Influence of Air Velocity on Thermal Comfort and Performance of Students in Naturally Ventilated Classrooms in Tropical Climate

Mohamad Nor Azhari Nor Azli1, Azian Hariri*, Chong Zi Yao1, Muhammad Aidil Khasri1, Amir Abdullah Muhamad Damanhuri2, Mohd Syafiq Syazwan Mustafa3 and Hashim Kabrein4

1Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, Malaysia
2Faculty of Engineering Technology Mechanical and Manufacturing, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
3Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), UTHM Pagoh Campus, Pagoh Higher Education Hub, Km 1, Jalan Panchor, 84600 Panchor, Johor, Malaysia
4Faculty of Engineering, Safat College of Science and Technology, Khartoum, Sudan

Abstract. Air velocity is among the most important factors influencing thermal comfort in naturally ventilated spaces in hot and humid tropical climates. It is important to have air velocity that suits comfort needs and enhances the student's learning performance in the classroom, especially in schools that rely only on natural ventilation assisted by ceiling fans. In this study, the thermal comfort and learning performance of students in a selected naturally ventilated classroom at a secondary school in Segamat, Johor, Malaysia, were experimentally evaluated under different air velocity conditions during the peak temperature period during the school session. Throughout the experiment, physical measurement and a subjective evaluation questionnaire were conducted for thermal comfort analysis and to gather the student's thermal environment evaluation in the classroom. Students' learning performance was assessed through simple reaction and digit span tests based on the WHO Neurobehavioral Core Test Battery (NCTB). All the assessment results were statistically analyzed, and the relationships among indoor air velocity, thermal comfort, and learning performance were obtained. The result showed optimal learning performance was significant when students felt "slightly cool" and air velocity was more than 0.95 m/s. Hotter environments and a lack of air movement were found to be causes of declining student performance. In conclusion, it is suggested that the comfort zone in a naturally ventilated classroom for school students should be set within the range of -1 (slightly cool) with an air velocity greater than 0.76 m/s.

1 Introduction

The indoor environment quality (IEQ) in the classroom is associated with student performance and health, with thermal comfort playing a particularly significant role [1-3]. Students normally spend about six hours in school, mainly in the classroom, where most learning activities occur. Long-term exposure to an inadequate classroom would result in significant poor performance and adverse health effects. Therefore, it is mandatory to encourage a thermally comfortable classroom to provide a conducive learning environment in the school building.

Numerous studies have reported the relationship between the thermal environment and student’s learning performance, with most concentrating on the effect of classroom temperature on students’ learning performance. Siqueira et al. analyzed the cognitive performance of undergraduate students in Brazil and found that their cognitive performance was likely to increase at 23.3 °C according to their thermal perception [4]. Zhang and de Dear studied Australian university students' cognitive performance under two cooling set points. They found that students’ performance was relatively stable at 22 °C compared to 24 °C, where their performance was observed to be in a trend of decline [5]. In Korea, Cho investigated the effect of summer heat on academic achievement and discovered that higher temperatures during the summer had a negative impact on student test scores [6]. Wargocki and Wyon studied the effects of moderately raised classroom temperatures and classroom ventilation rates on the performance of schoolwork by children in Denmark. They found that schoolwork performance increased when the temperature was reduced from 25°C to 20°C [7]. Jiang et al. studied students' performance in a Chinese primary school, and thermal comfort found that optimal performance was obtained when students felt slightly cool to cool at 14 °C [8]. Recent studies on the effect of indoor air temperature on student performance under
summer conditions by Wang et al. revealed that optimum student performance in summer conditions was obtained at 28 °C [9]. Based on the results of those studies, to be effective, a learning environment must consider both the ideal temperature range and its impact on student performance.

