Effects of Evaporative Cooling Air Conditioning on Classroom Pollutants and Thermal Environment

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ABSTRACT: Indoor particles and carbon dioxide concentration are major indices to evaluate indoor air quality. Based on the two-dimensional filler sieving model of the direct evaporative cooling segment, the porous media model was used for the simulation of the water filler section, the filtering efficiency of particle was simulated by adjusting the water drenching density and airflow velocity in different operating conditions. The three-dimensional classroom model used to change the exhaust outlet position and control the use of air conditioners simulated the indoor thermal environment and the changes in pollutant concentration. The Euler method and Lagrangian method were used to analyze the indoor flow field and particle sieving in the direct evaporation section, respectively. Conclusions show that in the application of evaporative cooling and stratum ventilation air conditioning system in classroom, the position of the exhaust port affects the concentration of carbon dioxide in the student's breathing area. The water filler section can effectively reduce the concentration of particle and carbon dioxide supplied indoors. The filtration efficiency of particle in outdoor air passing through the direct evaporative cooling section based on diffusion, inertial collision, and interception is affected by the combined effect of particle size, onward wind speed, and water spray density. The filtration efficiency of particle increases as the density of the spray water increases. With the increase of head-on wind speed, the filtration efficiency of coarse particulate matter is higher than that of fine particulate matter. The research results help policy makers decide whether to install evaporative cooling air conditioning in schools and determine which exhaust outlet positions are most effective in improving indoor air quality.

KEYWORDS: Classroom, carbon dioxide, outlet, indoor environment, ventilation

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Introduction

Following the improvement of economic level, people gradually attach importance to a comfortable and healthy environment. Indoor fine particles and carbon dioxide concentration determine the quality of indoor air. Occupants are exposed to various particle sources.[1] There is a significant correlation between indoor particulate matter concentration and outdoor.[2,3] The concentration of indoor particulate matter is related to indoor source emissions, and the source emissions of different places are different. Traffic-generated air pollutants has a certain impact on the internal environment of public buildings under the action of wind.[4] The Air Quality Life Index report indicates that particulate pollution has reduced the global life span by nearly 2 years and that the average life expectancy of Chinese will increase from 76 to 79 years once China reaches the particulate matter concentrations guidelines in World Health Organization. Particles in the indoor environment will shorten the life expectancy of a person by 3 to 6 minutes with natural ventilation per hour in China.[5] Respiratory disease burden in terms of disability-adjusted life year (DALYs) in China is substantial among adolescents and young adults.[6] Particle size decides the location of particulate matter in the respiratory tract, and the chemical composition of particles determines the health hazards of particulate matter.[7,8] Carbon dioxide (CO_2) is a central respiratory stimulant required by human physiology, but people have limited tolerance to CO_2. Excessive concentration of CO_2 can cause dizziness and other neurological symptoms, which can cause irreversible harm to the human body.[9] Outdoor atmospheric CO_2 concentrations increased gradually year by year,[10] air-conditioned buildings that increase the supply air temperature of the room can reduce carbon dioxide emissions. The indoor carbon dioxide concentration depends on the carbon dioxide exhaled during the breathing process of the indoor occupants, the carbon dioxide concentration in the fresh air, and the ventilation mode.[11,12] The time students spend in the classroom accounts for a large proportion of their growth, and indoor air quality significantly affects their physical and mental health and learning efficiency. It is necessary to effectively reduce the concentration of carbon dioxide and particulate matter inside the classroom.

Regarding the indoor air quality of schools, some scholars at home and abroad have carried out relevant research. Morawska et al[13] conducted a comprehensive analysis of the exposure pathways of indoor particulate matter in schools and concluded that the resuspension process was the main source of the sharp increase in PM10 concentrations. Slezakova et al[14] analyzed the characteristics of ultrafine particles in different indoor microenvironments such as school classrooms and restaurants, and assessed students' inhaled doses. Research shows that the ratio of indoor and outdoor concentrations is 0.30 to 0.85, and outdoor emissions have an impact on indoor particle concentration. Elbayoumi et al[15] measured particulate matter in classrooms in the Gaza Strip, Palestine, and the study showed that the concentration of particulate matter varies significantly with seasons. Indoor pollution control research is more important than analysis of pollutant sources. Indoor and outdoor air exchange plays a major role in indoor pollution control. Ventilation is the easiest way to avoid the accumulation of indoor pollutants. Tong et al[16] installed a wall-mounted air filtration system air handling unit with a fresh air outlet in the classroom, and considered the research on the air quality of the classroom under different ventilation modes. The study showed that the recirculation mode reduced the most pollutants, followed by the mixed air supply and fresh air mode. Ventilation is the replacement of stale indoor air with fresh outdoor air. For a healthy learning environment, air conditioners are popularized in schools.

Evaporative cooling air conditioning can achieve cooling and energy-saving effect based on abundant dry air energy, and the energy efficiency ratio is higher than that of mechanical refrigeration air conditioners. The evaporative cooling air conditioning cools the air through the evaporation of water. When the water evaporates, it absorbs heat from the surrounding air, so the cooled air can be used as indoor air supply. It has been widely used in residential and commercial buildings at home and abroad, especially in dry and hot areas such as northern China, the Middle East, Indian subcontinent, East Africa, the southwestern United States, Australia, and northern Mexico.[17] Li[18] studied the application of direct evaporative cooling air-conditioning in the workshop, comparing the traditional mechanical ventilation methods to show that direct evaporative air conditioning has a low air supply and low energy consumption. Direct evaporative cooling filler as a key part of evaporative cooling air conditioning. Li et al[19] conducted experimental tests on the evaporative cooling efficiency and resistance of metal aluminum foil fillers with different thicknesses under different combinations of oncoming wind speed and water spray density, and determined the optimal thickness, oncoming wind speed and water spray density of aluminum foil fillers. Huo et al[20] established an orthogonal experiment of outdoor wet bulb temperature, oncoming wind speed, and water-to-air ratio to study the influencing factors of heat transfer efficiency of paper packing to determine the operating conditions with the highest cooling efficiency. The water drenching filler section of the direct evaporative cooling air conditioner can be used as a wet filter to filter particles of different sizes, and control indoor ambient air pollutant levels.[21]

Proper airflow distribution can not only effectively control indoor pollutant levels, temperature, and humidity, provide a comfortable indoor environment for human beings, but also improve the energy efficiency of buildings.[22] The premise of energy consumption control must not be at the expense of indoor environmental quality.[23] The combination of evaporative cooling and other ventilation technologies has been effectively complementary in recent years.[24] Huang et al[25,26] conducted a test study on the operation of the evaporative cooling and displacement ventilation combined air conditioning system in the gymnasium, showing that the system can deliver the processed fresh air to the indoor occupant, to achieve good ventilation and energy saving and environmental protection. Xu et al[27] had applied research on the combination of evaporative cooling and station air supply technology in textile workshops. The research showed that it can improve the comfort requirements of workshop personnel and the process requirements of equipment positions. Stratum ventilation as a new ventilation mode, the air delivery mode is shortened, which reduces the average air age, increases the efficiency of ventilation, and improves the air quality of the breathing area.[28] Stratum ventilation is suitable for classrooms with a high density of occupants and high neutral temperatures.[29] The new mode of combining evaporative cooling air-conditioning units with stratum ventilation can consume energy and give full play to the advantages of air-conditioning units.

