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Research on the effect of different position on classroom ventilation in a “L” type teaching building

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ABSTRACT

The ventilation effect in different places in the teaching building is different. The aim of this paper is to study the relative ventilation relationship of the rooms in “L” type middle school teaching building. Taking Xiamen in the subtropical region as a typical city, different aspect ratio for 1:1, 1:1.5 and 1:2 were set as variables, using the CFD simulation method. Combined and separated effects of the defined parameters on natural ventilation performance are evaluated using the ratio of age of air area as criteria. The result shows that the “L” type teaching building ventilated condition presents several characteristics as the approaching wind direction changed. Corner, long wing and short wing of building have some influences on the wind environment for classrooms. In addition, different aspect ratio “L” type buildings correspond to different optimal inlet wind angles. The research results in this paper can help architects to design buildings more scientifically and reasonably.

1. Introduction

Architecture as the common residential location usually accounts for the largest part of energy consumption. Thereinto, heat and cooling system takes away more load of energy than other equipment such as water, lighting etc. [1] According to several works done so far, HVAC (heating ventilation air-conditioning) system took up approximately 60–70% amount of energy consumption for residential building [2]. It follows that the ventilation system has great potential on energy efficiency. As the ventilation could provide fresh air and saving building energy consumption, it has attracted more and more attention of scholars and research community in 21st century, especially under the contemporary negative circumstance of COVID-19 [3]. Under this special serious circumstance around the world, displacement of fresh air appears more important.

1.1. Ventilation manner

As a sustainable building design manner, natural ventilation has been known to human for centuries [4], [5] This method has been proved to be an efficient mean to improve indoor air and achieve building energy harvesting although it is not prevalent than mechanical means [6]. While, the manner of mechanical ventilation takes up the largest proportion more than 50% energy consumption of building [7]. For this reason, various literatures have been made to study the airflow patterns and relative temperature, comfort level, contaminants etc.

1.2. School ventilation manner

Classrooms can utilize two type of ventilation patterns of natural and mechanical or hybrid manner of them. Recently, increasing researches have been done to study the school ventilation condition. Controlled ventilation technology is one of the effective design methods for buildings to improve classroom air quality [8]. It is significantly to investigate the issue of classroom ventilation since the students commonly aggregate long terms learning in a closed space. Haverinen-Shaughnessy et al. investigated 104 US schools and concluded that 87 schools had lower ventilation rates than ASHRAE Standard 62.1 [9,10]. Firstly, IAQ (indoor air quality) is a research focus in this area thereinto, especially concentrates on the carbon dioxide situation in school because of the negative impact has been proved on the students’ study attention of carbon dioxide [11]. Basing on some available data, a lot of carbon dioxide concentration of classrooms exceeded 1000 ppm [12]. In terms of the peak value, L. Stabile et al. field measured the carbon dioxide

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situation of primary school and found that the largest carbon dioxide concentration could reach more than 5000 ppm and the averaged amount located between 1400 and 3000 ppm [13]. Several different works have been done to focus on the method to improve IAQ. S. Petersen et al. adapted the mechanical ventilation system to improve the ventilation rate from 1.7 l/s per person to 6.6 l/s per person resulting in the carbon dioxide concentration decreased to 900 ppm from 1500 ppm enhancing the learning efficiency of students [14]. In addition, when the opening windows positioned opposite to the students gathering region, the ventilation rate could also be enhanced apparently and having beneficial effect to impair carbon dioxide level [15]. As pointed in some similar studies that the suitable ventilation mode could efficiently remove the negative effect of carbon dioxide in classroom. Apart from the aforementioned investigation of carbon dioxide situation, for

Table 1
Recent researches about school ventilation condition within five years.