Previous studies have found that classroom temperature substantially impacts students’ thermal comfort and learning performance. The ability to control and adjust classroom temperature effectively, as air-conditioned classrooms will greatly improve thermal comfort and learning performance. However, almost all government school rooms in Malaysia were naturally ventilated and only assisted by the ceiling fan. Thus, the existing classroom provides no options for students to adjust and control the surrounding temperature according to their preferences. In fact, due to the effect of high outdoor temperatures and humidity throughout the year, a few studies in Malaysian schools have reported that the thermal environment in the classroom was inadequate. Makhtar et al. studied thermal comfort condition in technical schools and found that 70% of the students in the classroom were dissatisfied with the existing thermal comfort condition [10]. Tazilan et al.’s conducted the thermal comfort assessment and the results showed that the environmental condition of the school’s classroom was warm to hot on the 7-point ASHRAE scale [11-12]. Furthermore, Puteh et al. addressed a few constraints and issues related to the existing classroom in Malaysia. The first issue was the unfavorable learning environment; some students reported that the classroom got too warm (51.7%), especially in afternoon classes, and they could not focus on their work. The second complaint made by the students was that the warm classroom was bad for their health. While in the classroom, they feel stress, difficulty breathing, and headaches. For that reason, to improve the classroom environment for students, a suitable indoor air velocity was required to achieve a thermally comfortable classroom and optimize learning performance [13]. Hence, this study aims to establish an appropriate air velocity for efficient learning in a Malaysian school classroom. The relationship between air velocity, students’ thermal comfort, and learning performance were investigated.

2 Methodology

2.1 Classroom description

The study was carried out in a secondary school located at Gemereh, Segamat, Johor (latitude 2° 49’ north and longitude 102° 79’ east) located in the southern peninsula of Malaysia. It was held in the early months of February, when it was the hottest month of the year, with mean, minimum, and maximum temperatures of 28.5°C, 23°C, and 34°C, respectively. As shown in Figure 1, the mean indoor operative temperature of the selected experimental classroom was at 28.4 °C with prevailing mean outdoor temperature of the 7 days prior to the experiment was at 27.9 °C, which is highly acceptable as it falls within the 90% and 80% acceptability limit according to ASHRAE 55 [12].

The classroom with a room size of L×W×H=9.23×7.31×3.7 m³ equipped with three sets of 5-gear speed ceiling fans was set up just as during the normal school session. All doors and windows were wide open, with daylight as the main illumination source. This study used measurement instruments, namely KIMO AMI 310, to measure environmental parameters. It was placed under the ceiling fan located in the middle of the classroom to record air temperature, mean radiant temperature, air velocity, and relative humidity. The instrument was set up at 1.1 m in height following guidance from ASHRAE 55 for a sitting person [12]. Four sets of tables and chairs were set up around the instrument with directions facing the whiteboard. There was at least 1.5 m of space between students to prevent interaction between them. Specific measurement points of the instrument, the position of the student, and classroom details are shown in Figure 2 (a). The instrument setup is shown in Figure 2 (b).
Individual student backgrounds may influence comfort perception. Thus, the student's participation in the experiment must meet the appropriate criteria through a few selection phases. Initially, 36 students were chosen with the assistance of their teacher based on how similarly they scored on the previous exam. The number of students were then reduced to 20, chosen based on their individual historical backgrounds, which included having lived locally since birth, no history of serious health problems, and similar social backgrounds. The remaining students were then required to complete a pre-experiment in which their learning performance in the normal classroom environment was evaluated. Overall, 12 students who performed similarly in the pre-experiment were chosen to be the subjects of the formal experiment. They were balance in proportion of gender with 6 males and 6 females. The students were introduced to the procedure and the experiment setup, as well as given a guide to filling out the questionnaire. All the participants were required to rest properly and maintain a normal lifestyle before the formal experiment.

2.3 Procedures and experimental conditions

Balanced Latin-square design was used in line with the method suggested by D. Wang et al. [9] and J. Jiang et al. [8], which is an efficient and effective way to avoid tiredness caused by temporal or sequence effects. The students were divided into three group consisting of two males and two females. Each group was required to participate in all the conditions and were subjected to only one condition per day. In each condition student were required to remain seated and engage in completing the survey and learning performance task. Each group finished in about an hour. For details, the Latin-square design of the experiment is provided in Table 1. The ceiling fans used in the classroom were three units, 3 blade ceiling fans (KDK Regular type K15VC) with the length of each fan blade was 150 cm.

