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Experimental and numerical studies on indoor thermal comfort in fluid flow: A case study on primary school classrooms

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ABSTRACT

Indoor thermal comfort in primary classrooms is important to students' learning and health. The studies focusing on it, especially under the subtropical plateau monsoon climate, are scarce. In this study, the indoor thermal comfort surveys and parameter measurements were made over the period from October 2018 to December 2018 in Kunming, China. A series of indoor thermal comfort and outdoor parameters were measured each 1 h and subjective questionnaire surveys were performed on the selected 20 students every week except on holidays. A series of three-dimensional numerical simulations were carried out using ANSYS Fluent.

1. Introduction

Students in primary schools spend the majority of their daytime in classrooms and are more vulnerable for air contaminants than adults, and thus the classroom indoor thermal environment has substantial impact on students' health and performance. Previous studies have shown that a comfortable indoor thermal environment is more conducive to improving students' learning efficiency [1,2], while excessive indoor temperature is likely to make students feel headache and chest tightness, leading to decreased attention [3]. There have been standards that guide the thermal comfort environment in educational sector, such as the ISO Standard 7730 [4], the ASHRAE standard 55 [5], and the European Standard EN15251/2007 [6].

In order to improve understanding indoor thermal comfort not only take into account the thermal comfort standards but also pay more attention to the thermal comfort of ventilation mode, and the thermal adaptability of psychology, physiology and behavior. It is vital to evaluate the natural ventilation thermal comfort in primary classroom.

The studies on students' thermal comfort in primary schools were scarce and mainly focused on the typical climates, such as hot or cold climates [7,8]. It was found that thermal comfort depends on local meteorological condition, season and ventilation strategy. In remote or underdeveloped regions, natural ventilation is generally the ventilation strategy used in primary school classrooms, thus the temperature range is wider than that with mechanical ventilation strategy [9–11]. A bulk of thermal comfort parameters based on natural ventilation have been set up for the analysis of indoor climates and used to analyze the effect of parameters and to improve indoor air quality [12]. However, The study by S ter Mors et al. [13] found that the students aged 9–11 years old in naturally ventilated primary school classrooms felt more comfortable at the actual temperature which is lower than that calculated with the PMV (predicted mean vote) model. It has great potential to improve indoor environment condition by simple natural ventilation strategies [11].

To our best knowledge, limited experiment data were obtained on the subtropical climate [14]. Studies of thermal comfort mainly

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Nomenclature

M	the metabolic rat
W	external work
P_a	partial water vapour pressure
Ps	saturated vapour pressure
T_i	indoor mean temperature
T_{cl}	surface temperature of clothing
T_{mrt}	mean radiant temperature
T_g	black globe temperature
A_{DU}	body surface area of a human
RH	air relative humidity
v_{ar}	relative air velocity
f_{cl}	ratio of body's surface area
I_{cl}	clothing thermal resistance
ρ	air density
u_i	velocity
f_i	unit mass force
τ_{ji}	air Viscous stress
h_c	convective heat transfer coefficient
k	heat conductivity coefficient
k_i	thermal conductivity due to the effect of turbulence
S_h	volume heat source term
m_l	the mass of component l per unit volume
D_l	diffusion coefficient
S_l	the rate of formation of components per unit volume
W_b	body weight
H_b	body height

focuses on urban office building [15], residential building [16], university classrooms [17] and other building, little research on primary school classrooms, especially under the subtropical plateau monsoon climate.

The remainder of this study is organized as follows. The field survey, thermal comfort theory, the governing equations, and the numerical methods are briefly described in Section 2. A series of results are benchmarked in Section 3. The observed behavior of the interaction from CFD results, together with the experimental results, is presented and discussed in Section 4. Finally, the conclusions are drawn in Section 5.

2. Methodologies

2.1. Field survey

In order to evaluate the indoor thermal comfort, a series of measurement parameters were carried out from October 2018 to December 2018, over the period of 8:00 am to 5:00 pm in the daytime. By recording the indoor environment parameters (air temperature, relative humidity (RH), air velocity, globe black temperature) and outdoor conditions (ambient air temperature, mean radiant temperature, and air velocity) in a test classroom. The south-facing classroom was on the second floor of the five-storey building in a primary school Kunming, China. The computational domain used in the numerical simulation is of the dimensions H×B×L (Height×Width×Length) = 3.4 m×8.0×11.0 m, which are the same as for the physical classroom. The classroom has four windows of the size of 1.7 m×1.7 m, and two doors of the size of 1.2 m×1.8 m. The windows are 0.8 m above the floor surface.