| Author                        | Data       | Location                          | Ventilation manner | Method         | Conclusion                                                                 |
|-------------------------------|------------|-----------------------------------|--------------------|----------------|-----------------------------------------------------------------------------|
| S. Petersen et al. [14]        | 2015       | Aarhus, Denmark                   | Mechanical         | Measurement    | The increasing of ventilation rate could enhance significantly the learning efficiency of students |
| Jorn Toftum et al. [16]        | 2015       | Danish, Denmark                   | Mechanical&Natural  | Measurement    | Employing natural ventilation strategy classrooms have a better performance in terms of carbon dioxide concentration than mechanical manner. |
| Maite Gil-Baiz et al. [17]    | 2017       | Andalusia (Europe Mediterranean climate) | Mechanical&Natural  | CFD            | The natural ventilation system applied in school under Africa climate enabled 18–33% energy harvest level comparing to mechanical ventilation system in a same premise of comfort level. |
| Rogério Duarte [18]           | 2017       | Portugal (Mild)                   | Natural            | Measurement    | Manual window-airing of classrooms is appropriate with outdoor running mean temperatures larger than 19 °C. |
| Batterman et al. [19]          | 2017       | Michigan, USA(Mild)               | Mechanical         | Measurement    | Larger classrooms with unit ventilators or radiant heating reduces apparently ventilated rate |
| Luca Stabile [13]             | 2017       | Cassino, Italy (Mild)             | Mechanical         | Measurement    | Airing strategy of opening size, origin and dynamics condition impacts significantly the interior pollutants situation. |
| Nematchoua, Ricciardi, et al. [20] | 2018    | Madagascar (Africa)               | Mechanical         | CFD&Measurement | The period of 24.6 to 28.4 °C was the most comfort temperature and 80% of peoples were satisfied in school |
| Bart Mereema [21]             | 2018       | Brugge, Belgium (cold)            | Mechanical         | Measurement    | Demand controlled ventilation (DCV) integrated in ventilation system could apparently archive a good indoor air quality performance even at lower air flow rates condition. |
| W.J.Trompeter [23]            | 2018       | New Zealand(mild)                 | Natural            | Measurement    | HVAC system provided good control of temperature and humidity instead of interior fresh air supply. |
| Mark Luther et al. [24]       | 2018       | Victoria, Australia (Hot)         | Mechanical         | Measurement    | In classrooms with carpet, it is necessary to employ special air strategy to disperse the additional dust caused by carpets. |
| Anna Heeboll et al. [33]      | 2018       | Copenhagen, Denmark (Cold)        | Natural            | Measurement    | In temperate climates the mechanical ventilation system and both systems with automatic window opening are the recommended systems for classrooms in temperate climates. |
| Li Yang et al. [15]           | 2019       | Xiamen, China (Hot region)        | Natural            | CFD            | Different positions on Line type school building have disparate effects on classroom ventilation performance. |
| Branko Simanic [26]           | 2019       | Sweden (cold)                     | Mechanical         | Measurement    | Mechanical ventilation system integrated with demand control could provide satisfactory indoor comfort environment. |
| Luca Stabile et al. [27]      | 2019       | Cassino, Italy (Mild)             | Mechanical         | Measurement    | Both mechanical and natural ventilation approach have positive effect on the ventilated heat loss. |
| Filipe Rodrigues and Manuel Feliciano [28] | 2019   | Portugal (Mild)                   | Natural            | CFD&Measurement | Under high occupation rates of classroom, the larger opening area and longer periods are needed to impair the discomfort and health risk of students aroused by interior air pollutants. |
| Li Xianli et al. [29]         | 2020       | Tianjin, China(Cold region)       | Natural            | CFD            | New innovative ventilated construction on façade control the classroom indoor carbon dioxide concentration under 1000 ppm and low energy consumption extent. |
| Antonio Pacitto et al. [30]   | 2020       | Barcelona, Spain(mild)            | Natural            | Measurement    | The air purifiers with windows could significantly filter the outdoor pollutants in air even under the circumstance of closing used in school gym. |
| Peng et al. [31]              | 2020       | Qingdao, China(cold)              | Mechanical         | CFD&Measurement | An innovative integrated low-energy ventilation system was created to keep the classroom carbon dioxide concentration around 900 ppm. |
| Luca Stabile [27]             | 2020       | Cassino, Italy (Mild)             | Mechanical         | Measurement    | Application of mechanical ventilation system with energy recovery unit significantly save 32% energy consumption via post ventilation retrofit for school. |
| Sepideh Sadat Korsavi et al. [23] | 2020    | UK(Mild)                          | Natural            | Measurement    | Opening strategy should also take the season condition into consideration in order to improve indoor air quality. |
| Beunyoung Park and Sihwan Lee [33] | 2020    | Tokyo Japan(Mild)                 | Natural            | CFD&Measurement | An improved ventilation strategy could effectively build needed interior situation and decrease the energy consumption of approximately 30%. |
| Jiawei Zhuang and Yongfa Diao [34] | 2020    | Shanghai, China(Mild)             | Natural            | CFD&Measurement | Radiation could affect the interior heat flux situation and then influence the ventilation rate and buoyance force. |
| Ismail, Suzan T., Miran, Miran, Fenk D [35], | 2020  | Erbil,Iraq(Hot)                   | Natural            | CFD&Measurement | Wind catchers for school building in middle east less than 9 m could provide enough ventilation rate to reduce mean radiant temperature 5 °C. |
| S Subhashini and K Thirumaran [36] | 2020   | Madurai,India(Hot)                | Natural            | CFD&Measurement | Three factors of courtyards with an aspect ratio of 1:2, directions of openings at an angle of 0–20 to the predominant wind angles and the overall percentage of openings between 15 and 30% in buildings obviously improve the natural ventilation and thermal comfort for students. |
classroom wind environment, the ventilation manner of mechanical or natural is another significant point deserves to do research.

In the case of mechanical ventilation system research, mechanical ventilation method is classified into two forms basing on approaches of control which refers to constant air volume (CAV) and variable air volume (demand controlled ventilation). Table 1 presents the overview of the literatures done within past five years in terms of the education organization indoor air research. Jorn Toftum et al. tested the carbon dioxide concentration in Denmark school and found employing natural ventilation strategy classrooms have a better performance in terms of carbon dioxide concentration than mechanical manner [16]. Peng et al. invented an innovative integrated low-energy ventilation system to keep the classroom carbon dioxide concentration around 900 ppm [31]. Mechanical ventilation equipment adopted some additional components to enhance the energy efficiency such as heat recovery unit [27]. A renewed concept of demand controlled ventilation (DCV) could be integrated into mechanical ventilation system and has significantly function for building energy consumption in future [21]. Branko Simanic proved this DCV integrated system successfully enabled indoor satisfactory climate [26]. However, David L. Johnson found that the HVAC system provided good control of temperature and humidity instead of interior fresh air supply [22]. On the other hand, ventilation rates of classroom have significantly influence on indoor environment. It has been discovered from some researches that the larger classrooms with unit ventilators or radiant heating performs lower ventilated rate [19]. While, enhancing of this type of rate lead to more cost on heating, ventilating, and air-conditioning system which seem like a small price to pay given the evidence of health and performance benefits [37]. In terms of heat losses issue via air flow, the mechanical and natural ventilation mode has similar positive influence [27]. Anna Heeboll et al. obtained that mechanical and natural with automatic window opening mode were suitable for classrooms air flow in temperate climate [25].

1.3. School natural ventilation

Currently, natural ventilation literatures are less than the mechanical one as the enhancing degree of dependence on the equipment of building. In China, most of classroom employ the natural ventilation mode to exchange the air between indoor and outdoor [38]. Modeste Kameni Nematchoua et al. investigated the comfort indoor air temperature of school and found that the period of 24.6 to 28.4 °C was the most comfort temperature and 80% of peoples were satisfied [20]. The natural ventilation system applied in school under Africa climate enabled 18–33% energy harvest level comparing to mechanical ventilation system in a same premise of comfort level [17]. In addition, the indoor natural ventilation rate in school could apparently enhance the heat loss degree under the constant of indoor temperature in winter [39]. For ventilation strategy, the period of opening and condition affect the indoor carbon dioxide concentrations obviously [13]. An improved ventilation strategy could effectively build needed interior situation and decrease the energy consumption of approximately 30% [33]. Furthermore, for classrooms with carpets, it is indispensable to utilize special air strategy to disperse the additional dust caused by carpets [23]. Sepideh Sadat Korsavi et al. pointed out that opening strategy should also take the season condition into consideration in order to improve indoor air quality [32].

According to aforementioned investigations and table from direction of energy efficiency, ventilation manner and school ventilation, it can be seen that the air quality has been investigated strongly in recent years especially for classroom. Carbon dioxide as an important factor affecting students’ learning performance which is commonly regarded as perform indicator to study the ventilation manner diversity. For school mechanical ventilation, researches done so far mainly focused on the issue of equipment efficiency such as using other instruments to improve the ventilation rate. Furthermore, for school natural airflow condition, most of investigations designed to exploit opening mode and area. Therefore, it lacks of the works on study about the natural ventilation manner in terms of the view of classroom position.