The fan speed can be varied from 216 RPM to 264 RPM, and the fan speed used in the study was 18.0 m/s (speed 3), 19.5 m/s (speed 4), and 21.0 m/s (speed 5) and were denoted by C1, C2, and C3, respectively. All the measurement session and duration of the data collection for each condition are presented in Figure 3.

2.4 Experimental physical measurements

The air temperature, mean radiant temperature, velocity, and humidity were measured continuously in the 1-minute interval from the start to the end of the data collection duration of 60 minutes. Each instrument was calibrated prior to the experiment. Movement at 1 m distance from the instrument was restricted to avoid disturbance of the data collection.

2.5 Subjective measurements (Satisfaction survey)

The questionnaire included subjective perceptions of students regarding air temperature and wind speed. It consists of the thermal sensation vote (TSV), thermal preference vote (TPV), air movement sensation vote (AMSV), and thermal acceptability vote. TSV and TPV were cast on the ASHRAE 7-point thermal sensation scale, which includes cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), and hot (+3) [12]. AMSV were cast on the 7-point scale which include too still (-3), still (-2), slightly still (-1), just right (0), slightly windy (+1), windy (+2) and too windy (+3). Satisfaction votes with the indoor temperature and wind speed were cast on the very dissatisfied (-3), dissatisfied (-2), slightly dissatisfied (-1), neutral (0), slightly satisfied (+1), satisfied (+2), and very satisfied (+3). The satisfaction survey was conducted for 10 minutes after 30 minutes adaption time of the students with the environment.

2.6 Learning performance assessment

The tasks for the performance test were selected based on participants’ knowledge level and comprehension that cover an important aspect of learning. In addition, to avoid learning performance tests taking too much time and making the task easier for the student experience, an Android application called Neuro-test was developed specialized for this study. In the app, two tasks will be used to evaluate learning performance. The tasks are simple reaction tests (SRT) from attention categories and digits span from memory-learning categories. A person's simple reaction time was a measurement of how quickly a person react. It
necessitated the students’ full attention. The students’ task was to tap the display when the display turned green for 10 trials. The digit span test was a focused attention test of immediate (short-term) memory. The digit span test was comprised of two different parts, forward digit span (the student to type the numbers in the same order as they are appearing) and backward digit span (the student to type the digits in the opposite direction after they appeared). Each consisted of twelve pairs of progressively longer sequences of random numbers. These tasks follow Neurobehavioral Core Test Battery (NCTB) recommended by WHO.

The raw score for both tasks will appear each time the student completes the task and will be recorded manually by the researcher. The duration of both learning performance tests took approximately about 20 minutes. After the two tasks were completed, the recorded performance tests score was reviewed, calculated, and converted to a standard score by using Equation (1) and Equation (2). Learning performance (LP) was calculated in an average of both tests score using Equation (3). Linear proportional standardize method in Equation (4) was used where extreme value of established relationship between indoor environment condition and learning performance were standardize to 100% [14].

\[
SRT\ score = \frac{\text{Raw score} - \text{mean}}{\text{Standard deviation}} \times 10 + 50
\]

\[
DS\ score = \frac{\text{Raw score} - \text{mean}}{\text{Standard deviation}} \times 10 + 50
\]

\[
LP = \frac{SRT\ score + DS\ score}{2} \times 100\%
\]

\[
LP(\%) = \frac{LP}{\text{Max LP}} \times 100\%
\]

Table 2. Measured indoor environment parameters by design condition (Mean ± SD).