Kunming (latitude 25.6^{o} N, longitude 103.8^{o} E) is located in the subtropical monsoon climate zone. The outdoor air temperatures fluctuates between 7.6 °C to 19 °C, and the average outdoor air temperature is 15 °C. It has unique climatic characteristics of distinct dry and wet seasons, low air humidity in winter, and the rainy seasons from May to October. The prevailing wind change is not drastically, with the prevailing wind direction is south and southwest, and at the wind velocity of 1–3 m/s. Effective natural ventilation strategy is good at the indoor air condition in Kunming.

2.2. Indoor thermal comfort

Indoor thermal comfort is the condition, which satisfaction with the indoor thermal environment. The subject assessment of indoor thermal comfort mainly depend on indoor thermal environment, personal factors, and outdoor environment. This work adopt 7-point PMV thermal sensation scale according to the ISO ASHRAE thermal comfort. Some primary school students feel uncomfortable in the indoor environment due to the ability of heat resisting cold difference. To be clear illustrate the difference, the Predicted Percentage of

Table 1
The relationships between PMV-PPD scales and indoor thermal comfort.

PMV	Thermal sensation	PPD (%)
+3	Hot	100
+2	Warm	75
+1	Slightly warm	25
0	Neutral	5
1	Slightly cool	25
2	cool	75
3	cold	100

Dissatisfied (PPD) was used [18] (See Table 1).

The PMV-PPD model is given by Eqs. (1) and (2) [19,20]:

$$\begin{aligned} \mathrm{PMV} = & \left(0.303e^{-0.036M} + 0.028\right)\{\mathrm{M} - \mathrm{W} - 3.05 \times 10^{-3}[5733 - 6.99(\mathrm{M} - \mathrm{W}) - \mathrm{Pa}] \\ & -0.42[(\mathrm{M} - \mathrm{W}) - 58.15] - 1.7 \times 10^{-5}\mathrm{M}(5867 - \mathrm{Pa}) - 0.0014\mathrm{M}(34 - Ti) \\ & -3.96 \times 10^{8} f_{cl}\left[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4\right] - f_{cl}h_c\left(T_{cl} - T_i\right)\} \end{aligned} \tag{1}$$

$$\mathrm{PPD} = 100 - 95\exp\left[-\left(0.03353\mathrm{PMV}^4 + 0.2179\mathrm{PMV}^2\right)\right] \tag{2}$$

where $M(W/m^2)$ is the metabolic rate, $W(W/m^2)$ is the external work, Pa is the partial water vapour pressure, T_i (^oC) is the indoor mean temperature, f_{cl} (-) is the ratio of body's surface area when fully clothed to body's surface area when nude, T_{cl} (^oC) is the surface temperature of clothing, T_{mrt}(^oC) is the mean radiant temperature, h_c (W/m^2 k) is convective heat transfer coefficient between the occupant and the environment.

The surface temperature of clothing T_{cl} (^oC) is calculated by

$$Tcl = 35.7 - 0.028\left(\mathrm{M} - \mathrm{W}\right) - I_{cl}\left\{3.96 \times 10^8 f_{cl}\left[(T_{cl} + 273)^4 - T_{mrt} + 273\right)^4\right] - f_{cl}h_c\left(T_{cl} - T_i\right)\right\} \tag{3}$$

the convective heat transfer coefficient h_c (W/m^2 ·k)can be valued by means of the following relation:

$$h_c = \begin{cases} 2.38(T_{cl} - T_i)^{0.25} & \text{if } (T_{cl} - T_i)^{0.25} \geq 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & \text{if } (T_{cl} - T_i)^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \tag{4}$$

Where v_{ar} (m/s) is relative air velocity is given by Ref. [18]:

$$v_{ar} = v_a + 0.005(M/A_{DU} - 58.15) \tag{5}$$

$A_{DU}(m^2)$ is the body surface area of a human calculated according to Dubois formula as a function of the body weight W_b(kg) and the body height H_b(m):

$$A_{DU} = 0.202 W_b^{0.425} H_b^{0.725} \tag{6}$$

f_{cl} (-) is calculated by

$$f_{cl} = 1.0 + 0.3 \quad I_{cl} \tag{7}$$

Where I_{cl} is clothing thermal resistance.

