 2.6 m are measured using HX94AC sensors with an accuracy of ±0.6 °C in temperature and ±2.5 % in relative humidity. The walls of the chamber as well as the ceiling temperatures are measured using K-type thermocouples.

Two types of experiments were conducted. The first consists of using the DV system without the M-cycle setup, and the second uses the integrated setup of the DV and M-cycle systems. The second experiment needs a supply of water in order to wet the fabric placed in the wet channel of the M-cycle setup. Water was supplied manually every 30 minutes in order to ensure continuous wetting of the fabric and aid the DV system in removing additional sensible load.

Table I: Experimental and Simulation Results Comparison

	DV Exp.	DV Sim.	% Error	CCDV Exp.	CCDV Sim.	% Error
Avg. Wall Temp. (°C)	22.55	23.3	3.2	23.47	23.8	1.3
Ceiling Temp. (°C)	23.1	23.3	0.85	21.25	20.26	4.8
Room Temp. at 1.1 m (°C)	23.6	23.8	0.84	23	23.96	4
Room Temp. at 2.6 m (°C)	23.9	23.7	0.84	23.6	23.45	0.63

The performed experiments had a fixed supply air temperature of 21 °C with a relative humidity of 60 %. The internal load was set to 400 watts. Comparison of the results between the conducted experiments and the corresponding simulations are showed in Table I. Good agreement were found between the measured experimental values and the integrated model simulation values of the walls, ceiling and room temperatures. The results showed an improvement in sensible load removal of about 20 % between the DV system and the suggested integrated one.

6. Results and Discussion

In order to study the performance of the integrated system, simulations were performed at supply flow rate of 0.14 m^3/s and temperature of 22 °C. Three values of relative humidity were taken; low, medium and high, which are 10%, 20% and 90% respectively. Simulation results for the total sensible load removed when using the DV system alone were recorded and then simulations were done to get the improved load removal by the combined evaporative cooled ceiling and DV system.

Fig. 4 shows the variation of the total sensible load removed in W/m^2 at 10%, 50% and 90% supply air relative humidity, for the DV system alone and the integrated one. Results showed that the load removed by the DV system was 40 W/m^2 and it was constant for the different relative humidity values, however; the load removed by the integrated system was maximum and equal to 68.9 W/m^2 at the lowest relative humidity of 10% and it decreased to reach 47.46 W/m^2 at the highest relative humidity of 90%. The improvement in sensible load removal when using the proposed integrated system was 18.65%, 44.3% and 72.25% at relative humidity of 10%, 50% and 90% respectively. This shows that the integrated system has better sensible load removal at lower supply air relative humidity.

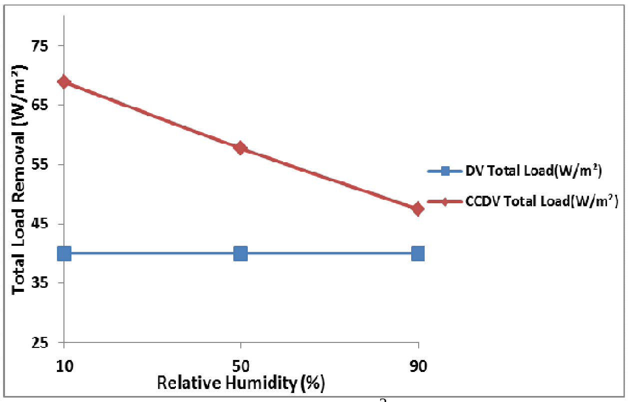

Fig. 4. Total load Removal in W/m^2 at different supply air relative humidity

7. Conclusion

Simulation results showed that the displacement ventilation system combined with a novel evaporative cooled ceiling can improve the displacement ventilation cooling capacity with no additional energy consumption. Mathematical modeling of the proposed system was performed and validated through experimentation. Results showed enhancements of the proposed system between 18.65% and 72.25% at supply air relative humidity between 10% and 90% respectively. Better cooling performance was attained at lower supply air relative humidity. A suggestion can be made to enhance the performance of the proposed system in hot and humid climates by using desiccant dehumidification systems to lower the humidity of supply air before it enters the space to cool it.

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References

[1] U.S. Environmental Protection Agency, Report to Congress on indoor air quality, Washington, DC (1989), Vol. 2, EPA/400/1-89/001C.

[2] www.eia.gov/forecasts/aeo

[3] Z. Jiang, Q. Chen and A. Moser, "Indoor airflow with cooling and radiative/convective heat source", in ASHRAE Transactions, 1992, 98(1):33–42.

[4] M. Mossolly, N. Ghaddar, K. Ghali and L. Jensen, "Optimized operation of combined chilled ceiling displacement ventilation system using genetic algorithm", in ASHRAE Transactions, 2008, 143(2):541–54.

[5] A. Bahman, W. Chakroun, R. Saadeh, K. Ghali and N. Ghaddar, "Performance comparison conventional and chilled ceiling/displacement ventilation systems in Kuwait", in ASHRAE Transactions, 2008, 115(1):587–94.

[6] T. Miyazaki, A. Akisawa and I. Nikai, "The cooling performance of a building integrated evaporative cooling system driven by solar energy", in Energy and Buildings, September 2011, Vol. 43, Issue 9, Pages 2211-2218.

[7] B. Riangvilaikul and S. Kumar, "An Experimental Study of a Novel Dew Point Evaporative Cooling System", in Energy and Buildings May 2010, Vol. 42, Issue 5, Pages 637-644.

[8] K. Ghali, N. Ghaddar and M. Ayoub, "Chilled Ceiling and Displacement Ventilation System: An Opportunity for Energy Saving in Beirut", in International Journal of Energy Research, 2007, 31: 743-759.