Typical studies focus on the effect of evaporative cooler structural parameters on its heat and mass exchange performance,[30] structural optimization,[31] and operating conditions suitable for year-round applications.[32] Researchers did less research on evaporative cooling stratum ventilation system, a new model of evaporative cooling air conditioners to combine with higher air supply temperature to meet thermal comfort of indoor occupants. It can be seen that the previous experimental research focused on analyzing the influence of factors such as packing, water drenching density, and oncoming wind speed on the heat and mass exchange heat efficiency of direct evaporative cooling. Numerical simulation studies of the removal performance of direct evaporative cooling packing for particulate matter removal from fresh air when considering the combination of water spray density and oncoming wind speed are rarely reported. The scientific nature of airflow organization directly affects the effect of the air conditioning system. The location of the exhaust vents affects the indoor airflow organization.

The objectives of this study are first to analyze the distribution of indoor carbon dioxide in the evaporative cooling stratum ventilation system in primary school classrooms under 3 different vent positions, and second to simulate the change in the concentration of outdoor particles delivery indoors through the direct evaporative cooling section of the evaporative cooling air conditioning unit. Considering the combination of water drenching density and head-on wind speed, there are few reports on the numerical simulation study of the particle removal performance of the water spray filler of the direct evaporative cooling section on the fresh air flow. The analysis is made from 3 perspectives: the sedimentation mechanism of particles in the filler, the improvement of indoor environment, and the feasibility of installing evaporative cooling air conditioning in high density of occupants indoors.

Methodology

China has a vast territory and obvious climate differences. Professor Huang[24] proposed to use wet bulb temperature (ts) as a single indicator to divide the application range of evaporative cooling air-conditioning. The critical values of the zoning

Table 1. Design zoning of evaporative cooling air-conditioning.

DESIGN PARTITION	PARTITION METRICS	PARTITION NAME
I	ts < 20°C	Ventilated zone
II	20°C ⩽ ts ⩽ 23°C	High adaptation zone
III	23°C ⩽ ts ⩽ 28°C	Adaptation zone
IV	ts ⩾ 28°C	Non-adapted zone

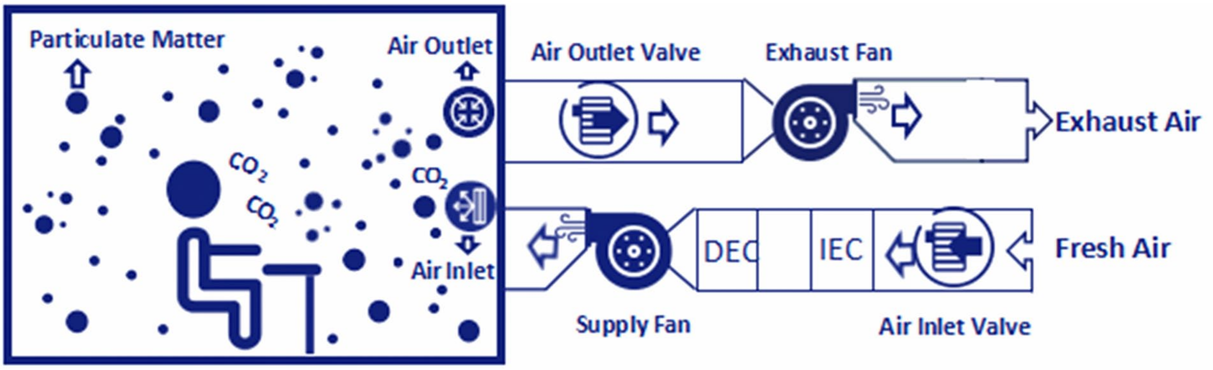

Figure 1. Flowchart of the evaporative cooling and ventilation air conditioning system.

indicators are 20, 23, and 28°C. The range of zoning is shown in Table 1. The research city was Taiyuan City, Shanxi Province, China, the calculated outdoor wet-bulb temperature is 23.8°C, which belongs to the adaptation zone. After the application of evaporative cooling ventilation air conditioning system judgment, Direct Evaporative Cooling (DEC) and Indirect Evaporative Cooling (IEC) of the 2-stage evaporative cooling ventilation air conditioning unit, an indirect section efficiency of 60%, a direct section efficiency of 80%, and an air volume of 6000 m^3/h was used (Figure 1). The air in the direct evaporative cooling section is in direct contact and cross-flow with water. Driven by the temperature difference, heat and mass transfer occurs between the air and the water, the air transfers the sensible heat to the water, and the dry bulb temperature of the air decreases, thereby achieving the purpose of cooling the air. The filler in the direct evaporative cooling section can be used as an air filter, which is a wet dust filter that reduces the concentration of particles in the air. At the same time, part of the carbon dioxide in the air is dissolved when passing through the filler, reducing the carbon dioxide concentration in the air inlet.

Filler sieving model

The description of the movement of particles in the filler used a porous media model to analyze the migration dynamics of particles.[33] The porous media model was simulated by considering the action of solid packing in the flow region as a distribution resistance added to the fluid. Porous media were modeled by adding momentum source terms to the standard fluid flow equations, including viscous and inertial loss terms. The fitting calculation between air resistance and speed can obtain the inertia resistance coefficient C_2 and the viscous resistance coefficient $1/\alpha$. The continuum method of porous media was used to describe the movement of fluids and pollutants in porous media. Using the method of macroscopic average, the movement of the fluid was represented by the macroscopic average value. The specific motion of fluid molecules and the specific surface morphology of solid skeletons were not considered. The motion of the particles was tracked using the Lagrangian discrete phase model for steady-state particle tracking. The sieving effect of porous media has an obvious effect on filtering large-diameter particles. A two-dimensional rectangular packing model with a width of 200 mm and a height of 570 mm was established via the Integrated Computer Engineering and Manufacturing code (ICEM). ICEM is used as the standard meshing software for FLUENT. Then used FLUENT 2020 R1 for calculations.

Model assumption

The main assumptions of the model are as follows[31]:

(a) Adequate wetting of the filler surface;
(b) The water film formed on the surface of the filler is a steady continuous flow;
(c) Air flow is regarded as incompressible flow;
(d) The heat and moisture transfer inside the packing material is not considered;
(e) Low particle concentration has no effect on the surrounding flow field;
(f) Coagulation, phase transition, and resuspension of particles are not considered.

Table 2. Physical parameters of spray water.

PARAMETER	VALUE
Water temperature (°C)	20
Volumetric weight (kN/m³)	9.804
Density (kg/m³)	999.7
Dynamic viscosity (×10⁻³ Pa s)	1.307
Kinematic viscosity (×10⁻¹⁰ m²/s)	4.76

Boundary conditions and parameter settings

The air inlet was set as the constant velocity inlet boundary, 4 velocity values of 1.5, 1.9, 2.2,and 2.8 m/s, and the discrete phase was the wall jet; the air outlet was set as the free outflow boundary, and the discrete phase was the trap boundary; the spray inlet was set as the constant mass flow inlet boundary, the mass flux of water was set to 0.94, 1.42, 1.89, and 2.36 kg/m^2 s, and the discrete phase was the trap boundary; the spray outlet was set as the free outflow boundary, and the discrete phase was the trap boundary. The selected material for the simulated particles was coal-lv with a density of 750 kg/m^3. The air density was 1.091 kg/m^3, and the dynamic viscosity was 1.954×10^{-5} Pa s; the physical parameters of spray water were shown in Table 2.