The partial water vapour pressure may be obtained using Eq. (8):

$$\mathrm{Pa} = \mathrm{PsRH} \tag{8}$$

Where RH(%) is the air relative humidity, Ps is the saturated vapour pressure can calculated by Ref. [20]:

$$\mathrm{Ps} = -\log^{-1}\left[30.59051 - 8.2\log(T_i + 273.16) + 0.0024804(T_i + 273.16) - \frac{3142.31}{T_i + 273.16}\right] \tag{9}$$

T_{mrt}(^oC) is the mean radiant temperature can calculated by

$$T_{mrt} = T_g + 2.4V_{ar}^{0.5}\left(T_g - T_i\right) \tag{10}$$

Where T_g (^oC) is the black globe temperature.

2.3. Experimental measurements

The experimental instruments and the measuring variables are listed in Table 2. All measurement cycle is one month and the interval was 1 h. To reduce the effect of solar radiation and airflow, the i75-H2 temperature and humidity recorder was placed in the

Table 2
Experimental instruments, measured variables and the accuracy.

Measuring instrument	Measuring variable	Accuracy
I75–H2 temperature and humidity recorder	indoor/outdoor temperature& humidity	Temperature: ± 0.1 °C Humidity: ± 0.1%rF
ZROF-F30 anemometer	Outdoor air velocity	± 0.05 m/s
CENTER 309 Thermocouple	Temperature	± 0.1 °C
hot-wire anemometer	Indoor air velocity	± 0.01 m/s
TBQ-2 pyranometer	Solar radiation intensity	± 5W/m^2

Table 3
Hunan body data of primary students.

Gender	Participate numbers	Mean Age(y)	Mean Height(m)	Mean Weight(Kg)
Male	10	7.4	1.25	21.0
Female	10	7.7	1.22	19.8
Total	20	7.6	1.23	20.5

shady area and 1.5 m above the ground. The ZROF-F30 anemometer was located outside the open area and 1.5 m above the ground, in order to reduce the influence of building and greenery wind velocity and direction. The temperature and humidity measurement elements were placed in the center of the classroom and 0.6 m above the ground. The thermocouple was located on the surface of walls and 0.8 m above the floor.

A series of experiments were carried out from October 2018 to December 2018 in the test primary classroom, thus obtain the bulk of thermal comfort indicators data. A total of 20 temperature conditions, which represent the typical climate of Kunming during the test period, were used during the experiment. The indoor air temperature, air velocity, black globe temperature, relative humidity, and radiant temperature were monitored.

The subject questionnaire for the primary school students includes the main six factors of thermal comfort on classroom (air temperature, air humidity, air velocity, mean radiant temperature, students human metabolic rate and clothing thermal resistance). It also takes into account of the influence of objective factors (age, gender, living habits). The questionnaire survey was carried out after the surveyed students entered the classroom and stayed for more than 30 min to ensure the authenticity of the questionnaire.

For the validity of the experiment data, a representative total of 20 primary school students were selected to take part in the experiments. The human body data of the student is shown in Table 3. All students were healthy, were instructed to wear clothes and were qualified to understand the physical experiments. All students successfully completed the experimental procedure, including a large number of questionnaires on the classroom thermal comfort environment.