It can be obtained basing on the above review that most researches have emphasized the influences of poor air quality in classroom and corresponded solutions. However, natural ventilation strategy investigations are significantly less than other works such as indoor air quality and mechanical ventilation, only focuses on opening pattern and area. In terms of the correlation between natural ventilation condition and classrooms position have not been studied around the world. In order to contribute in filling this gap of knowledge, the aim of the present paper is to investigate this position relationship problem, this paper used CFD method to simulate and compare the “L” type teaching building ventilation characteristics following the Li Yang et al. research [15]. Final results were conducive for architects to arrange the classroom positions more scientifically in line with the airflow performance which was significant for some classroom requiring for special airflow demand such as laboratory calling for strong air velocity to disperse additional pollutants. Age of air concept was defined as the measurement evaluating standard. To this purpose, the middle school placed in Xiamen, China was investigated during summer. This study consists of four sections. In Section 2, the simulation method and the validation study are briefly outlined. The computational boundary settings and parameters for the CFD simulations are also described in this section. Section 3 analyses the simulation results and finally, the conclusion is provided in section 4.

2. Methodology

CFD analysis was used to investigate the indoor ventilation performance in this study. The first software using for CFD was PHOENICS which the edition of 2014 was utilized for this research. Basing on previous researches, RNG k-ε model appeared good performance in terms of simulation precision for indoor wind flow field. Age of air introduced by Sandberg [40] was adopted to evaluate the indoor air quality as performance indicator. In addition, in order to balance the computational time and guarantee the final results credibility, this investigation also conducted a grid sensitivity analysis and CFD validation progress.

2.1. Governing equation

This paper performed all airflow simulation using RNG k-ε model because this method was appropriate for simulating indoor ventilation condition which was proved in the past [41] and it could also provide sufficient accuracy under acceptable numerical cost [42].

The form of the time-averaged governing equation which included energy, momentum, and mass for the neutral and incompressible fluid was the following equation (1) [43]: [44].

\[
\frac{\partial \phi}{\partial t} + \nabla \cdot (\rho \mathbf{u} \phi) = \nabla \cdot (\Gamma \nabla \phi + S) \tag{1}
\]

In the above equation, \( \phi \) represented the scalars such as: the velocity under different vectors, \( \mathbf{u} (m/s) \), \( v (m/s) \) and \( w (m/s) \); the turbulent kinetic energy \( k (m^2/s^2) \) and the turbulent dispassion rate \( \varepsilon (m^2/s^2) \). The mean velocity vector was represented by \( \mathbf{u} \); \( \Gamma \) was the effective diffusion coefficient for every variable; \( S \) was the source term in this equation which is decided by experimenter.

Turbulent kinetic energy (Eq. (2)):

\[
\Gamma_k = \alpha_k \mu \varepsilon \tag{2}
\]

Turbulent dispassion rate (Eq. (3)):

\[
\Gamma_\varepsilon = \alpha_\varepsilon \mu \varepsilon \tag{3}
\]

where, \( \mu \) was the effective turbulent viscosity; \( \alpha_k \) and \( \alpha_\varepsilon \) expressed the inverse effective Prandtl numbers for \( k \) and \( \varepsilon \), respectively.
The turbulent viscosity was different in fluent governing equations which was also the criterion that distinguishes different equations. The RNG k-ε turbulence model turbulent viscosity was represented as followed equation (4):

\[
d \left( \frac{\rho \sqrt{\overline{\nu^2}}}{\sqrt{\overline{\nu^2}}} \right) = 1.72 \frac{\nu}{\sqrt{\overline{\nu^2}}} - 1 + C_\nu \sqrt{\frac{\nu}{\sqrt{\overline{\nu^2}}}}
\]

In the above equation, \( \nu \approx \frac{\mu \text{eff}}{\rho} \), \( C_\nu \approx 100 \). Apart from this, this equation could be expressed as the followed equation (5) in high Reynolds number condition:

\[
\mu_t = \rho C_\mu^2 \rho \frac{k^2 \varepsilon}{\nu}
\]

\( \rho \) represented the fluid density and \( C_\mu = 0.085 \).

In addition, RNG model was more accurate than standard k-ε model, since that RNG added another strain-dependent term, \( R_\varepsilon \). This RNG model was good at solving the rapid strain and streamline curvature under the \( R_\varepsilon \) term (Eq. (6)) [45].

\[
R_\varepsilon = \frac{C_\mu \rho \nu (1 - \eta \eta_0)}{1 + \beta \eta_0^3} \frac{\dot{\varepsilon}}{\nu}
\]

In the equation, \( \eta_0 = 4.38 \), \( \beta = 0.012 \), \( \eta = \frac{\nu}{\nu} \).

2.2. Perform indicators

In order to quantitively assess the indoor airflow condition, this research utilized the concept of age of air proposed by Sandberg [40]. Etheridge explained this idea in detail and presented that the age of air represented the time had elapsed as the wind entered the area passing some openings [46]. Nevertheless, so as to statistically measure the ventilation situation more conveniently, this research defined a new concept as area ratio of age of air (AOA) which was used in China green building assessment standard [51]. It expressed the area ratio of age of air under some times in a classroom and was computed as follows Eq. (7):

\[
\text{AOA (\%)} = \frac{X}{Y} \times 100\% = \frac{X}{Y} \times 100\%
\]

\( X \) (the area of age of air in a time) \( Y \) (the area of age of air in a whole classroom)

Basing on the definition, AOA can reflect the indoor wind environment of classrooms. The lower time AOA area was bigger, the ventilation condition was better. Contrarily, the longer time AOA area was bigger, the ventilation condition was worst.

Fig. 1 presented a contour graph of age of air in an enclosure area. X indicated the area of age of air in a time such as X1 with 28.12s(second), X2 with 31.25s, X3 with 34.37s. Y represented the whole area of entire space which was the sum of various X values. In this case, to evaluate the indoor ventilation condition conveniently, accumulated AOA was counted to evaluate air situation. For example, the accumulated AOA value for X2 suggested the area range with age of air lower 31.25s, which also meant the percentage area ratio lower than 31.25s age of air. It can be estimated by the equation of \((X1+X2)/Y\).

