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Thermal Comfort and Energy Saving Evaluation of a Combined System in an Office Room Using Displacement Ventilation

A. Q. Ahmed, S. Gao

***Abstract*—**In this paper, the energy saving and human thermal comfort in a typical office room are investigated. The impact of a combined system of exhaust inlet air with light slots located at the ceiling level in a room served by displacement ventilation system is numerically modelled. Previous experimental data are used to validate the Computational Fluid Dynamic (CFD) model. A case study of simulated office room includes two seating occupants, two computers, two data loggers and four lamps. The combined system is located at the ceiling level above the heat sources. A new method of calculation for the cooling coil load in Stratified Air Distribution (STRAD) system is used in this study. The results show that 47.4% energy saving of space cooling load can be achieved by combing the exhaust inlet air with light slots at the ceiling level above the heat sources.

***Keywords*—**Air conditioning, Displacement ventilation, Energy saving, Thermal comfort.

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I. INTRODUCTION

IN recent decades, Displacement Ventilation (DV) systems have become more popular than Mixing Ventilation (MV), in view of its ability to improve thermal environment around the occupants and potential to reduce energy consumption[1]. In this system the conditioned air discharges at low velocity near the floor level. By contacting the conditioned air with the heat sources such as occupants, equipment and lights, a convective thermal plume will be generated and move up towards the upper part of the room, which causes stratified temperature layers [2], [3]. Thermal stratification is one of the main features of displacement ventilation system which have a central role to improve the indoor air quality (IAQ) and energy saving through pushing the warm air towards ceiling.

Park and Holland [4] studied the impact of heat sources locations in the occupied zone on thermal stratification and temperature distribution in rooms served by displacement ventilation. They concluded that, in displacement ventilation systems, heat sources locations play a significant role in air and temperature distribution and reducing cooling load in the occupied region. Tian et al. [5] concluded that the performance of STRAD system depends on the distribution of the heat sources inside rooms. Therefore, more attention should be paid to the heat sources locations in STRAD system design. The performance of STRAD system in terms of thermal comfort and energy saving is significantly affected by the locations of heat sources and diffusers. Olivieri and Singh [6] studied the impact of the exhaust and return locations on the air distribution and energy saving. They found that, the thermal stratification and cooling coil load ware greatly influenced by changing the diffusers locations in the room.

Gorton and Bagheri [7] investigated the influence of the return inlet position on the cooling coil load, and they found that, extra energy saving can be achieved by locating the return inlet in cooled zone near to floor level. Lam and Chan [8] studied the temperature and air distribution in gymnasium. They concluded that the location of the exhaust inlet opening had a significant effect on thermal stratification and cooling coil load in the gymnasium. Awad et al. [9] studied experimentally the impact of the extract terminal locations in ventilated chamber on the characteristic of the air flow pattern in rooms. They found that the locations of exhaust air inlet had a significant impact on the thermal stratification layers level which consequently affects the cooling coil load. Filler [10] found that extra energy saving can be achieved by placing the return inlet opening close to the perimeter walls in the room where the convective heat will be removed directly by means of return inlet before reaching to the occupied zone.

The depth, strength and the temperature of the thermal stratification layers in the upper part of the room depend on the location and the size of the inlets air openings [11], [12]. Zheng et al. [13] conducted experimental study by using three different types of diffusers in office, conference room, and classroom. They revealed that the different thermal stratification layers were formed for each diffuser, depending on the diffuser type, space type and locations. Holmberg and Chen [14] investigated the air flow and contaminant distribution in classroom using different strategies of ventilation system. They found that, in displacement ventilation system, the locations of exhaust air inlet have a significant impact on the IAQ, thermal comfort and energy saving.

The previous studies have demonstrated that the performance of the STRAD system and the energy consumption were significantly influenced by exhaust inlet locations. Xu et al. [15] investigated the impact of separating the return and exhaust locations in STRAD systems on thermal comfort and energy consumption, they found that extra energy saving can be achieved by separating diffusers

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A. Q. Ahmed is with the Department of Engineering, University of Leicester, Leicester LE1 7RH, UK (phone: +44(0)116 252 2874; fax: +44(0)116 252 2525; e-mail: aqaa2@ le.ac.uk).