The dust removal efficiency of particles of different sizes passing through the water spray packing section is affected by the water drenching density and the front airstream speed. Simulated particulate data in the 4 weather conditions of sunny, breeze, gale, and rain were used to utilize number concentration measured by the CLJ-BII laser dust particle counter as the initial data for the unfilled segment, and the instrument has 6 particle size counting channels that can be detected simultaneously.

Breeze means that the wind level is the first level, and the wind speed value is 0.3 to 1.5 m/s. Gale means that the wind level is the third level, the wind speed is superimposed with the multi-frequency gust, and the wind speed value is 3.5 to 5.4 m/s. Particle number concentration in the 3 particle size ranges of 1 to 3, 3 to 5, and 5 to 10 µm were considered, which were subject to the Rosin-Rammler (R-R) distribution. Figure 2 shows the frequency distribution curve of the particles.

Governing equation

Continuity Equation for Porous Media was described as equation (1)[33]:

$$\frac{\partial}{\partial t}\gamma\alpha_q\rho_q+\nabla\cdot(\gamma\alpha_q\rho_q\overrightarrow{v_p})=\gamma\sum_{\substack{p=1\\p\neq q}}^{n}(\dot{m}_{pq}-\dot{m}_{qp})+\gamma S_i \qquad (1)$$

Where γ is the porosity, the value is 0.9, α_q is the volume fraction of the qth phase fluid, ρ_q is the density of the qth phase, $\overrightarrow{v_p}$ is the qth phase velocity, and $\dot{m}_{pq}$, $\dot{m}_{qp}$ represents the mass transfer between the 2 phases, and S_i is the source term. The porous media were modeled by adding momentum source items to the standard fluid flow equation, as expressed as equation (2)[33]:

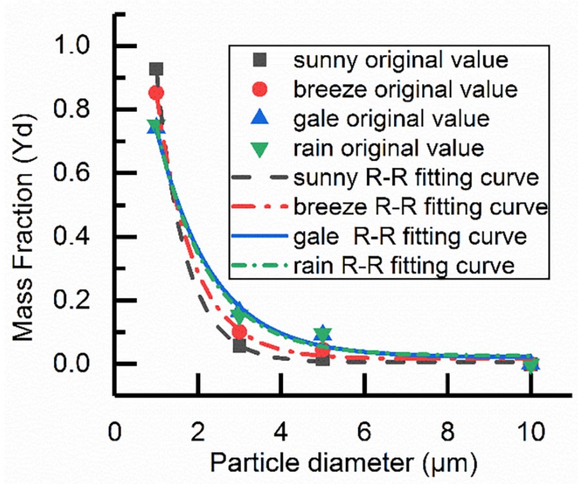

Figure 2. The Rosin-Rammler distribution curve of particle size.

$$S_i=-\left(\frac{\mu}{\alpha}v_i+C_2\frac{1}{2}\rho|v|v_i\right) \qquad (2)$$

Where α is permeability; μ is fluid viscosity (Pa s); v is velocity (m/s); $1/\alpha$ is viscous resistance coefficient (1/m^2); C_2 is inertia resistance coefficient (1/m). Fitting function based on air resistance and velocity as expressed as equations (3) to (5)[33]:

$$\Delta P=A\times v+B\times v^2 \qquad (3)$$

$$A=\frac{\mu\Delta n}{\alpha} \qquad (4)$$

$$B=\frac{1}{2}\rho C_2\Delta n \qquad (5)$$

Where ΔP is air resistance (Pa); ρ is the fluid density (kg/m^3); Δn is the thickness of the filler (m); Based on experimentally measured airflow speed and pressure drop fitting function to obtain the inertial and viscous loss coefficients of the porous media.[34] Particles concentration passed through the filler section in 16 situations was the value sent into the classroom ambient air concentration.

Sedimentation mechanism

Analysis of particulate matter after permeating evaporative cooling air conditioning filler section, using the particle layer filtration theory of filler.[35,36] Three basic mechanisms of interception, inertial collision, and diffusion are considered for aerosol particles are deposited onto the filler process. The movement of small size particles is mainly diffused by Brownian motion. The existence of Brownian motion increases the probability of small particles moving to the surface of the filler, allowing

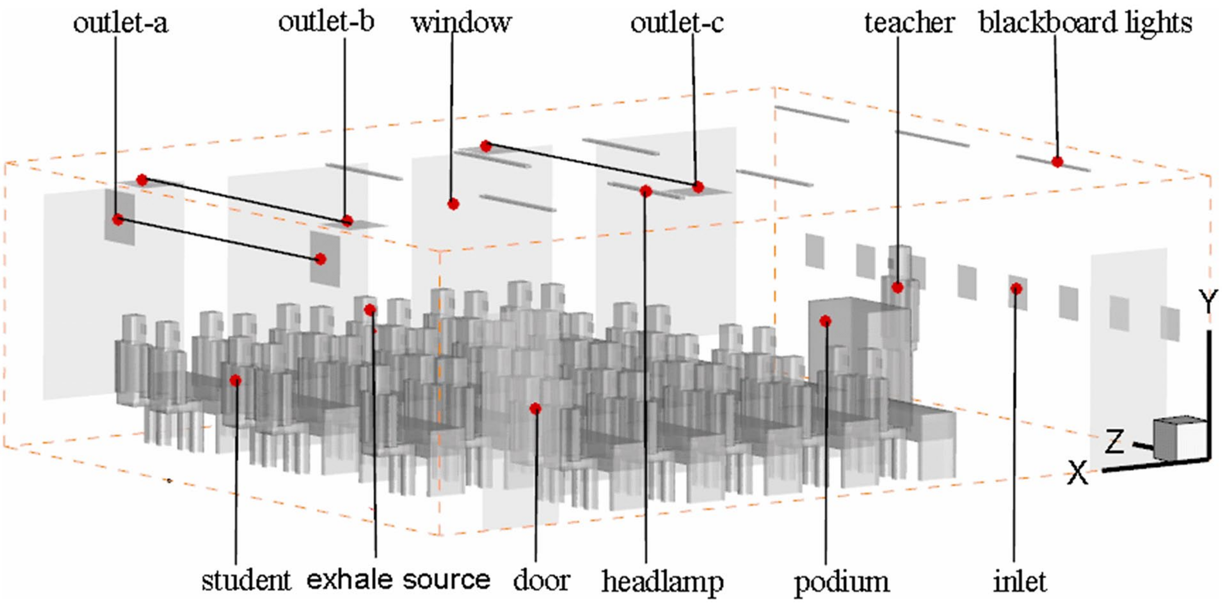

Figure 3. Classroom layout with inlet and outlet location.

small particle size particles to be trapped and filtered. PM1-3 concentration under the same water drenching density increases with the increase of airflow velocity, shortening the time to pass through the packing section, dust removal efficiency is reduced. For the same airstream speed, as the water drenching density increases, the contact area between air and water increases, improved dust removal efficiency. Filter efficiency during diffusion η_D was calculated by equation (6):

$$\eta_D = 2(\frac{d_e v}{D})^{-\frac{2}{3}} \tag{6}$$

There is a phenomenon of circumfluence of the gas streamline at the packing filter medium. Once the particles affected by inertia cannot change direction with the airflow in time, they will hit the packing surface and be captured. Equation (7) was employed as filter efficiency during the inertial collision η_I, *Ku* is Kuwabara hydrodynamic factor, was described as equation (8):

$$\eta_I = N_S \frac{\left(29.6 - 28\alpha^{0.62}\right)R^2 - 27.5R^{2.8}}{2K_u^2} \tag{7}$$

$$K_u = -\frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} \tag{8}$$

Filter efficiency during the intercept η_R, given as equation (9):

$$\eta_R = \frac{\left(1-\alpha\right)R^2}{K_u(1+R)} \tag{9}$$

where the dimensionless parameter R represents the ratio of the aerosol particle size dp to the average diameter de of the particulate filter filler, α is solidity, N_S is a probability of particles hitting the filler barrier, and v is airflow velocity.