In accordance with the GB/T 50378–2019 assessment standard for green building (50378–2019, 2019), public interior wind environment can be evaluated employing area ratio age of air as followed Table 2. This assessment standard determines the later evaluation of classroom ventilation performance. Table 2 presents the level of AOA and corresponding wind environment performance. For school, it is sure that the higher the level, the better ventilation and it is recommended for achieving above the medium level.

### Table 2

| Area ratio of age of air (AOA) | Wind environment performance |
|-------------------------------|-------------------------------|
| 0%-60%                        | Poor                          |
| 60%-70%                       | Fair                          |
| 70%-80%                       | Medium                        |
| 80%-90%                       | Good                          |
| 90%-100%                      | Excellent                     |

Fig. 1. Area ratio of age of air illustration graph.
2.3. Model settings and grid analysis

This study considered the middle school teaching building as the research object. All computed domain size was defined by the model height H. According to the relevant practice guidelines by Franke et al. [47] and Tominaga et al. [48], the upstream and downstream domain lengths were set to 5H and 15H, respectively. Therefore, the domain size was 128.8 × 369.1 m as shown in Fig. 2.

Through the mesh produced software ICEM, calculated meshes were created in structured cell. Building was covered by the compact grids and the other areas were filled by the sparse cells (Fig. 3). A grid sensitivity process was conducted to make decision for selecting best mesh resolution for processing CFD simulation. Three different resolution meshes with number of 1.8, 2.54 and 1.27 million which was produced by a factor value of √2 were made to compare the grid sensitivity. In the middle of classroom A, two tested lines L1 and L2 along diagonals were positioned to monitor the normalized wind speed values under three resolution meshes as shown in Fig. 4. Normalized wind speed referred to the specific value of measured airflow velocity (U) with approaching wind speed (Uref). The averaged deviation between coarse and medium mesh was 4.3%, moreover, it was 2.1% between fine and medium grid. So, the medium mesh was chosen as the mesh resolution for further analysis.

In order to assure the precision of entire computation, the domain contained almost 2.1 million cells and the corresponded Re number was approximately 3.76 × 10⁶. High quality grid in the classroom was set to improve the simulation accuracy. The minimum length of cell was 0.02 m and the maximum was 5 m, respectively. The length from the centre point of the wall adjacent cell to the wall, for the upstream, downstream, roof and ground were all about 0.020 m. In this case, the corresponded y⁺ value located between 30 to 500 which guaranteed the centre point of adjacent wall was positioned within the logarithmic layer so as to utilize the standard wall function.

2.4. Boundary conditions

This paper chosen the Xiamen in China as the studied position, which located at the south of China. The climate in the region is warm and humid, with the coldest month mean temperature above 10 °C and the hottest month average temperature between 25 and 29 °C [52]. Fig. 5 presented the wind direction performance in summer and winter and the local mean airflow velocity was 3.6 m/s.

In the RANS model, the RNG k-ε model was decided as the simulated model because of its better ventilation performance in indoor and outdoor of buildings [41]. [49] This paper used the PHOENICS 2014 as the CFD simulation tools to calculate the wind environment which was the world’s first CFD software. The inlet wind profile was defined as the power law Eq. (8) as follows [50].

\[
\frac{U(y)}{U_{ref}} = \left( \frac{y}{H} \right)^{0.22}
\]

where H was the reference height and Uref was the reference wind velocity at this height. 0.22 referred to the roughness index which was determined by the surrounding environment. In this case, in order to eliminate other different factors, it is assumed that the building located at the suburb which corresponded the roughness index of 0.22. The turbulence model was set to RNG k-ε model and SIMPLE was the pressure-velocity coupling algorithm. Each simulation had to go through more than 8,000 iterations to achieve convergence. Symmetry conditions were set at the top and lateral sides of the domain. The pressure interpolation method was a staggered scheme format called PRESTO. When the calculation error was decreased and maintained at a reasonable level, the computed progress would be terminated and the all probe values would remain at a constant condition either. The calculation error named convergent values of residuals were specified as follows: \(10^{-4}\) for continuity, \(10^{-5}\) for k, c, and every axis velocity. Other variables air speed, temperature and age of air were steady or fluctuated within acceptable ranges. All computations are performed by Phenics 2014 on an 8-core workstation (Intel Xeon E5 2680 v3, 2.7 GHz) with 16 GB DDR of system memory.

2.5. Model cases

Research done so far by Yang et al. [15] has studied the ventilation of different classrooms in “Line” type plan of teaching building. Hence, this paper mainly studied the ventilation characteristics in “L” type plan of teaching building.

This research took Xiang’an Middle School as the prototype which was shown in Fig. 6. Basing on this prototype, “L” type teaching building was set as three aspect ratio of 1:1, 1:1.5 and 1:2 so as to study the ventilated feature of “L” type building in comprehensive which was shown in Fig. 6. The aspect ratio meant the specific value of the two wings with L1 and L2 for the ‘L’ teaching building. Fig. 6b showed the naming scheme for different cases and aspect ratio calculated rule. L1 classrooms were named as capital letters A,B,C,D,E,F,G and L2 class rooms were viewed as lowercase a,b,c. Every classroom condition was identical with each other in addition to its positions.

In China, middle school classrooms mustn’t be arranged above the fifth floor in teaching building, basing on the national standard. Hence, the third floor was regarded as the tested floor to conduct the study. In order to discuss the results more precision, the abbreviation was shown as below Table 3.

The simulated inlet approaching wind velocity is set 3.6 m/s. All windows in different classrooms are the same with each other in terms of position, size and opening condition. According to the statistics of outside field measurement, outdoor temperature is assigned as 25 °C.
Entire building air tightness meets the requirement of local standard and all windows remain same maximum opening situation. Besides, as this school locates in a new development zone, surrounding buildings are less and far away. Hence, it is no need to take consideration of surrounding buildings because of the weak impacts. In a word, other factors remain constant and same with each other such as wind velocity,
temperature, opening condition and so on in order to study the position effect specifically.