<table>
<thead>
<tr>
<th>Design condition (fan speed)</th>
<th>Air temp. (°C)</th>
<th>Air velocity (m/s)</th>
<th>Mean radiant temp. (°C)</th>
<th>Relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (18.0 m/s)</td>
<td>27.9 ± 0.8</td>
<td>0.55 ± 0.03</td>
<td>28.4 ± 0.8</td>
<td>82.8 ± 2.7</td>
</tr>
<tr>
<td>C2 (19.5 m/s)</td>
<td>28.2 ± 0.7</td>
<td>0.71 ± 0.06</td>
<td>28.7 ± 0.8</td>
<td>82.0 ± 3.5</td>
</tr>
<tr>
<td>C3 (21.0 m/s, max)</td>
<td>30.5 ± 1.1</td>
<td>0.88 ± 0.08</td>
<td>31.1 ± 1.2</td>
<td>79.7 ± 5.8</td>
</tr>
</tbody>
</table>

3.2 Subjective measurement result

The results of the votes for thermal sensation, thermal acceptability, and air movement sensation under different indoor air velocities are shown in Figure 4. Thermal sensation votes moved toward "cool" as the air velocity increased and then toward "hot" when the air velocity decreased, as seen in Figure 4 (a). It also indicated that nearly 50% of the students felt warmer at air velocities below 0.54 m/s. Meanwhile, it can be observed in Figure 4 (b) that most students were "dissatisfied" or "very dissatisfied" when air velocity was lower than 0.63 m/s. "Very dissatisfied" was voted by more than 50% at air velocities lower than 0.6 m/s. Figure 4(c) indicated that air velocities lower than 0.52 m/s are too still, and more than 50% of the students felt air velocities to be "just right" when higher than 0.72 m/s. This explained why the student felt warmer and dissatisfied due to air movements that are too still.

![Physical Measurement](image1)

![3. Measurement session and duration of the data collection](image2)

3 Result and Discussion

3.1 Physical assessment result

The physical environment parameters that was measured for each design condition are presented in Table 2. As expected, air velocity was different in each design condition when ceiling fans speed was adjusted. Indoor air temperature, mean radiant temperature, and relative humidity values were close for each designated condition.

![Percentage of thermal sensation votes](image3)

(a)

![Percentage of thermal acceptability votes](image4)

(b)
The regression between air velocity, thermal sensation, air movement sensation, and thermal preference vote is shown in Figure 5. It shows that the thermal sensation vote and air movement sensation vote varied from -3 (cold) to +3 (hot) and -3 (too still) to +3 (windy), respectively, in the air velocity range between 0.5 m/s and 0.95 m/s. The linear fit line shows that both votes were nearly identical, with the air movement sensation vote slightly higher than the thermal sensation vote. The R-square value were slightly close for both line with 0.57 for TSV and 0.70 for AMSV. This indicates there is a moderate regression relationship between the air movement sensation and thermal sensation. In addition, students felt neutral at an air velocity of 0.76 m/s and felt the air velocity was just right at 0.83 m/s. However, the thermal preference fit line was below the thermal sensation vote and the air movement sensation vote, showing that students prefer a much cooler and higher air movement environment than the existing classroom’s condition.

Fig. 5. Regression analysis between air velocity, thermal sensation vote (TSV), air movement sensation vote (AMSV) and thermal preference vote (TPV).

3.3 Learning performance result

The relationship between learning performance and air velocity is presented in Figure 6. The result of the regression analysis found that the relationship between learning performance and air velocity is linear with an R-square value of 0.3375 and a significance value lower than 0.001. The linear fit line shows that learning performance increased when air velocity varied from 0.52 m/s to 0.95 m/s. The relationship of learning performance (LP) was described as a function of air velocity (v) in Equation 5.

\[
LP = 29.91v + 78.598
\]  

(5)

To describe the relationship between learning performance and thermal sensation vote as well as air movement sensation vote, the learning performance obtained from establishing the relationship of learning performance as a function of thermal sensation vote and air movement sensation vote, as shown in Equations 6 and 7, was standardised using equation 4.

\[
LP = \frac{29.91(TSV) + 78.598}{29.91(TSV) ^ 2 - 2.1918(TSV) + 98.944}
\]  

(6)

\[
LP = \frac{0.4707(AMSV) + 99.646}{0.4707(AMSV) ^ 2 - 1.8482(AMSV) + 98.944}
\]  

(7)

As shown in Figure 7, an inverted U-shape relationship can be observed. It shows that the relationship between learning performance and thermal sensation was quadratic with an R-square value of 0.2477 and a significance value lower than 0.01. The learning performance first increased and then decreased when the
thermal sensation reached -1.23, indicating that the learning performance was optimal at a "slightly cool."