Classroom model setup

The study location was based on typical primary school classrooms, and the study population are susceptible children with poor air quality.[37] The length (X) × width (Z) × height (Y) of the classroom is 9 m × 7.2 m × 2.75 m. Figure 3 shows the location of air inlets and outlets and the configuration of equipment and occupancy in the classroom. Eight air-delivery openings of 0.32 m × 0.32 m in size are located on the side of the wall near the podium at a center height of 1.24 m. The exhaust openings, which measure 0.5 m × 0.5 m in size, exist in pairs, taking into account the 3 exhaust end positions (outlet-a, outlet-b, outlet-c). The center coordinates of the longitudinal side air outlets A, B, and C near the door are (9, 2.4, 1.8), (8.65, 2.75, 1.8), and (4.5, 2.75, 1.8) in Cartesian coordinates, respectively. The center coordinate z direction of the other longitudinal side is an interval of 3.6 m.

The inlet boundary was set as the velocity inlet, constant supply air velocity of X-axis direction is 1.5 m/s, and the thermal boundary condition of the air outlet was set to a user-defined function that changes from time to time. The outlet boundary condition is set to free outflow. The thermal conditions of the external walls and windows were set to convection, and the heat transfer coefficient is based on the design parameters of Taiyuan City, respectively 0.52 and 2.2 W/m^2 K, and the free stream temperature is 26°C.[38] The school desk, doors, interior walls, ceilings, and floors are set as thermal adiabatic conditions. The study made simplified assumptions on the wall conditions, considering that the enclosure structure has good air tightness. The luminaires in the classroom were are arranged as 9 sets of 36 W dual-tube T8 controlled shade lights, 3 sets of 36 W single-tube T8 blackboard lamps, the average illumination of the tabletop was 445.36 1×, and the desktop uniformity of illuminance was 0.71. The luminaires

Table 3. Anthropometric data of occupant.

MEMBER	NUMBER	AGE	WEIGHT (KG)	HEIGHT, H (CM)	BODY HEIGHT, BH (CM)	HEAD HEIGHT, HH (CM)
Male student	25	12	41.2	150	60	27
Female student	20	11.5	38.4	145	58	26.1
Male teacher	1	25	65.3	173	69.2	31.4
Total	46	12.1	40.9	148.3	59.3	26.7

were set to be 2.1 m away from the tabletop to meet the needs of indoor lighting. Earlier studies mostly used empty rooms or fewer subjects, but it was not available to obtain the real staying environment of the classroom. In this model, there are 45 students (25 male, 20 female) and 1 male teacher in the classroom, which meets the maximum quantity limit of primary and secondary school design specifications. The thermal conditions between male and female students consider a constant heat flux of 75.66 W/m^2 based on physical activity level.[12]

Satisfying the thermal comfort of the evaporative cooling air-conditioning room is the result of the combined effect of the evaporative cooling air conditioner and the room heat load and researchers analyzed the heat and mass exchange process of the evaporative cooler earlier.[31] The heat load calculation of the classroom refers to process.[39] Temperature efficiency in the classroom can be determined by equation (10):

$$\varepsilon_t = \frac{T_E - T_S}{T_O - T_S} \tag{10}$$

Where T_E is the temperature of the exhaust air, T_S is the temperature of the supply air, T_O is a plane of 1 m above the ground temperature of the occupied area. The effective draft temperature θ at the location of the first row of students is an important indicator of thermal comfort that needs to be considered under the condition of stratum ventilation,[40] was described as equation (11):

$$\theta = (T_i - T) - 8(V_i - 0.15) \tag{11}$$

Where T_i and V_i respectively represent the temperature and airflow velocity at a specific point in the classroom, and T represents the average indoor temperature. Indoor carbon dioxide consists of the exhaled part of the occupants and the part of outdoor infiltration through ventilation equipment. The rate at which CO_2 is generated is related to human physical activity level. Carbon dioxide concentration exhaled by people can be obtained by a simple mass balance equation is given as equation (12)[41]:

$$Ce = Q_{CO_2} / Vo \tag{12}$$

where

Ce = Human exhaled CO_2 concentration (ppm),

Q_{CO_2} = Human CO_2 generation rate (L/s), and

Vo = Outdoor airflow rate per capita (L/s).

In line with research shows that people of different ages and genders have different CO_2 exhalation rates in the same indoor environment.[12] The exhalation CO_2 rate of male students, female students, and male teachers in this study were set to 0.0037, 0.0029, and 0.0047 L/s, respectively. ASHRAE Standard 62.1 stipulates that outdoor airflow rate per person of 5 L/s in classrooms with age 9 plus students. Metabolic rate of 75.595 W/m^2 in a quiet sitting position according to ASHRAE Standard 55. The physical parameters of an occupant in the classroom are based on the average data of Chinese adolescents, see Table 3. CO_2 concentration generated by Chinese has corresponding empirical formula comparison is described as equation (13)[42]:

$$Q_{CO_2} = \varepsilon_i \frac{0.202RQ \cdot M \cdot H^{0.725} W^{0.425}}{21(0.23RQ + 0.77)} \tag{13}$$

where

ε_i = Correction coefficient of empirical equation,

RQ = Respiratory quotient,

M = Metabolic rate (W/m^2),

H = Human height (m), and

W = Human weight (kg).

The ε-values of male students, male teachers, and female students are 0.85, 0.85, and 0.75, respectively. The Respiratory quotient is defined as the volume ratio of carbon dioxide produced to oxygen consumed. Different dietary styles have different RQ values, and the RQ values defined in this study were 0.83.[41] The pollution source size set near the mouth and nose of the occupants is 0.1 m × 0.1 m, and the CO_2 concentrations exhaled by male and female students and teachers are 740, 580, and 940 ppm, respectively.