2.4. Numerical methodologies

The flow of air in the classroom was regarded as steady, incompressible, low-velocity turbulent flow due to very low natural ventilation air velocity. The governing equations include the mass conservation, momentum conservation, energy conservation, and species diffusion equations are as follows:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{11}$$

$$\frac{\partial \rho u_i}{\partial \tau} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{\partial \tau j_i}{\partial x_j} + \rho f_i \tag{12}$$

$$\frac{\partial \rho t}{\partial \tau} + \frac{\partial \rho u_i t}{\partial x_i} = \frac{\partial}{\partial x_i}(k + ki)\frac{\partial t}{\partial x_i} + S_h \tag{13}$$

$$\frac{\partial \rho m_l}{\partial \tau} + \frac{\partial \rho u_i m_l}{\partial x} = \frac{\partial}{\partial x}\left(D_l \frac{\partial m_l}{\partial x_i}\right) + S_l \tag{14}$$

where ρ is air density, u_i is the velocity. f_i is unit mass force, τ_{ji} is air Viscous stress. k is heat conductivity coefficient, k_i is thermal conductivity due to the effect of turbulence, m_l is the mass of component l per unit volume, D_l is diffusion coefficient, S_l is the rate of formation of components per unit volume.

According to the experiment data, a series of three-dimensional simulations used Airpak in ANSYS Fluent were conducted to obtain solutions.

Table 4
Experimental results at the 5 points in the classroom.

	Air Temperature (^{0}C)	Air Velocity (m/s)	Black globe temperature (^{0}C)	Relative humidity (%)	Mean radiant temperature (^{0}C)
1	22.806	0.465	21.925	49	22.8
2	22.027	0.693	21.925	64	22.8
3	21.729	0.381	21.925	53	22.8
4	23.900	0.509	21.925	51	22.8
5	21.035	0.598	21.925	67	22.8

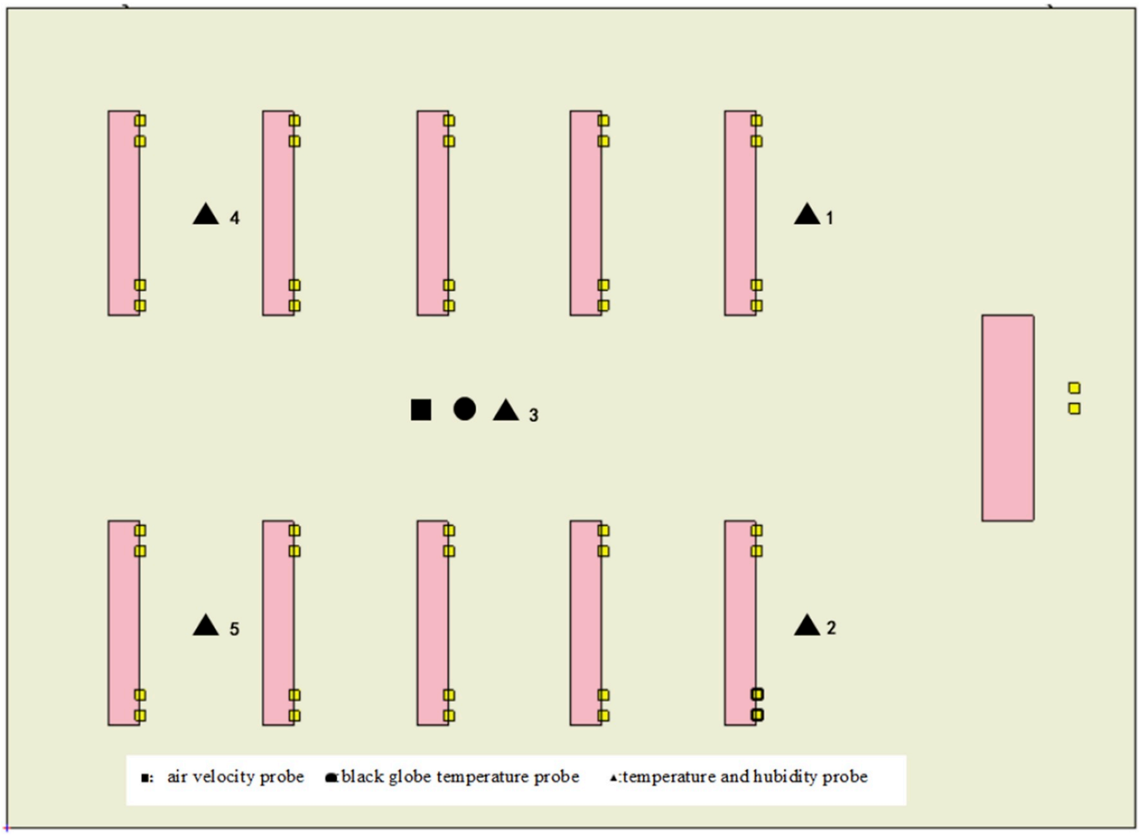

Fig. 1. The locations for the five points used in both the experimental measurements and the numerical simulations.