S. Gao is with the Department of Engineering, University of Leicester, Leicester LE1 7RH, UK (phone: +44(0)116 252 2536; fax: +44(0)116 252 2525; e-mail: sg32@ le.ac.uk).

locations, and also proposed a new method to calculate the cooling coil load in the occupied zone by using computational fluid dynamics (CFD) simulations. Cheng et al. [16] proposed a new method to calculate the reduced amount of cooling coil load in STRAD systems. For the same set room temperature, STRAD systems are different from MV systems in cooling coil load calculations. In this paper, the combination between the exhaust inlet air and light slots at the ceiling level are investigated in rooms using a STRAD system as a main ventilation system. The validated CFD model is then used to examine the influence of combining the exhaust inlet with light slots on both energy saving and thermal comfort in the occupied zone.

II. METHODOLOGY

A. Validation of the CFD Model

The aim of this validation is to demonstrate the ability of the CFD model to predict the thermal environment indoor by using available experimental data. In the present study, the Realizable $k - \varepsilon$ model is used to simulate the indoor air flow. Experimental results carried out by [16] in full scale climate chamber served by displacement ventilation system were selected to validate the CFD model used in this investigation. Case (1) and case (2) represent two different heights of return air inlet mentioned in the original experiments [16] as shown in Table I. Point I, II and III shown in Fig. 1 represent the different locations of measured data inside the room. Fig. 2 shows the comparison between the experimental and simulation results for the temperature profiles. The results show good agreement between the simulations and the experimental results.

TABLE I
CASES UNDER STUDY

Cases	Case 1	Case 2
Height (m)*	2.40	1.65

*The height is from floor to the bottom edge of the return inlet opening.

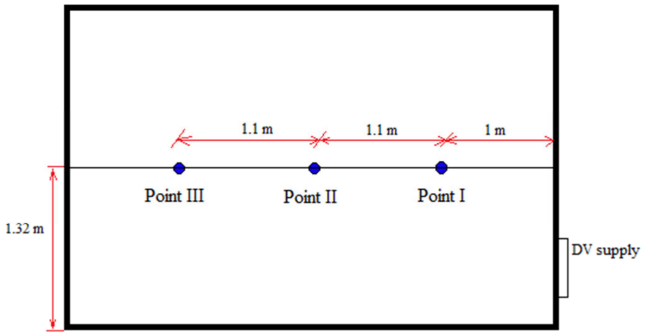


Fig. 1 Temperature measurement positions

B. Simulation Case Descriptions

A typical small office room is used in this study, which is illustrated in Fig. 3. The dimensions of this room are 4 *m* long, 2.7 *m* wide and 2.4 *m* in height. The inlet of displacement ventilation DV (1 *m* × 0.6 *m*) is located at the side wall close to the floor level. The return inlet (1 *m* × 0.1 *m*) is arranged in the lower level of the opposite wall of the DV supply, and the exhaust inlet air (0.7*m* × 0.15*m*) is combined with the light slots and located at the ceiling level. Two seating occupants, two computers, two data loggers and four lamps are used as heat sources inside the examined office room. The side walls, floor, ceiling and tables are assumed as adiabatic walls. Table II illustrates the cooling load for each heat sources. The air is supplied from DV diffuser at 0.14 *m/s* with supply temperature at $19^{o}C$. The set- point temperature of the room is $25^{o}C$. The total supply flow rate is 84 *l/sec* and the return flow rate is 35 *l/sec*. The rest of the air is extracted from the exhaust inlet air which is combined with the light slots at the ceiling level. Fig. 4 shows the combined system of exhaust and light slot. Three positions (point I, point II and point III) located at the centre of the simulation room, which are the same locations as used in the experimental work [16] shown in Fig. 1, are used to represent the vertical temperature profiles in order to investigate the temperature differences between thermal stratifications.