Grid and step size independence verification

For the meshing of the classroom model, firstly, set the grid priority corresponding to the equipment and people inside the model; secondly, refer to the length in the corresponding direction of the model to determine the maximum grid spacing of the X, Y, and Z axes, which is 0.45, 0.25,and 0.3 m; then rough mesh division; finally, mesh refinement for areas such as heat sources and walls. After continuous adjustment and optimization, considering the number of grids of 1 158 937, 2 574 916, and 3 757 397 to verify the grid independence of the classroom

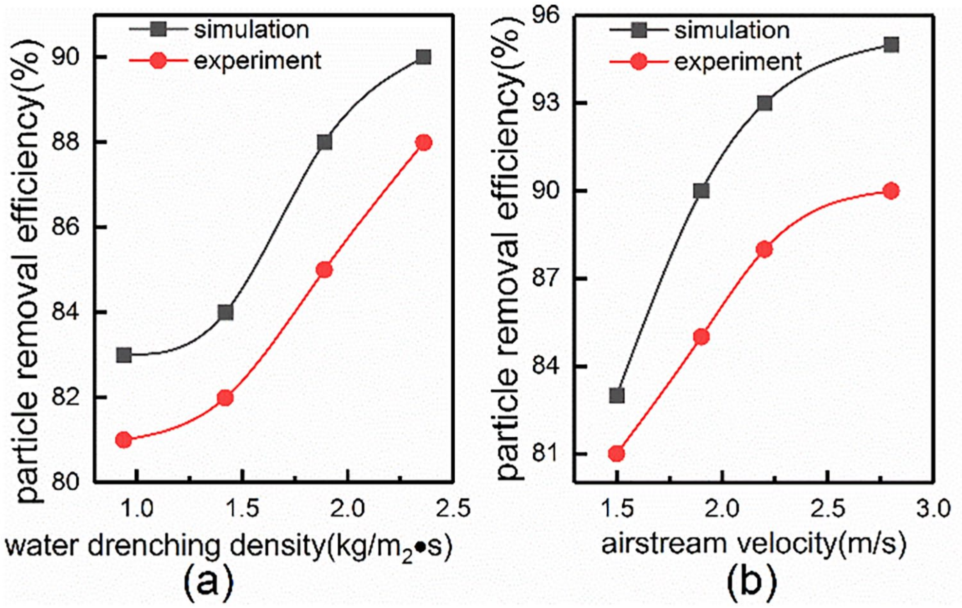

Figure 4. Comparison of particle removal efficiency between experimental and simulated data.

model, the air velocity at a height of 1 m in the classroom was calculated to be 0.018, 0.039,and 0.036 m/s. Taking into account the calculation time, select the number of 2 574 916 grids for calculation, the grid type is Hexa unstructured. The time step size of the model is considered to be 1, 60,and 300 seconds, and the calculated average CO_2 concentration at 1 m height is 612.17, 612.31, 612.62 ppm at 13:00. The difference in calculated concentration is small, and the calculation time and accuracy are integrated, and the time step is set to 60 seconds.

Model validation

The filler filter model in this study was verified by reference to the experimental data of Jin[34] and Huan et al,[43] regarding the direct evaporative cooling section, the experimental packing is corrugated regular aluminum orifice plate. The experimental system was a metal wetted media air filtration system. The combination of experimental conditions is 1.5, 1.9, 2.2, 2.8 m/s 4 oncoming wind speeds and 0.94, 1.42, 1.89, 2.36 kg/(m^2 s) 4 water spray flows, and the counting efficiency of dust particles is tested. The staggered arrangement of adjacent corrugated plates forms a specific inclined and tortuous channel of airflow, and the surface of the packing has a better wetting function. Control the air volume of the fan and change the headwind speed of the air flow; under the action of the water pump, the water is drawn out from the water tank, and is evenly sprayed onto the packing by the spray device, so as to control the flow rate of the water pump and change the water density. A gas stream of dopant particles passes through the packing. Using FLUENT simulation software, the simulation was carried out under the same geometric parameters and operating conditions as the experiment, and the simulation results were compared with the experimental results to verify the accuracy of the model. CLJBII laser dust particle counter has different particle channels, 3 μm is one of the channels, and PM3 is used to represent the particles with aerodynamic equivalent diameter of 1 to 3 μm in ambient air. Particle removal efficiency comparisons for PM3 between simulated and experimental data was shown in Figure 4a and b under different water drenching densities and air current velocity conditions. The error does not exceed 10%, which indicates that the two-dimensional filter sieving model established in this study can be used to predict the filtration performance of the spray filler. Numerous studies have proved that the renormalization group k-ε model can be better used to simulate indoor turbulent motion than the standard k-ε model.[44,45] The RNG k-ε model shows accuracy in model validation and is therefore available for this study.

Results and discussion

Particle concentration

The lowest concentration of particulate matter on gale day is due to the increase in wind speed up the dilution and diffusion of pollutants. For PM1-10, the inertial effect of the particles is positively related to the particle size, and the filtration efficiency of the particles changes accordingly. The increase in water drenching density and air current velocity strengthens the interaction between air and water and increases the inertial collision efficiency. The movement of particles in the airflow supplied by the fan within the filler is affected by the filler structure. When the particles move with the streamline, the distance between the streamline and the filler obstacle is less than the particle size, and the particles are intercepted and captured. The larger the particle size, the more efficient the intercept capture. The total filtration efficiency is the sum of the efficiency under the 3 effects. PM1-3 particles concentration under the same water drenching density increases with the

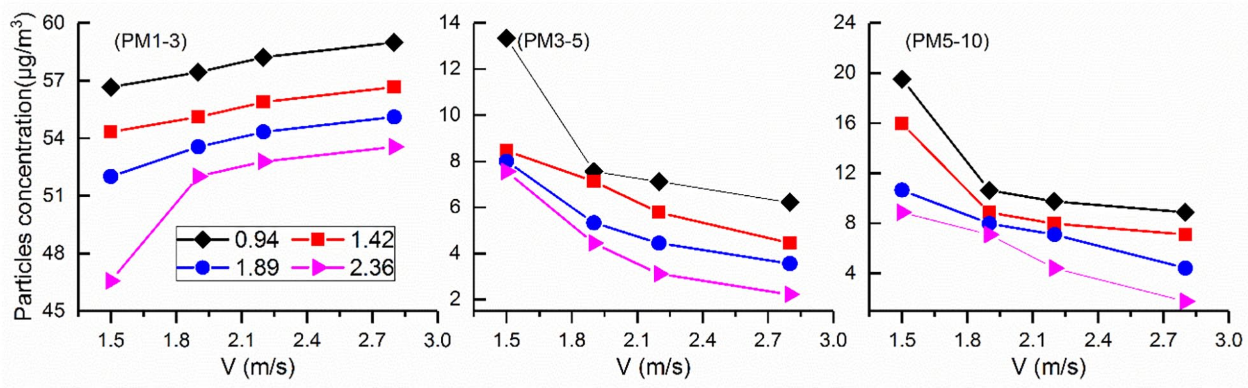

Figure 5. Sunny particle concentration.

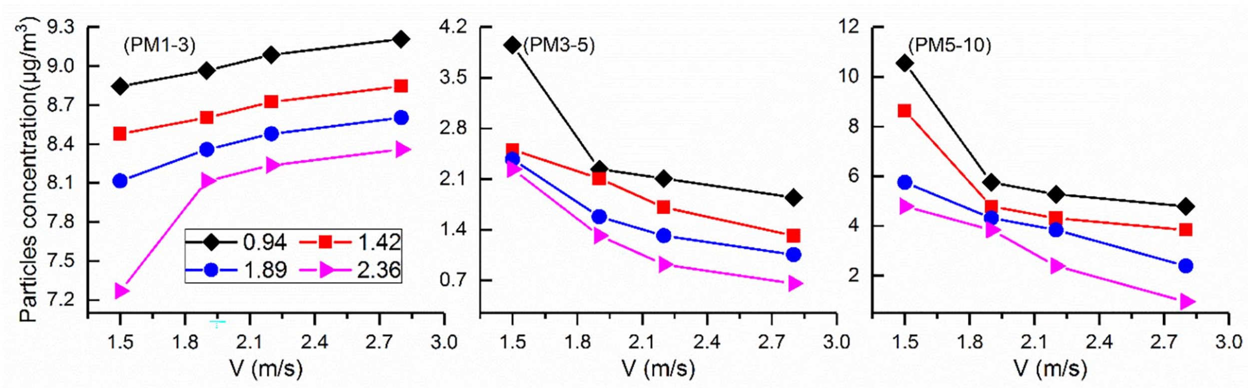

Figure 6. Breeze particle concentration.