3. Results and discussions

3.1. Experimental results

The experimentally measured data are presented in Table 4. The locations for the five points used in both the experimental measurements and the numerical simulations were shown in Fig. 1. The black globe temperature and mean radiant temperature of five points were the same due to the small classroom area. The light heat was not taken into account in this study.

3.2. Numerical results

In the simulation, the size and exact position of windows, doors and air vent are same as the physical environment parameters. The room seat twenty students, who seat 5 rows and 4 lines. The average air velocity is 2.1 m/s, the relative humidity is 50%, and temperature of south-out wall and windows are 21 °C and 19 °C based on the experiment data. The temperature distribution of the cross sections which is at the height $y = 1.1$ m (the height of the neck when the students sitting), is shown in Fig. 2.

It can be seen from Fig. 2(a) that the temperature at the neck of the point 2 and 4 is between 20.8 °C and 22.5 °C, and the point 1, and 5 is between 22.7 °C and 26 °C. The point 3 is 21.2 °C. It can be seen that the students near the windows feel a little cold, because the four windows were opened for natural ventilation in this study. According to GB/T18049-2000 [21], the temperatures were in the

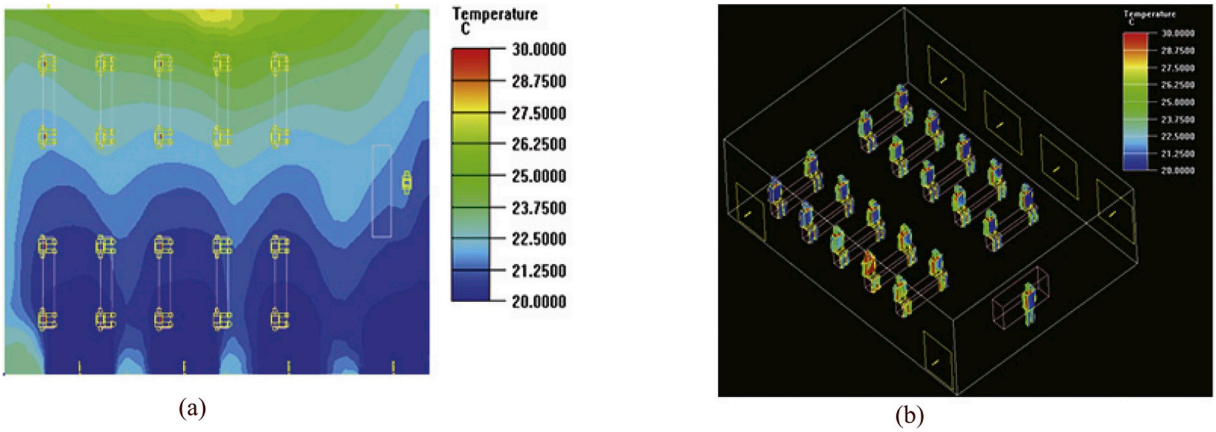

Fig. 2. The temperature distribution of at the cross-section plane at height y = 1.1 m (a) and the temperature of body of students (b).