C. *Simulation Model*

In order to obtain accurate results of the indoor air flow simulation, more attention should be paid to selecting proper turbulent model and correct boundary conditions. The commercial CFD code, ANSYS Fluent [17] is used in the present work to solve the turbulence model for the indoor air flow. Among turbulence models, the Realizable $k - \varepsilon$ model is chosen with enhanced wall treatment and full bouncy effect to be the suitable model to solve the turbulent flow problems in the present work. The Realizable $k - \varepsilon$ model is better than the standard $k - \varepsilon$ model in view of predicting accurate air flow pattern indoors [18]. The incompressible ideal gas is used for the density model. As a result of the complexity of the room and equipment, tetrahedral unstructured meshes with four layers of prism mesh around the occupants are generated in the present work. The mesh around the occupants and others heat sources as shown in Fig. 5 are finer enough to capture the behaviour of thermal environment around the heat sources and to meet the requirement of y+ values. The discrete ordinates (DO) radiation model is employed in this study to show the impact of the heat sources radiation on room air flow and temperature distribution. In addition, the SIMPLE algorithm is used to for the velocity and pressure field coupling, and the PRESTO! scheme is employed for the pressure. The details of the CFD model are summarized in Table III.

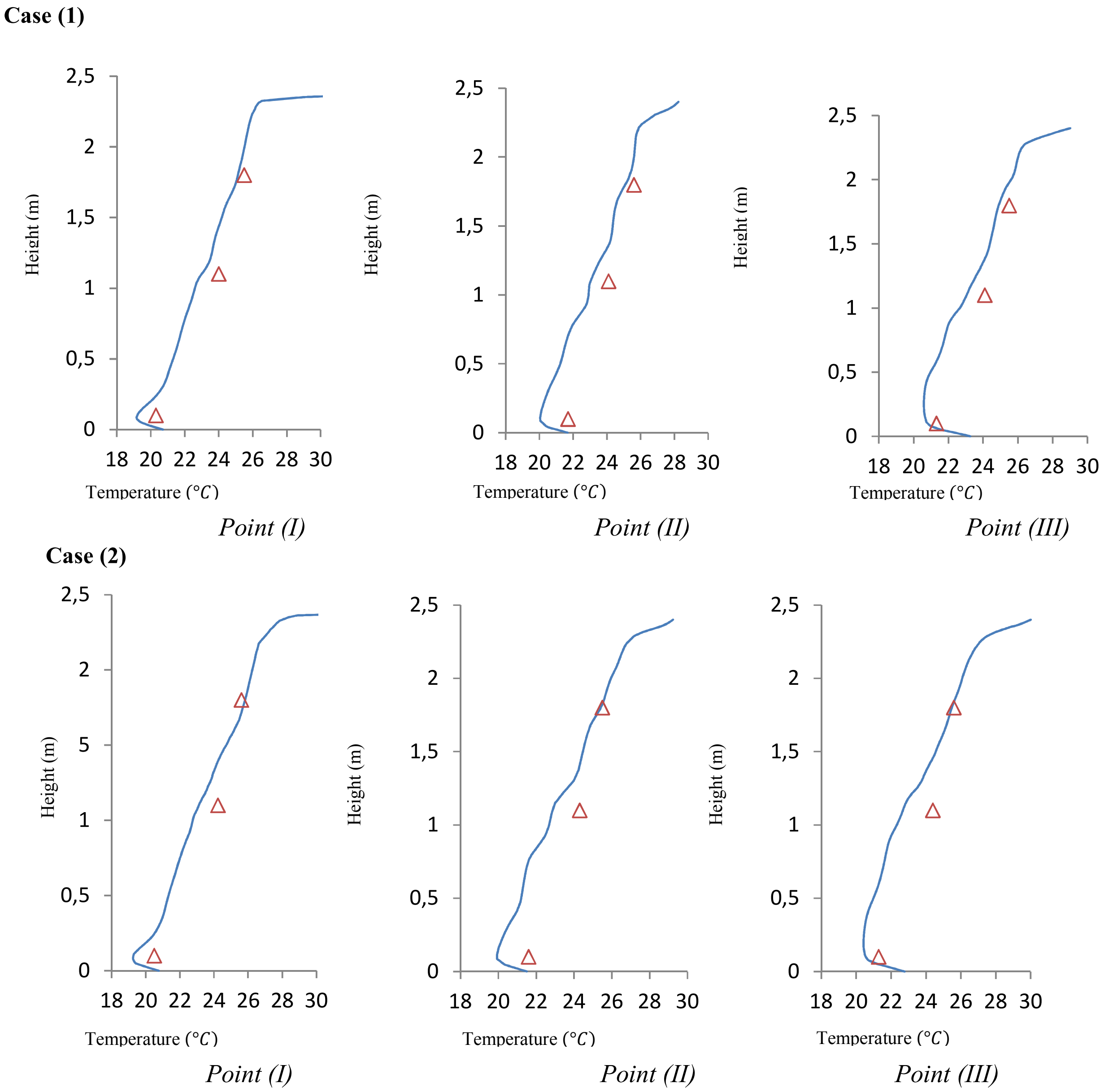


Fig. 2 Comparison between the simulations and experimental results for the vertical temperature profiles (triangle symbol: experimental results; solid line: simulated results)

TABLE II
HEAT LOAD USED IN THE SIMULATION CASES

Heat sources	Occupant (human body)	Computer	Lamp	Data logger	Total Load
Cooling load (W)	80×2	100×2	24×4	25×2	506

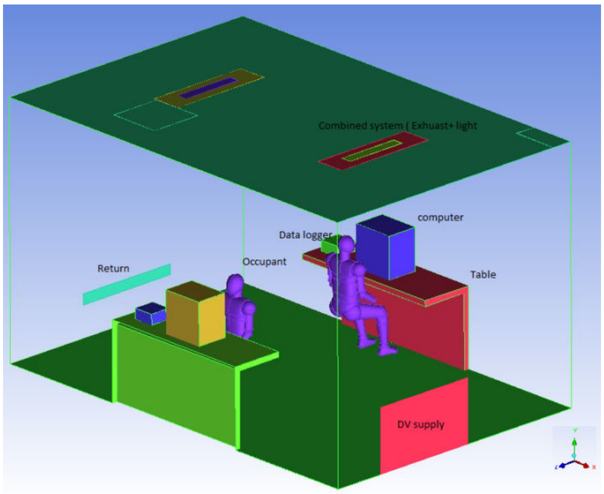


Fig. 3 Simulated office room with equipment

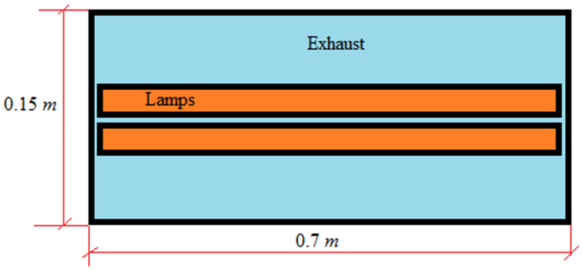


Fig. 4 The simulated system combining the exhaust with light slots

TABLE III
CFD MODEL DETAILS

Turbulence Model	Realizable $k-\varepsilon$ model
Scheme for pressure	PRESTO!, Second order; SIMPLE algorithm
Radiation model	Discrete ordinates (DO)

D. Cooling Coil Load Calculations

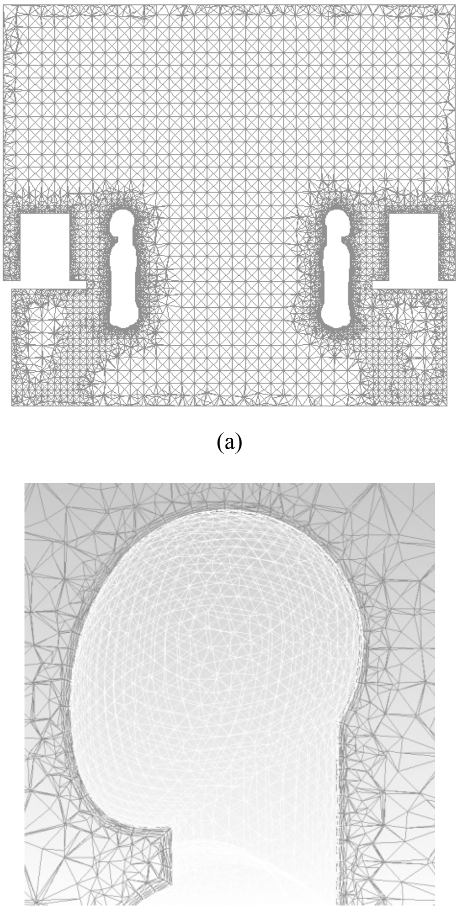
In STRAD system, only the occupied zone is required to be air conditioned which leads to increasing the potential of energy saving. Depending on the CFD simulation results, [16] developed a method to calculate the cooling coil load in room served by STRAD system and to evaluate the potential of energy saving. At the same set-point room temperature (t_{set}), the calculation of cooling coil load in STRAD system is different from the calculation of cooling coil load in the mixing ventilation system.