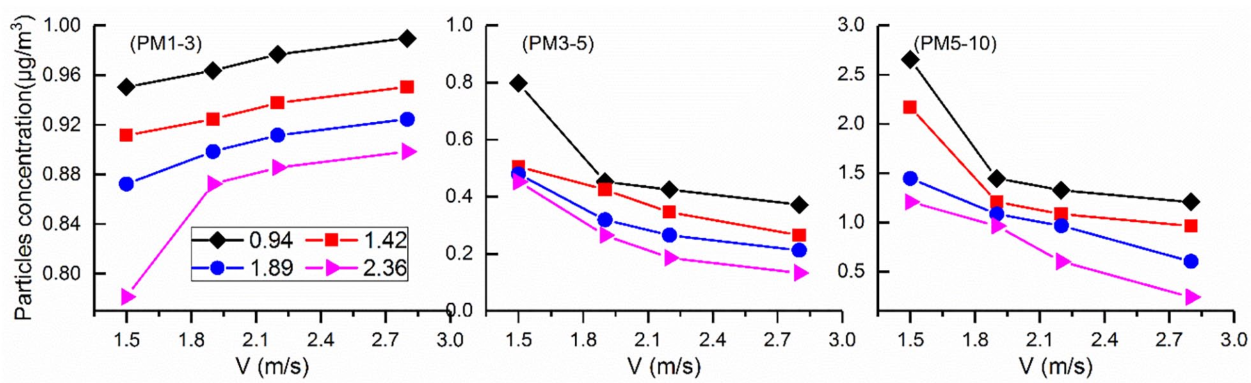

Figure 7. Gale particle concentration.

increase of the head-on air current speed, shorten the time to pass through the packing section, and dust removal efficiency decreased. Under the same head-on airflow velocity circumstance, the contact area increases between air and water with an increase in water drenching density and improves dust removal efficiency. For particles in the PM3-5 and PM5-10 interval, as the airflow migrates, once the filler is contacted, a part of particles is filtered as a result of a combination of mechanisms. The probability of impact to the obstacle is positively related to particle size, and the greater the filtration efficiency, and the number of large particle size particles is more filtered. The trend of change in the concentration of the initial particulate matter under the 4 weather conditions after the change of the water drenching density and the head-on wind speed is shown in Figures 5 to 8.

Indoor environmental parameters

Temperature parameter. The air supply parameters of the evaporative cooling air conditioner are affected by outdoor hourly dry-bulb temperature calculation change. The air-conditioning system combined with stratum ventilation has a high air supply temperature, which has the effect of energy-saving and environmental protection. Considering that the analog period time

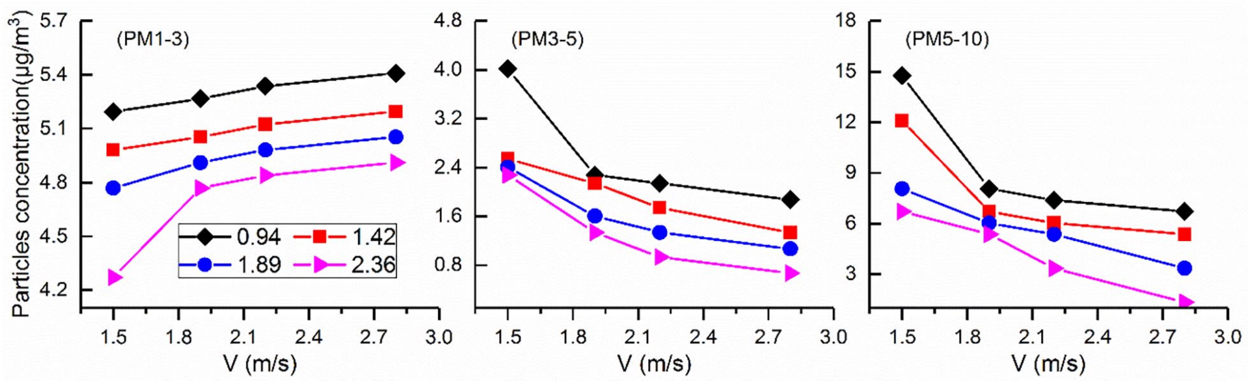

Figure 8. Rain particle concentration.

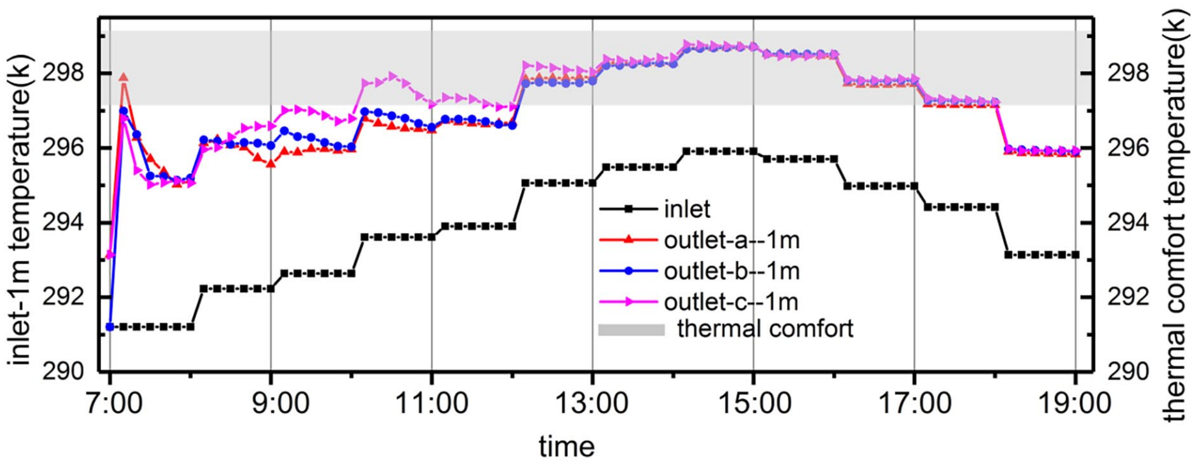

Figure 9. Inlet temperature, average temperature of 1 m height plane, and thermal comfort temperature zone. The left-*y* axis reflects the temperature value of the inlet and a plane of 1 m above the ground. The right-*y* axis reflects the temperature value of the thermal comfort. The shaded area indicates the range of thermal comfort.