Furthermore, with an R-square value of 0.3041 and a significance value less than 0.001, the relationship between learning performance and air movement sensation was cubic. The learning performance first increased and then decreased, with a air movement score of -0.37. This indicates that optimum learning performance can be obtained when air movement is "just right."

![Fig. 6. Regression analysis between learning performance and air velocity.](image1)

![Fig. 7. Regression analysis between learning performance, thermal sensation vote (TSV) and air movement sensation vote (AMSV).](image2)

The effective air velocity for optimum learning performance was calculated using Equations 8 and 9 as shown below, obtained from the relationship between air velocity and thermal sensation vote, as well as air movement sensation vote, in Figure 5.

\[
TSV = -6.7058v + 5.1039 \tag{8}
\]

\[
AMSV = -6.9494v + 5.7782 \tag{9}
\]

From the calculation, the learning performance for the thermal sensation vote and the air movement sensation vote were optimum at 0.94 m/s and 0.88 m/s, respectively. These values were much higher than the air velocity obtained when the occupant felt thermally neutral and air movement was just right. This explains why students prefer a classroom with much higher air velocity. The effective air velocity is also within the range of the air velocity limit specified by the ASHRAE 55 adaptive model [12].

### 3.4 Research practical implication

The findings of this study have important practical implications for the design, operation, and maintenance of naturally ventilated classrooms in hot and humid tropical climates. Specifically, the study provides guidance on the optimal air velocity range and thermal comfort level for promoting student learning performance.

To improve building design, architects and engineers can use the findings to optimize the design of ventilation systems, such as the placement and number
of ceiling fans, to ensure that the desired air velocity range and thermal comfort levels are achieved. Additionally, they can consider incorporating natural ventilation strategies, such as using windows or louvers, to supplement mechanical systems and enhance air circulation.

Facility managers and building operators can use the findings to adjust the operation of ventilation systems to ensure that the desired air velocity range and thermal comfort levels are maintained. This may involve adjusting fan speed, opening or closing windows or louvers, or modifying temperature setpoints to maintain optimal thermal comfort.

Educators and school administrators can use the findings to improve learning performance among students. They can ensure that classrooms are properly ventilated and maintained within the optimal thermal comfort range to promote student comfort and concentration. Additionally, they can encourage the use of appropriate clothing and hydration to help students cope with hot and humid conditions.

Overall, the findings of this study can inform the design, operation, and maintenance of naturally ventilated classrooms in hot and humid tropical climates, leading to improved thermal comfort and learning performance among students.

4 Conclusion

This experimental study of learning performance was conducted at various air velocities (0.52–0.95 m/s) by adjusting the ceiling fan speed. The environment parameters, subjective evaluation, and learning performance were measured in each adjustment. The relationship between air velocity and learning performance was obtained. The conclusions were summarised as follows:

- The air movement that was too still in the classroom caused the students to feel warmer and dissatisfied with their environment.
- Based on TSV result, students felt thermally neutral when air movement was 0.76 m/s. Meanwhile, AMSV result indicated their felt neutral at air movement 0.83 m/s. However, their prefer much cooler classrooms with more air movement.
- Learning performance was calculated from the results of two tasks completed by each student in all conditions. The relationship between learning performance and air velocity was significantly linear, with learning performance increasing with respect to increases in air velocity.
- A quantitative relationship was also obtained between the TSV and the AMSV. The student performed well when their body felt "slightly cool," and air movement was "just right" at air velocities of 0.94 m/s and 0.88 m/s, respectively.

This work was supported by the Ministry of Higher Education (MOHE) of Malaysia through Fundamental Research Grant Scheme (FRGS/1/2020/W/AB02/UTHM/02/7). The study was also supported with permission from the Ministry of Education and the State Education Department. The authors would like to express gratitude to the school administration and students who contributed to this study. The authors also acknowledge the technical support from Mr. Mohd Azizi bin Mohd Afandi during the data collection.

References