2.6. CFD validation

In order to verify the effectiveness of the simulation method, this study used a wind measurement anemometer apparatus to test the wind velocity of each classroom in the middle school. The Xiamen Science and Technology Middle School Xiang’an Campus was selected as the research object (Fig. 7). The northern most end of the teaching building can be approximated as a linear building which could be regarded as the north part of ‘L’ type teaching building. L1 classrooms of A,B,C were regarded as the filed measurement location. In every classroom, five measured points were distributed throughout the classroom in order to depict the wind field in detail (Fig. 7c). Another monitor point was positioned outside the classroom to record the inlet wind situation (Not shown in Fig. 7). The whole measurement process was from May 1st to

| Abbreviation | Explanation |
|--------------|-------------|
| BR – L1/L2   | Building ratio |
| WPG          | Wind pressure gap |
| WP           | Wind pressure |
| AOA          | Area ratio of air age |
| SW           | Short wing |
| LW           | Long wing |
| CLOSER       | the closer to the direction of the wind, the better the ventilation effect |
| CORNER       | the closer to the corner, the better the ventilation effect |

Table 3 Explanation of several abbreviations.
30th 2017, and the wind velocity was recorded every 15 min, from 8am to 5pm.

Since the purpose of this study was to investigate the relative ventilation relationship between classrooms, this study conducted a simulation experiment using CFD method under the same circumstance with field measurement, simultaneously. Based on the simulated and field measurement results, the classroom A, B and C wind velocity were counted to compare the gap between the value of simulation and field measurement to prove the simulation validation. So as to conduct the validation more efficiently, the normalized wind speed was defined to reflect the simulation precision.

\[
\text{Normalized wind speed} = \frac{U}{U_{\text{ref}}}
\]

(U is the site airflow velocity; \(U_{\text{ref}}\) is the inlet wind speed)

Firstly, the measured data and the simulated data were under the same direction as shown in Fig. 8. That meant the measured and the simulated wind velocity were tested at the same location. As was shown in Fig. 8, it could be obtained that the simulated results were generally consistent with measurement consequence. The mean deviation for all points was around 5% in velocity and another deviation was 15° in terms of approaching wind direction. Hence, it can be concluded that the simulation settings could be used for further analysis.

3. Results and discussion

In order to study the different ventilation condition of “L” type teaching building more conveniently, the models are classified into three cases in terms of the BR values. Fig. 6 presents the plan of case A, case B, and case C which corresponds the BR value of 1, 1.5 and 2 respectively. All cases are performed to simulate under 12 approaching wind directions ranging from 0° to 270°. Note that as the plan shape of case A is self symmetric, this case only needs to simulate under 0° to 120°.

3.1 1:1 “L” type building wind simulated situation

Fig. 9 shows wind simulation contour condition for Case A under different inlet wind directions, it can be observed that the age of air for two wings L1 and L2 are minimum under 0° and 90° respectively. As the angle of the approaching wind increases, the ventilation relationship among room A, B and C has changed. Room A is the best under 0° to 60°, however, it changes to the worst among the three rooms under 90°. Room b and c ventilation relationship also presents a trend of fluctuation. It should be noted that the ventilation effect of room “a” will not be investigated in this paper as a result of its larger area.

Fig. 10 presents the AOA condition of Case A under different approaching wind angles. It can be seen that AOA of A, B and C is similar.
with each other and b, c ventilation situation are much worse than A, B and C for Case A0 and A30. Case A60 shows that overall wind flow field changes significantly comparing to Case A0 and A30. In this circumstance, among the L1, ventilation of room C is the best and B is lightly better than room A. All three rooms start to ventilate under 60s age of air, while the area of age for room C under 60s accounts for the largest which is 14.81%. In Case A90, for L1 wing, room ABC wind environment decreases significantly than the above cases and room C ventilation is the worst. In a word, in the range of 0°–60°, for the L1 wing, the closer the room is to the approaching wind direction, the better the room

Fig. 9. Wind simulation condition for 1:1 “L” type building.

Fig. 10. AOA condition of Case A under different approaching wind angles.
ventilation effect is. However, under 90° approaching wind direction, this trend relationship between ABC reverses to 0°–60°. For L2 wing, the ventilation relationship between b and c has experienced fluctuating changes, which seem to be related to the interior wind directions.

It can be observed from above statistics of AOA for different cases that as approaching wind direction increased, all room ventilation relationships have changed a lot and the ventilation relationship between different cases may be completely opposite with each other. The reasons why the wind environment condition changing is attributed to the interior wind directions. As the result of the wind orientation has something to do with the wind pressure differences, the reasons will be investigated as follows basing on the wind pressure gaps.

Fig. 11 illustrates that wind pressure gap (WPG) condition for case A in different inlet wind directions. WPG for room A is almost same with B and C while as the end of L2 wing is approached, b, c WPG value is diminished. This can be explained that in this case, wind direction is vertical to the L1 wing, orientation of WPG for L1 is from north to the south and the WPG of L2 flows from west to east. However, under this circumstance, west of L2 WP is larger than east where is influenced by the wind shadow effect. Moreover, east WP of room c is bigger than b because it locates near the L2 end where is lessly affected by the wind shadow than b. Therefore, according to above analysis, it can be obtained that since east WP of c presents a bigger value comparing to the same place for room b, so WPG room c is smaller than the b. Fig. 11 presents the WP condition of “L” plan under 30° wind direction. From room C to A, the WPG gradually decreases along the L1 wing which is caused by the approaching wind direction. Under this wind angle, the closer the room is to the inlet wind the greater the north wind pressure. In contrast, L2 wind situation has some differences with case A0 since it is affected with the wind shadow which is caused by L1 blocking. In the light of room c, east WP becomes larger than case A0 as the shrinking wind shadow area made by the L1. Hence, interior wind of room c flows from east to the west which is contrary to that of case A0. The wind direction of room b remains unchanged because it is still within the wind shadow. For case A60, wind environment on L1 wing stay the same with above cases while ventilation condition of L2 wing has been changed a lot. No matter where the room is on the L2 wing, both b and c WPG direction flow from east to the west since the east WP is larger than the west. This can be explained that in this case, most parts of east L2 wing could be blown by the inlet wind directly without affecting by the L1 wind shadow.

When the inlet wind direction is 90°, as the result of the wind directly flows into L2 wing vertically, room b ventilation condition is similar with room c and are the best among all rooms. However, under this circumstance, the ventilation effect is significantly different with the above cases. Generally speaking, from room A to C, the WPG value presents a gradually smaller trend. That is because when the wind flows into L2 wing, the air is blocked and aggregated at the east of L2 wing

![Fig. 11. WPG condition for case A in different inlet wind directions.](image-url)
where is also the south of L1 wing simultaneously. Therefore, the WP at the east side corner of the L2 where the air gathers becomes larger, and increases greater than the WP on the north side. Finally, WPG flows from south to the north of L1 and room A is the biggest as south WP of L1 presents a gradually smaller trend from A to C. In these two cases of A120 and A150, as the room is closer to the approaching wind direction, the larger the south WP for the L1 wing, so the room C WPG performs the biggest than room A and B.