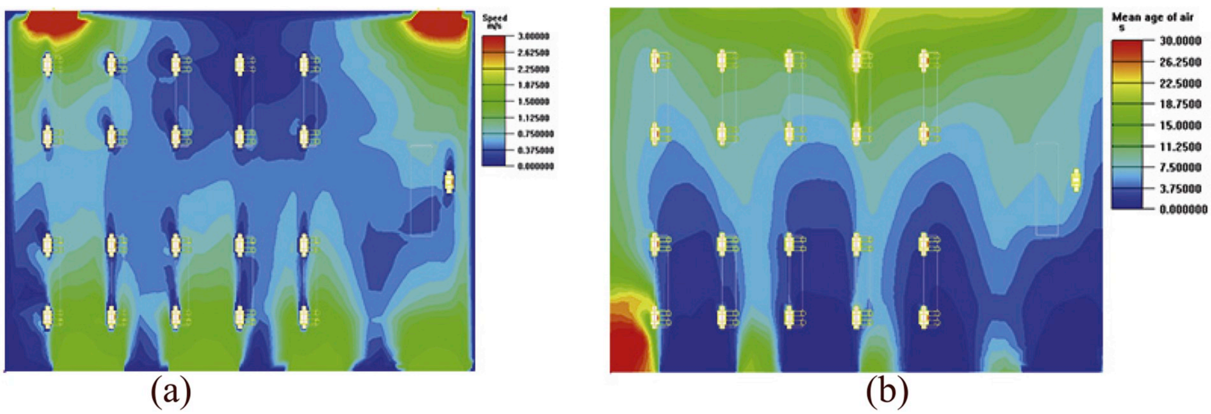

Fig. 3. The velocity distribution (a) and the mean age(b) at the cross-section plane at height y = 1.1 m.

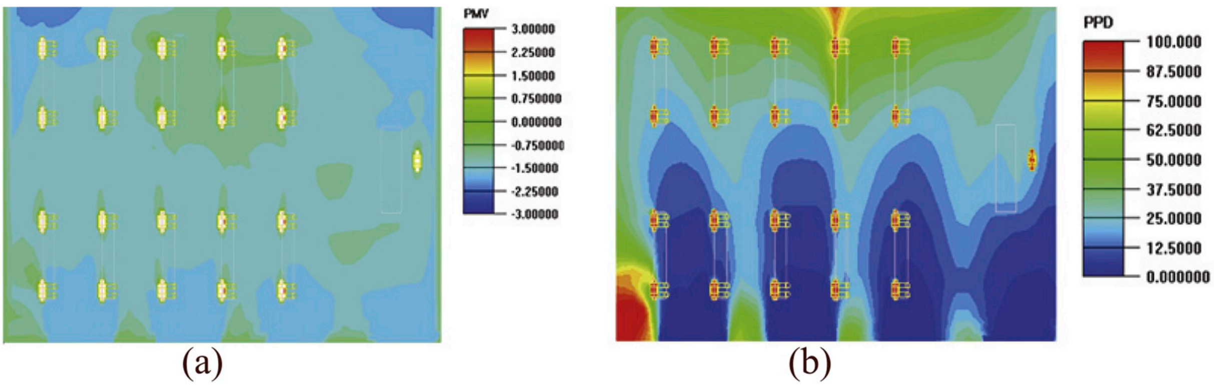

Fig. 4. PMV distribution (a) and PPD distribution (b) at the cross-section plane at height y = 1.1 m.

acceptable indoor thermal comfort range.

In order to study the temperature of the body of the students, it were depicted the force temperature as shown in Fig. 2(b). According to standard GB50736-2012 [22], it can be satisfied the indoor learning environment.

It is shown from Fig. 3(a) that the natural wind is provided by the air diffuse has an effect on the areas near the windows and door because of the supply air is spread to the surrounding. The air velocity of point 2 and 4 is about 1.3 m/s, is higher than others. The natural wind velocity changed little when the flow into the room through the windows. The convection between the windows and the doors plays an important role in the natural wind. The student felt cold near the corner of door because of convection.