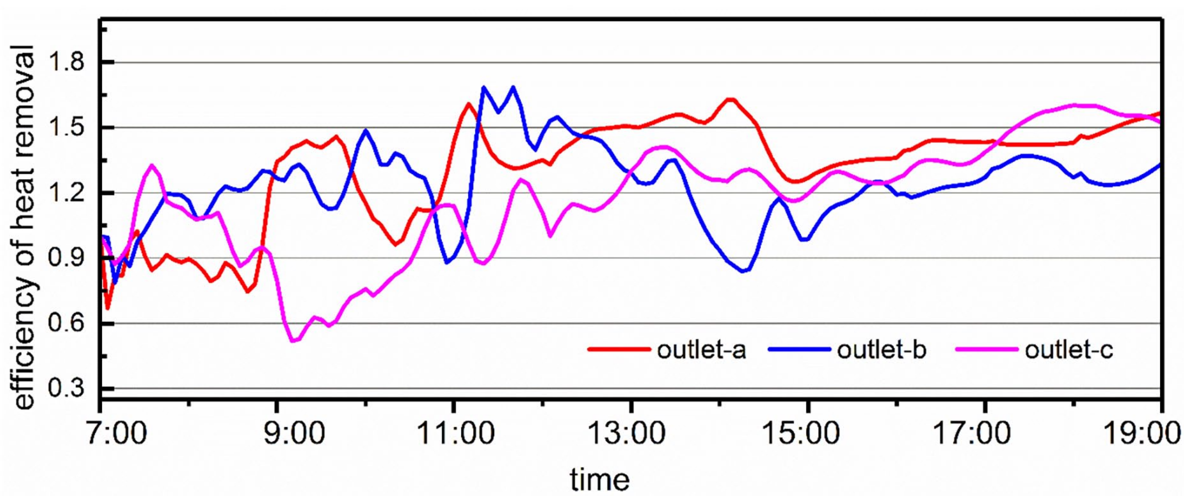

Figure 10. Temperature efficiency under 3 different outlet positions.

is 7:00 am to 7:00 pm, the Chinese standard GB50376-2012 specification states that the temperature range for thermal comfort level I is 297.15 to 299.15 K for cooling conditions[46] Figure 9 shows that the average temperature of the occupant area at a height of 1 m can satisfy thermal comfort during most of the simulation period time for the 3 exhaust positions. The thermal comfort performance of outlet-c is the best overall, and the effects of outlet-a, and outlet-b are similar. A temperature efficiency value is shown in Figure 10 greater than 1 means that when the inlet airflow in the lower middle area of the classroom is supplied to the occupant area, the temperature of the occupant area is lower than the temperature of the exhaust

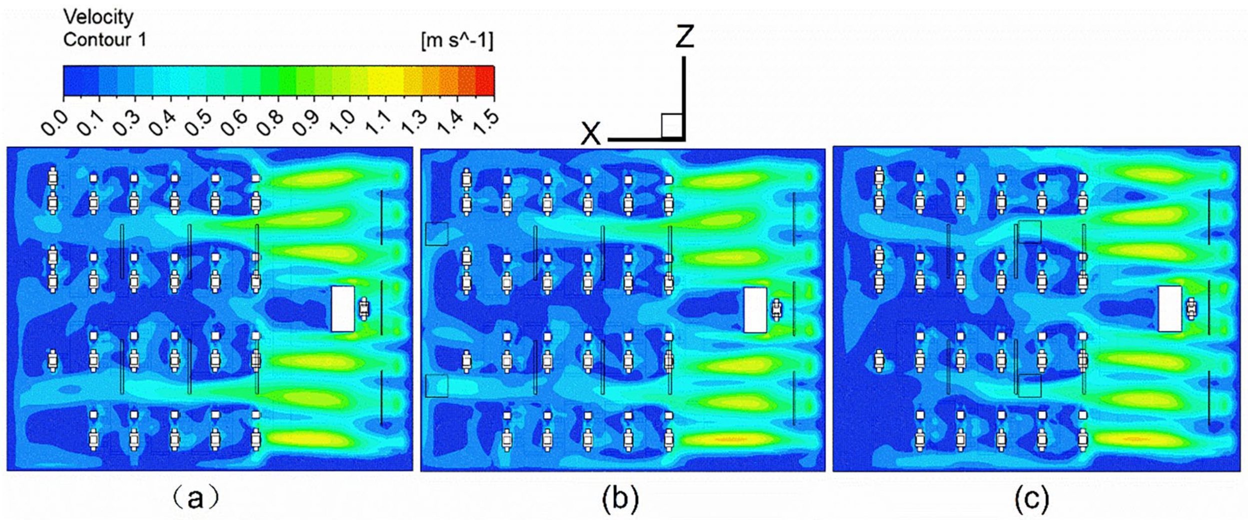

Figure 11. Velocity contour diagram of 1 m height plane at the 3 outlet positions, (a-c) represent outlet-a, outlet-b, outlet-c, respectively.

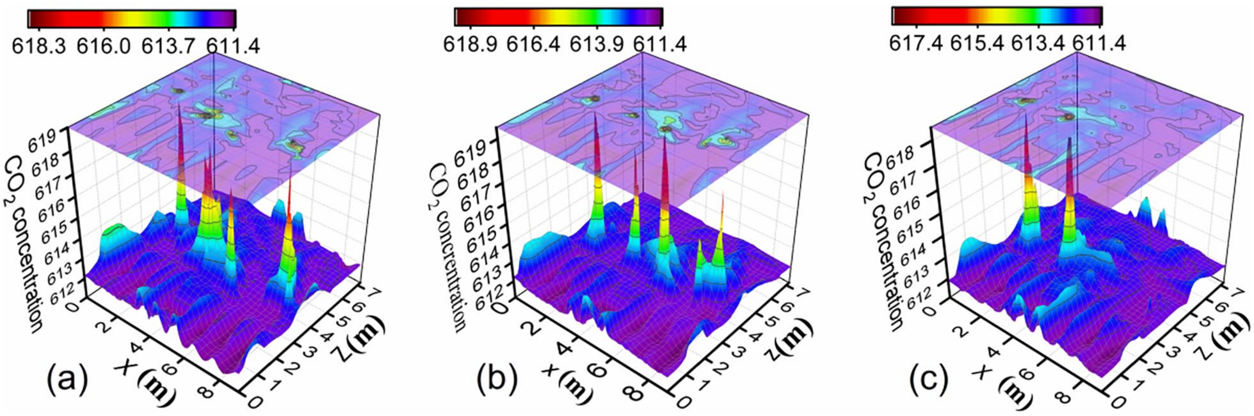

Figure 12. Three-dimensional surface diagram of the breathing zone CO_2 concentration at the 3 outlet positions without evaporative cooling air conditioning process, (a–c) represent outlet-a, outlet-b, outlet-c, respectively.

outlet. Velocity contour diagram of 1 m height of occupant area is shown in Figure 11, corresponding to the previously obtained temperature data, the wind speed is less than 0.25 m/s, and the effective draft temperature is from −0.8 to 0.3°C, which can make most occupant in the classroom have no sense of blowing. ASHRAE 55-2017 recommends that the vertical air temperature difference between the head and ankle of the human body should be controlled within 3°C, and the temperature difference between 0.1 and 1 m planes in this study classroom model meets the specifications.[47] Students have "hot head and cool feet," which is in line with the comfort of the human body.