According to the above analysis, it can be concluded from Fig. 12 that the ventilation relationship of different rooms under various wind approaching directions. For 1:1 “L” teaching building, in the range of 0° to 60° and 120° to 150°, the room closer to the inlet wind has a better ventilation effect such as room C because of the largest WPG. From 60° to 120°, as the inlet wind angle increased, the relationship between room ABC has undergone large fluctuations. At 90°, the room A which is in the corner performs best ventilation condition since the wind is blocked by a wing while under other wind angles, room A has always been the worst ventilation room. For room b and c situated at L2 wing, during 0° to 60°, due to shrinked shadow area as increased inlet wind direction, room c locating near the wing end ventilation effect changes gradually into greater and superior to room b in ventilation at 60°. When the airflow blow towards L2 wing in perpendicular, both room b and c present similar wind performance with each other furthermore after 90°, because of the wind gathering at the corner, room b gets more excellent ventilation situation than c.

In order to study the optimum approaching wind orientation for the building ventilation, the maximum age of air in different rooms and its standard deviation are counted to measure the best wind angle. Maximum age of air represents the overall ventilated intensity and standard deviation of them reflects fluctuation situation among all classrooms. The smaller maximum age of air average and standard deviation are, the better overall ventilation under corresponded wind direction. Fig. 12 indicates that the best inlet wind direction locates in the range of 120° to 150° which could meet requirements of minimum averaged age of air and standard deviation simultaneously. In addition, 60° to 120° is the second recommended angle and the worst that for building ventilation situates from 0° to 60°.

3.2. 1:1.5 “L” type building wind simulated situation

In order to study the ventilation condition for model of 1:1.5, twelve cases B were performed as the asymmetric model plan. Fig. 13 presents the ventilation situation for case B under different approaching wind directions. For case B0, all classrooms perform analogical wind environment except room b which considerably indicates the worst ventilation condition. Case B30 resembles with case B60 and ventilation in classrooms and both cases tends to be uniform compared with case B0. All classrooms seem to be ventilated in good situation for case 90B besides the room E which locating at the end of the building long wing. Therefore, it can be seen that although there is a room with the worst ventilated situation of case B0 and B90, overall other classrooms show fine ventilation performance.

As the inlet wind angle further increased, case B120, case B150, case B180 and case B210 present the similar ventilation results with each other. That is to say that wind flow field distributes evenly in teaching building under these cases. When the wind flows from 240° to 270°, short wing rooms of building apparently suggest better wind environment performance than long wing. While under case B300 and B330, all building classrooms shows alike wind environment situation with each other. Thus, from case B240 to B330, the distribution of wind field performs a state of fluctuation first then stabilized trend.

Fig. 14 presents the area ratio of age of air under condition different approaching wind directions for case B. For case B0, rooms situating at long wing considerably performs similar ventilation condition and much better than short wing rooms such as b and c. As the wind angle increased from 30° to 60°, the closer to the direction of the wind, the better the ventilation effect for room A to E. This result can be obviously observed in case B60 that AOA condition of room E presents much better than A. Meanwhile, for b and c, both of them airflow states are parallel with each other under case B30 while room c AOA evidently is higher than b under case B60. This is attributed to the transforming of the inlet wind. For case B90, when the approaching wind is vertical to the short wing, relationship between A and E indicates the converse result with case B30 and B60. This is mainly because that LW rooms locates under wind shadow area which generated by the SW blocking effect. In the wake of further augment of wind direction, room A to E under case B120 and B150 also perform analogical correlation among these LW units with case B30 and B60 that the closer to the direction of the wind, the better the ventilation effect. However, room b and c suggest adverse ventilation phenomenon with LW rooms owing to the aggregation effect of airflow blocked by corner. Room b wind environment illustrates almost 20% higher level AOA compared to c. For case B180, LW classrooms presents similar AOA values with each other as the wind direction is perpendicular with LW side. Nevertheless, relationship between b and c indicates inverse situation with case B120 and B150. This can be explained by the airflow aggregation range limitation which do not affect room c at the end of SW side. As the wind angle increased to more than 180°, ventilation performance improves from A to E of case B210 and B240 because of the wind shadow area which is blocked by SW shrinks along the LW side. All the wind characteristics for case B can be
attributed to the wind pressure differences between two sides of classrooms.

The wind pressure gap condition is shown in Fig. 15. For case B0, WPG condition are the same with each room in LW side. Along the direction to the end of the short wing, WPG shows a trend from large to small. This can be explained by that SW situates within the wind shadow area. The wind pressure on the east side of SW conducts larger at the end of SW where is less affected by the wind shadow, while, west pressure for SW indicates no changing with approaching inlet pressure. As approaching wind angle increased to 30°, north wind pressure of LW performs the appearance that the closer to the inlet wind, the bigger the wind pressure. So, the WPG of LW shows decreased trend from room E to A. As for SW, ventilation feature displays special results comparing to case B0. Under this airflow direction, wind shadow area no longer