The cooling coil load calculation in STRAD system:

$$Q_{coil\_MV} = Q_{space} + Q_{vent} \tag{1}$$

$$Q_{coil\_STRAD} = Q_{coil\_MV} - C_p \times \dot{m_e} \times (t_e - t_{set}) \tag{2}$$

where Q_{coil_MV} and Q_{coil_STRAD}: cooling coil load for MV system and STRAD system respectively. Q_{space}: space cooling load. Q_{vent}: ventilation load. $\dot{m_e}$:exhaust air flow rate (kg/sec). t_e: exhaust temperature (C). t_{set}: room set temperature (C).



(a)

(b)

Fig. 5 Grid distribution in the simulated room (a): grid distribution in middle plane x=1.35 m; (b): prism mesh layers around the human body

By comparing (1) and (2), it is clear that the item $C_p \times \dot{m_e} \times (t_e - t_{set})$ represents the reduction of the cooling coil load in STRAD system and named $\Delta Q_{coil}\,(w)$, and is used to calculate the amount of energy saving.

$$\Delta Q_{coil} = C_p \times \dot{m_e} \times (t_e - t_{set}) \tag{3}$$

III. RESULTS AND DISCUSSION

As illustrated in Fig. 6 of the STRAD system, the room is divided into two main parts, the upper part and lower part. In the lower part, which represents the occupation zone, the temperature and quality of inhaled air should be at acceptable levels to increase the thermal comfort and productivity of occupants. In the upper part, the convective heat transfer from heat sources inside room will be move up towards ceiling. Therefore, the exhaust inlet air is located at the ceiling level to extract the warm air and improve the potential of energy saving, because in this system the air in the upper part of the room is slightly warmer than the lower part. Therefore, the combination between the exhaust opening and light slots at the ceiling level in STRAD system may improve the potential of energy saving by means of removing a large part of light heat flux directly from the exhaust inlet before mixing with the room air.

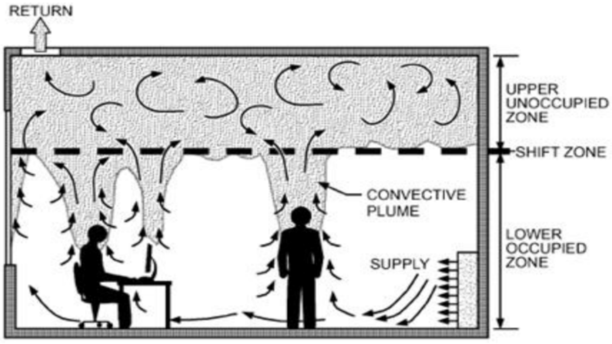


Fig. 6 Stratified air distribution system STRAD [16]

Fig. 7 presents the temperature distribution and air flow pattern in the simulation room using DV system. The thermal stratification and the improved thermal plume around the seating occupants are clarified very well in the mid room plan (x=1.35 m). Fig. 8 shows that the temperature distribution in plane (z=1.2m), which clearly shows that the convective heat transfer from heat sources moves up towards the ceiling. It also shows that the average room temperature in the occupied zone is around (24 °C), within acceptable range.