Carbon dioxide distribution

Part of the CO_2 in the outdoor air is dissolved in water through the water-sprinkling section of the evaporative cooling air conditioner, the process of dissolving in water involves both physical processes and chemical reactions. Part of CO_2 is dissolved in water to produce carbonic acid, and part of CO_2 falls into the water receiving disk in the form of hydrated carbon dioxide. The solubility of CO_2 in the simulated environment is 0.878, and the carbon dioxide supply into the classroom through the water spray filling section is 48.8 ppm.[48] Carbon dioxide concentration of the air inlet without evaporative cooling process for the outdoor atmospheric CO_2 is 400 ppm.[49]

Vent positions affect indoor pollutants concentration and are placed near the ceiling at a lower concentration in the breathing zone than near the floor.[50] Three simulated considerations for the location of the exhaust port near the ceiling (outlet-a, outlet-b, outlet-c). Considering the symmetrical distribution of the classroom layout and the difference in the position of the outlet, and the distribution of CO_2 concentration at a height of 1 m in the breathing zone are shown in Figures 12 and 13. Ventilation rate and human breathing frequency in the room are constant, and indoor carbon dioxide concentration fluctuates a little over time from 7:00 am to 7:00 pm (Figure 14). Low CO_2 concentration continuously supplies from inlet dilutes high CO_2 concentration in the breathing zone. Indoor carbon dioxide concentration is reduced and the air quality is improved with evaporative cooling air conditioning. The free outflow of exhaust pick up contaminants that move upward. The outlet-c position is closest to the student seating area, shortening the moved

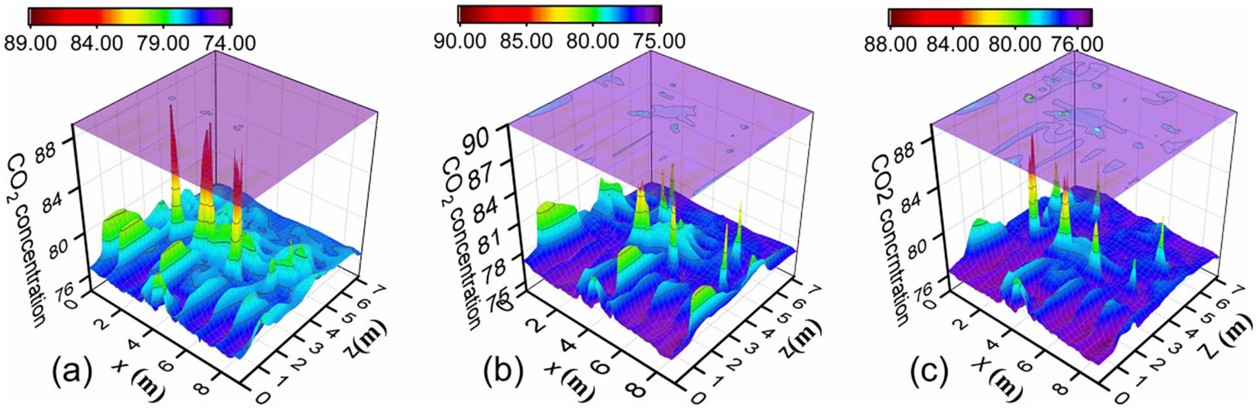

Figure 13. Three-dimensional surface diagram of the breathing zone CO_2 concentration at the 3 outlet positions under evaporative cooling air-conditioning, (a–c) represent outlet-a, outlet-b, outlet-c, respectively.

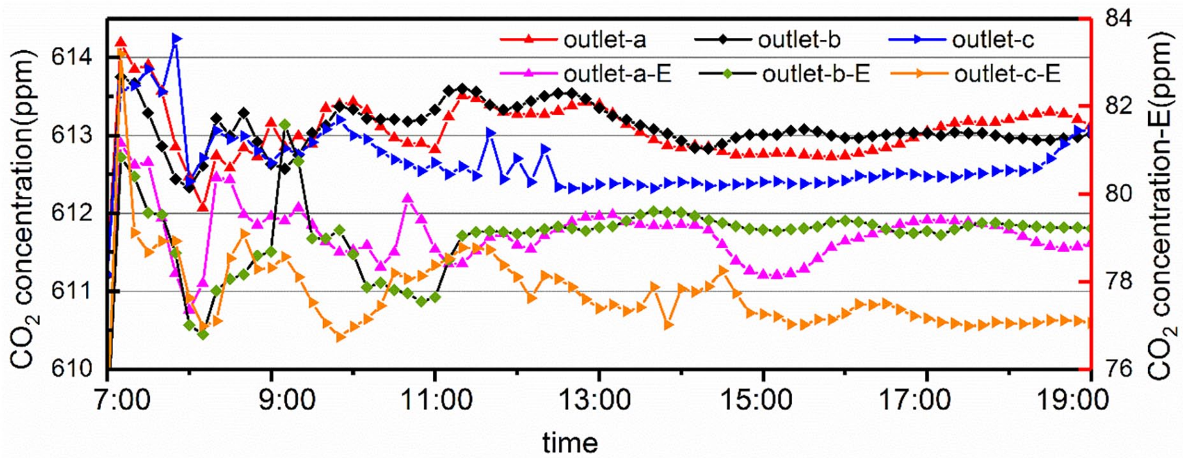

Figure 14. Whether the classroom used evaporative cooling air conditioner (E) CO_2 concentration change over time.

distance of indoor contaminants and accelerating pollutants removal. Similarly, outlet-a contaminant moved path is shorter than outlet-b, and the flow around the corner appears in outlet-b, weakening the decontamination effect.

Conclusions

Evaporative cooling air conditioning can not only adjust indoor temperature and humidity, but also remove particulate matter in the air, compared with traditional artificial refrigeration and dehumidification air-conditioning. Comparing the position of the exhaust vent in the middle of the classroom with the back of the classroom, the former has a better air pollutant removal effect. Stratum ventilation in primary school classrooms ensures that carbon dioxide concentration in the breathing area of students meets indoor air quality guidelines.[51] Evaporative cooling air conditioners can purify part of the particulate matter and carbon dioxide concentration of the fresh air sent into the room from the outdoor airflow, thereby improving indoor air quality. The average temperature of the occupant area corresponding to the change in the hourly changing supply air temperature parameter under evaporative cooling stratum ventilation can ensure indoor thermal comfort. The results of this study show that it is technically feasible to install evaporative cooling air conditioning in schools in hot and dry areas. Under the same spray water density, with the increase of the head-on wind speed, the residence time of the particles in the filler is shortened, the contact probability between the particles and the spray water is reduced, and the removal efficiency is reduced. The change of the spray water density promotes the change of the interaction between the air flow and the spray water, and the particles accelerate the sedimentation under the action of the spray water, which increases the particle removal efficiency. With the increase of water spray density, the contact area between air and water is increased, and the particle removal efficiency is improved.

The change factors considered in this study are not comprehensive enough, and the comprehensive analysis of numerical simulation and experiment for adjusting the material and thickness of the filler can be supplemented. Change of particulate matter concentration supply into indoors during the occupied period and particles source at the height of students' feet during inter-class activities need to be further studied. This research is only limited to the research at the technical level, and lacks the analysis at the economic level. The follow-up research considers the combination of economic, technological, and energy-saving factors to comprehensively analyze and determine the best application scheme.

Author Contributions

Lu Xiao: Conceptualization, Methodology, Writing-original draft. Zhenyu Du: Supervision, Validation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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