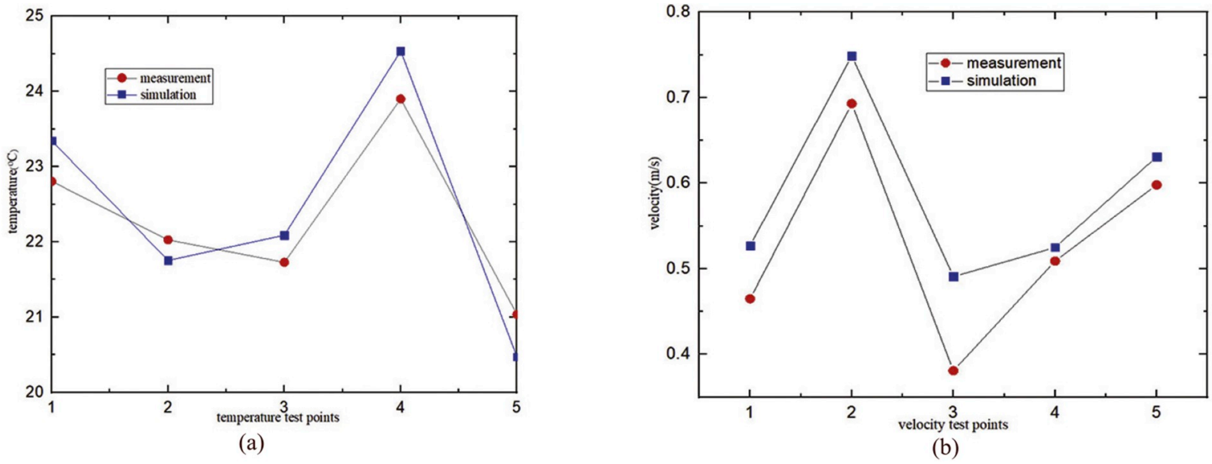

Fig. 5. Temperature (a) and velocity(b) between simulation and measurement.

Ventilation is intended to provide a “fresh” atmosphere and the “age” of the air within the space can be used as a measure of the “freshness”. In this sense, the age is a simpler and more general indicator of air quality [23]. Fig. 3(b) is the age of air distribution of the section of air supply port at $y = 1.1$. It can be seen that the air age nearly no impacted by the height decreases. The air is fresh between the zone of learning. The students seat near the wall, who felt a little uncomfortable fresh because of barrier of wall. It cased the air back-flow. The age of air near the windows is miner than other space, which were transmitted to the learning zone.

The PMV values of $y = 1.1$ m were range -0.5 to 0.5 as shown in Fig. 4(a). The value satisfy with the range of indoor thermal comfort standard, which was between -1 to 1. The PPD values, near the window of the primary classrooms was lowest as shown in Fig. 4(b), which was at around 3%. The PPD values near the middle of north-wall in the primary classrooms was highest, which was approximate 30%. According to stand GB/T18049-2000 [21], the PMV and PPD values of primary classrooms were satisfy with the acceptable range.

3.3. Comparisons between physical measurements and numerical simulations

In order to make the validity of the numerical simulations, there is comparisons with physical experiment. In this work, the air velocity and temperature was assigned the same point to ensure the validation of the indoor thermal comfort in primary classrooms. The measured results were compared with numerical simulation results as shown in Fig. 5(a) and Fig. 5(b).

It can be seen that the change tendency of 5 points between the measurements and simulations is the same. The physical measurement parameters is smaller than the numerical simulations because of the heat release from students’ body case the ground heat dissipating bigger than the simulations. The temperature of simulation is bigger than then measurements, which is important role in air velocity increases because of air density decreases as the temperature increase. Combined with the above analysis, the numerical simulation in this work is feasible.

In this work, it had only analyzes the temperature field, velocity field, PMV and PPD of the primary classroom, without considering the impact of desks and chairs on airflow partition, which had a certain impact on the simulation results. In the future work, more discussions will be do in this aspect.

Subject questionnaire of primary students should be conducted more long period cycle and frequently.

More points should be placed in the primary classrooms to measure indoor thermal comfort parameters as to be more accurate in the calculation of PMV and PPD.

4. Conclusion

It is clear that the numerical simulation result of air temperature and velocity were agree with the experiment results. The conclusions are drawn as follows:

(1) The subject questionnaire is vital to assess the indoor thermal comfort temperature according to the feedback from the primary students.
(2) Students can acceptable average temperature values of comfortable thermal comfort zone varied between 22.0 °C and 26.0 °C, air velocity mean values under 1.3 m/s in primary school.
(3) Natural ventilation have great potential on thermal comfort in primary school. The reasonable of opening or closing windows and doors were play an important role in indoor thermal comfort in primary classrooms.
(4) The results of this research enrich and develop the basic theory of the indoor thermal comfort design and control under the subtropical plateau monsoon climate.

Declaration of competing interest

Author has no conflict of interest at this stage.

CRediT authorship contribution statement

Yaowen Xia: Conceptualization, Writing - original draft. **Wenxian Lin:** Project administration. **Wenfeng Gao:** Writing - review & editing. **Tao Liu:** Validation. **Qiong Li:** Data curation. **Anran Li:** Investigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2020.100619.

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