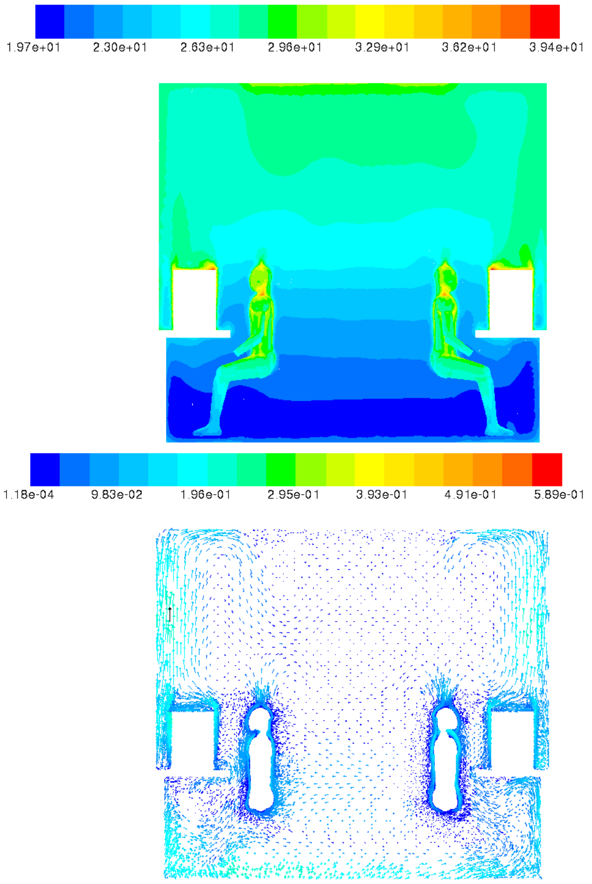


Fig. 7 Temperature contour and velocity distribution at plane x=1.35m

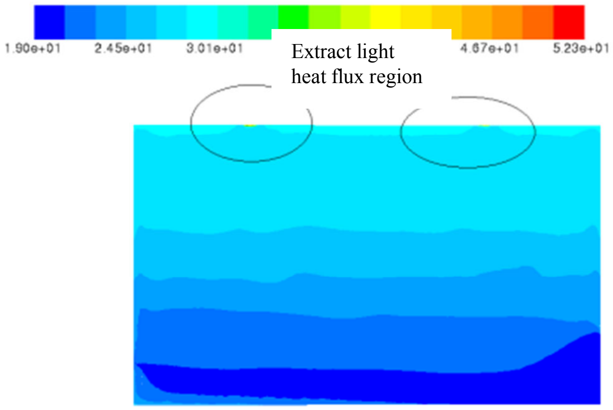


Fig. 8 Temperature contour distribution at plane z=1.35m

From the simulation results, it can be recognized that the temperature in the upper part of the room is slightly decreased by using the combined system of the exhaust inlet air and light slots. In this case a large part of the heat comes from the light will be removed directly from the exhaust inlet air before mixing with the room air. This system will contribute to increase the supply temperature, and consequently the potential of energy saving will be increased. The calculations of the cooling coil load by using (3) are carried out to find the impact of the combination of the exhaust inlet air with light slots on both energy saving and thermal comfort. Extra energy saving can be achieved by using the combination system, and Table IV summarizes the key temperature values and the energy saving of 47.7% for this system.

TABLE IV
CFD RESULTS FOR TEMPERATURE VALUES AND THE ENERGY SAVING

Temperature at exhaust outlet (t_e)	29 °C
Temperature at return outlet (t_r)	21 °C
Set room temperature (t_{set})	25 °C
The amount of energy saving (cooling coil load).ΔQ_{coil}	241.30 W
Energy saving in space cooling load $^{\Delta Q_{coil}}/_{\Delta Q_{space}}$	47.7%

IV. CONCLUSION

In order to provide a healthy environment for the occupant zone in an office room, air flow and temperature distribution should be taken into account. The main concern of this study is the human thermal comfort in the occupied zone and the energy saving for the cooling coil load in the office room served by displacement ventilation system. In this article, the performance of the combined system of exhaust inlet air with light slots at the ceiling level are investigated to show the impact on both cooling coil energy saving and thermal environment around the seated occupants. By using the CFD results, the energy saving and cooling coil load calculations are carried out by using the new method developed by [16]. By using the combination system, the exhaust air inlet will take part of light heat flux directly before mixing with other room air, which leads to reducing the temperature in the upper part of room as well as improving energy saving. Extra energy saving for the cooling coil load can be achieved by 47.7%.

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