Fig. 13. Wind simulation condition for Case B.
influences on room c east flow pressure except room b. Room c start to performance better east wind pressure than west which lead to WPG from east to the west. When inlet wind direction is 60°, compared to case 30B, LW wind environment still remains same condition. Nevertheless, both room b and c on SW ventilation situation move out of the wind shadow area which results in WPG direction from east to west. And WPG condition of c expresses bigger results than b as it is closer to the end of SW. With airflow angle changing further to 90°, all the units on the LW ventilate from south to north and gradually decreases from A toward E as airflow aggregates at the corner of building under this direction in turn wind pressure around corner performs larger than opposite. Case B120 ventilation condition is similar with case B150 and WPG enhances along LW from A to E. It should be noted that LW wind environment follows the law that the closer to inlet wind, the bigger wind pressure has been proved for SW room b, c wind environment under two cases B210 and B240. For case B270, with the vertical wind direction to SW, rooms on SW wind environment have no much disparities between these unites. Therefore, WPG for case B270 flows from the north to the south as shown in Fig. 15. As ventilation angle improved to 300° and 330°, wherever chamber is on SW or LW, ventilation condition follows the law of “the closer to inlet wind direction, the bigger ventilation condition” keeps the LW rooms because of the SW blockage effect. Furthermore, the closer the room is to the corner, the better the wind environment under inlet wind angle of 90°. For LW side, classrooms ventilated situation indicate nearly same presentations under the vertical wind direction. Note that as the aggregated influence around corner, east pressure of room b still expresses higher consequence than the west. But, WPG direction of c transforms to the east with the corner accumulated impact weaken towards the south end of SW. When the wind angle changes to 210° and 240° which is larger than 180°, ventilation of LW rooms gradually becomes more stronger along the LW from A to E. This mainly results of the surrounded corner room i.e. A, B, C lie within the wind shadow area caused by the SW blockage effect leading to the lower south pressure of these rooms. The above-mentioned law that the closer to inlet wind, the bigger wind pressure has been proved for SW room b, c wind environment under two cases B210 and B240. For case B270, with the vertical wind direction to SW, rooms on SW wind environment have no much disparities between these unites. Therefore, WPG for case B270 flows from the north to the south as shown in Fig. 15. As ventilation angle improved to 300° and 330°, wherever chamber is on SW or LW, ventilation condition follows the law of “the closer to inlet wind direction, the bigger ventilation condition” keeps the LW rooms because of the SW blockage effect. Furthermore, the closer the room is to the corner, the better the wind environment under inlet wind angle of 90°. As for SW, only in the range of wind direction from 210° to 360° follows
the law “the closer to inlet wind direction, the greater ventilation situation”. During 0°–60°, wind direction of classrooms on SW alter ultimately to adverse orientation since the air shadow area changing made by LW. In the range of 120°–150°, ventilation of room b is better than c following the “CORNER” law owing to the air aggregation effect at corner. Moreover, under 180°, classroom b presents the reverse ventilated orientation with c as the limited gathered air effect area around corner.

In order to pick the recommended wind angle which is beneficial for “1:1.5” type teaching building ventilation, maximum age of air averaged condition and standard deviation are counted as shown in Fig. 16. While, the recommended wind angles is shown in Fig. 17. The best inlet wind angles for classroom ventilation of “1:1.5” type teaching building is from 330° to 60° and the worst ventilated angle flows from 120° to 210°.

3.3. 1:2 “L” type building wind simulated situation

In accordance with the above analysis, the two ratio “L” type buildings have its unique wind characteristics. To investigate research of the teaching building ventilation law with increased aspect ratio, wind environment for “1:2” type model is calculated as follows.
It can be seen from Fig. 18 that almost all rooms of case C0 present analogical airflow features except c which poses the worst ventilation condition. For case C30, unit b and c display ultimately adverse wind direction with each other and ventilation intensity varies greatly. With inlet wind angle augment, room b and c ventilation situation become similar and ventilation from A to E gradually changes. However, when the approaching ventilation angle increased to 90°, case C90 indicates considerably special airflow features. Although other rooms’ ventilation condition performs similar results with case B, unit F and G of case C90 still reveal particular wind environment characteristic. When the angle of the wind lies between 120° and 150°, these two cases airflow situation resembles with each other, moreover, ventilation of b, c for case C180 illustrates contrary wind orientation. As wind direction angle magnified to more than 180°, case C210 has the alike air flow performance with case C240. However, case 270C shows distinct ventilation situation because of the wind specific environment for the two rooms F and G at the end of LW. It is indispensable to analyse the AOA coefficients so that study quantitatively the subject in detail.

Fig. 19 presents the statistics of area ratio of age of air for cases C under several approaching wind angles. The larger proportion of AOA displays the better ventilation condition for classrooms. Case C0 apparently indicates that room A to G performs alike AOA condition remaining around 100% and room b illustrates much larger than c. Case C30 and C60 indicates similar ventilated results that AOA situation decreases along LW from room G to A and c still performs better wind environment than b. What’s more, LW rooms ventilation show a trend of gradual deterioration from case C0 to C60. When the inlet wind direction is 90°, AOA condition gradually diminishes from A to F, but room G presents the biggest AOA condition among all classrooms in LW. This is mainly because that the ventilated direction has changed ultimately at G compared to other rooms. Thus, classroom G performs special wind environment which is reflected by AOA. As the approaching wind direction increases to the 210°, room G displays particular ventilated performance that is smaller than room F in AOA. This can be explained by that under this wind direction, the wind shadow area only could affect the room F without reaching to G. While, under 240°, wind environment gradually becomes better along LW from A to G owing to the whole LW is under the wind shadow area which is blocked by the SW. For case C300 and C330, AOA statistics decrease distinctly from room A to G along LW. All statistics of AOA is obviously shown in Fig. 19 and the reasons why lead to these ventilated conditions will be discussed as followed.

Fig. 20 shows that when the inlet wind direction is perpendicular to LW, classrooms’ ventilation performances seem almost alike mutually. Moreover, units on LW from case C30 to C60 follows the “closer” law which is same with “1:1.5” type building. For SW, under case C0, as the east wind pressure becomes bigger toward the end of SW, so the wind pressure difference between two side of SW rooms gradually change to small from head to end. The SW air stress state is caused by the shadow effect of LW. With the approaching air angle increased, SW east air pressure gradually aggrandize and wind direction transforms from east to west for case C30 and C60. While wind angle is 90°, the air aggre-gation effect around the corner results in some particular ventilation features for case C90. Ventilation results for SW of classrooms seem similar with each other because of the vertical air direction. However, in this case, LW ventilation displays distinct traits comparing with other cases. The pressure on the south near the corner declines from head to end along LW. From classroom A to E, the south pressure presents bigger than the north, therefore WPG flows from south to north of case C90. Nevertheless, as the LW is too long, airflow pressure difference at F, G blows opposite direction with A to E because that the south pressure decreases to smaller situation than north at F, G. From case C120 to C180, LW units meet the “closer” law that the G ventilation presents the best and A shows the worst. In terms of SW, three cases of C120 to C180 rooms’ wind environment display the trend of the closer to the corner,
the better ventilation. This is mainly because that the wind concentrates in the corner, so the inlet wind pressure near the corner is larger than the end. Therefore, the SW wind pressure difference diminishes from corner to the end and flows to the west for case C120 to C180.

For case C210, wind shadow area produced by SW has influenced on the LW. In wind shadow area, the edge pressure is larger than inside. Therefore, WPG magnifies from room A to E along the LW because that the E locating at the edge of wind shadow area has a larger inlet wind pressure. Moreover, airflow environment for room F and G follow the “closer” law owing to the two units has outed of the wind shadow district. For case C240, as the whole LW part lies within the shadow zone, room A to F ventilated performance follow the phenomenon that the further to the corner the room is the better and the wind direction is from the south to north. As the approaching wind angle increased to 270°, all LW part still situates within the shadow area produced by SW. However, it should be note that as the north pressure in this case is large, ventilated direction for LW presents some special features. Owing to the whole LW part rooms within the shadow area, south pressure enhances along the LW from head to end. When south pressure increases to bigger than the north at F, WPG changes to opposite direction compared with room A to E and magnifies along LW from F to G. When the inlet wind angle exceeds the 270°, LW ventilated performance distinctly follows the “closer” law. While for SW, during 210°–360°, the classrooms wind environment on SW always meet the rule of “CLOSER”.

It can be seen from above analysis that for case C, units on LW meet the rule of “CLOSER” during 0° to 60° and 120°–180°. Furthermore, under wind direction of 90° and 270°, all SW units obey the law of “CLOSER”. While, from 30° to 60°, the closer the corner of the room, the worse the ventilation. Simultaneously, SW classrooms

![Fig. 18. Wind simulation condition for 1:2 “L” type building.](image-url)
illustrate converse phenomenon that the further the corner of the room, the worse the ventilation compared to case C210 to C330 because of the wind shadow effect generated by LW. For case C0, the room near the corner indicates better ventilation.

In order to study the inlet wind angles which could be conducive for teaching building ventilated condition, every room maximum age of air is counted as the measurement standard as follows Fig. 21. The smaller the average and deviation values, the better the overall ventilation. It can be obtained that the optimal wind angles for “1:2” L type teaching building as Fig. 22.

4. Discussion

This investigation indicates the diversity of classroom interior airflow environment for “L” type school building which have some particular features. Researches done so for classroom ventilation mainly concentrates on carbon dioxide concentration, indoor comfort degree and ventilation manner selection fields. In terms of natural ventilation studies, opening condition and area are the hot point which attracts research community interests. However, as another significant impact factor on classroom ventilation performance, the classroom position related issue has not been paid attention to.

In this study, the issue of classroom ventilation was significantly studied under the same circumstance of opening position, area and using mode. This work innovatively contributes to the classroom natural ventilation research field and fills up a gap between indoor air quality and ventilation manner providing a new type of method to improve interior learning environment especially for a supplement of “Line” type work by Li Yang [15].

Architects could refer these investigation results to arrange classroom function in line with the ventilated requirement, for example, some laboratory rooms should be located at the position which has better ventilation performance according to local prevailing wind direction so as to disperse indoor harmful gas immediately without using mechanical system.

In addition, good ventilation environment is of great significance to the health of the occupants especially for students who tend to stay together for learning. Many infectious diseases, including COVID-19 pneumonia, SARS and others, are all transmitted through air and droplets. Therefore, reasonable airflow and high air change efficiency could dilute the concentration of virus in the air, so as to avoid the situation of indoor cross-infection. The conclusion of this investigation appears even more important.

However, there are still some limitations of this research. For school building types, apart from the pattern of “Line” and “L”, the “T” type building is also worth to be investigated because of the shape feature. Hence, further research should be performed to study the classroom position impact on indoor ventilation of “T” type school building. In this

![Fig. 19. AOA statistics of various case C.](image)
paper, disparate cases are simulated with constant of opening condition. Furthermore, earlier researches had shown the opening effect on classroom natural ventilation performance. The coupling influence of classroom position and opening configuration need to be investigated in future. In addition, future researches also need to investigate the indoor air quality influenced by the factor of classroom position and opening configuration.
position to supplement the disadvantage of this research.

5. Conclusions

This paper studies the natural ventilation relationship between classrooms’ position and inlet wind without consideration of mechanical ventilation for “L” type teaching building. The concept of age of air is used to be a perform indicator which could measure the indoor ventilated performance effectively. High-resolution grids and 3D steady RANS CFD simulations are performed for three cases with different aspect ratio of “L” type. The evaluation is based on validation with field measurements of mean wind velocity. The results of this paper mainly concentrate on the relative ventilation effect of classrooms in different positions and inlet wind angles. Therefore, the research findings can be referenced by architects in other similar climatic regions. However, architects should apply the conclusions according to the various ventilation requirement in different climatic regions. The following conclusions can be drawn:

a) 1:1 “L” type teaching building

This type of teaching building presents a symmetrical pattern. As the impact of shadow effect, in the range of some wind angles, the room closer to the inlet wind has a better ventilation effect because of the largest wind pressure gap. Taking consideration for meeting ventilate requirement of all rooms as much as possible, the best airflow angle commonly locates between a specific range.

b) 1:1.5 “L” type teaching building

This pattern teaching building has a feature of unequal size for two wings. In this case, as inlet wind angle increases, the ventilation condition of two wings indicates fluctuation changing situation. The shadow impact area is larger than the 1:1 teaching building. The airflow of long wing side performs better than the short wing because that it has a larger range of suitable inlet wind direction.

c) 1:2 “L” type teaching building

The wings differ greatly in length of 1:2 “L” type building. The shadow area blocked by long wing has a significant influence on the short wing. Hence, classrooms located on the long wing perform better than short wing in terms of ventilation condition. Most of classrooms are recommended to position at the long side. Meanwhile, the suitable inlet wind angle ranges of 1:2 type are the largest among three proportion pattern teaching buildings.

Apart from aforementioned points, it can be also concluded that the law of “the room closer to the inlet wind has a better ventilation effect” is appropriate for each type of building, only differs in operated wind angles. Differences in ventilation performance for all rooms are attributed to differential wind pressure gap. But the room located in the corner frequently indicates the worst ventilation situation.

Author statement

Xiaodong Liu: Conceptualization, Methodology, Software, Validation, Investigation, Resources Data Curation Writing, Original Draft Writing. Li Yang: Review & Editing, Supervision, Funding acquisition. Shengnan Niu: Formal analysis, Methodology, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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