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Quantifying Fenestration Effect on Thermal Comfort in Naturally Ventilated Classrooms

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Abstract: This study seeks to evaluate thermal comfort in naturally ventilated classrooms to draw sustainable solutions that reduce the dramatic energy consumed in mechanically ventilated spaces. Passive ventilation scenarios are generated using alternations of openings on the windward and leeward sides to evaluate their effects on thermal comfort. Twenty-eight experiments were carried in Bahrain during winter inside an exposed classroom, the experiments were grouped into five scenarios namely: "single-inlet single-outlet" SISO, "single-inlet double-outlet" SIDO, "double-inlet single-outlet" DISO, "double-inlet double-outlet" DIDO and "single-side ventilation" SSV. The findings indicate that single-side ventilation did not offer comfort except at high airspeed, while comfort is attained by using cross-ventilation at ambient temperature between 21.8–26.8 °C. The temperature difference between monitored locations and the inlet is inversely proportional to the number of air changes per hour. The DISO scenario accomplishes the lowest temperature difference. Using cross-ventilation instead of single-side ventilation reduces the temperature differences between 0.5–2.5 °C and increases airspeed up to three folds. According to the measured findings, the DISO cross-ventilation scenario is a valid sustainable solution adaptable to climatic variation locally and beyond with zero-energy consumption and zero emissions.

Keywords: naturally ventilated; cross ventilation; single-side ventilation; thermal comfort; adaptive systems; biomimetics

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1. Introduction

Around 40% of the global energy consumption is consumed in the building sector, a high portion of this percentage is used to ensure thermal comfort for occupants [1]. In addition, using active cooling consumes up to 70–80% of the total energy consumption inside buildings in such a hot climate [2]. Using inadequate ventilation systems leads to adverse consequences for students' health, learning, productivity and performance [3].

Several studies [4–8] discussed the relationship between ventilation rate, type, conditions and students' health as well as learning performance. The results of these studies indicate that a sufficient rate of ventilation with an acceptable level of indoor air quality contribute to enhancing students' health and learning performance. Passive ventilation is an energy-efficient tool to reduce carbon dioxide concentration and indoor air temperature [9]. The indoor pollutants' concentration levels in classrooms rely upon air permeability from fenestration (windows) and manual airing [10]. In addition, improving the ventilation performance reduces student absenteeism [11]. Therefore, it is recommended to install monitoring apparatus in classrooms to pursue the indoor conditions and enhance the installed ventilation system [12].

Ventilation rates play a crucial role in building energy consumption and occupants' health and comfort [13,14], while the overestimated ventilation rates cause serious consequences of energy consumption [15]. Chiesa and Grosso [16] revealed in their study that the cooling reduction potential due to application of natural ventilation as a heat dissipation technique is fairly high in all Mediterranean basin. The study recommended depending on passive cooling to reduce the cooling demand of buildings. Despite the vision and concern of Gulf Cooperation Council (GCC) countries to minimize the energy consumption in the building sector (zero energy building) by 2030, a limited number of publications were carried out in these countries with respect to the passive ventilation in classrooms [17]. Moreover, these countries do not have a standard of adaptive thermal comfort.

Hence, we introduce this experimental study in a naturally ventilated classroom at Gulf University campus which is in the Kingdom of Bahrain. The focus of this study is to examine the effect of fenestration (openings) on thermal comfort through different scenarios that are adaptable to climatic variation locally and beyond.

1.1. Challenge of GCC Countries' Climate and Dependency on Passive Ventilation

Kingdom of Bahrain is one of the GCC countries where the climate in the summer period persistently prevails with elevated air temperature and relative humidity. The extreme temperature in May reaches 46.7 °C, while the extreme relative humidity is 91% in June. From April to the end of October, the dependency on mechanical ventilation inside Bahrain's buildings is up to 100% [18]. In such a hot-humid climate, using natural ventilation is inadequate to provide a thermal environment during the summer season. Therefore, this study was carried in the winter season to check if this Gulf climate (or similar) in winter provides thermal satisfaction to occupants.

1.2. Thermal Comfort Perception of GCC's Learners

Over the last 50 years, few studies discussed thermal comfort in educational environments where students prefer a cooler temperature of thermal sensation [19]. Indeed, a few studies carried in GCC discussed the thermal comfort perception of these countries' students, to address the adaptive behavior and explore the students' thermal experiences in classes. A comparative study between Omani female and Saudi male students was carried through two separate studies in high schools. The findings received from students showed that thermal conditions subjected to indoor air temperature range of 24.3 ± 1.09 °C in Muscat's survey and 26.1 ± 0.92 °C in Jeddah's survey meet their satisfaction towards thermal comfort by using Griffiths' method [20].

The separation between boys and girls in GCC classrooms derived researchers to study the gender effect on thermal comfort. In this regard, a study conducted in Doha find women prefer a warm environment [21]. Using active ventilation in place of passive ventilation leads to duplication of the carbon dioxide concentration in Kuwait's school classrooms where occupants' density may reach four times compared to office occupants' density, while using split air conditioning as per the lack of providing adequate fresh air into classes. The findings of this study advised dependence on centralized air-conditioning systems rather than a split system in such environment to minimize the exceeded limits of CO_2 concentration [22].

The average neutral temperature for Kuwaiti students was around 21.5 °C, based on a study on students between 11–17 years in 14 classrooms, where the female sensation is less than the male with 1 °C. In addition, a comparison between students' actual mean vote (AMV) against PMV, ePMV and PMV10 indices showed under-predicted thermal sensation on the warm side and over-predicted on the cool side of ASHRAE seven scale of thermal sensation [23,24]. In Doha, a long-term field study for 30 months was carried out in ten offices that were mechanically ventilated using Griffiths' method. The results acknowledge that the comfort temperature was 24.0 °C and suggested a relation between outdoor air temperature and comfortable temperature for air-conditioned space ranged from $\frac{1}{2}$ to 10 K [25].

1.3. Influencing Factors on Thermal Comfort

For six naturally ventilated large-educational halls, a study conducted in upper Egypt found 224 out of 269 students (83%) are not adapted to the indoor conditions. This suggested that students can raise their productivity and focus more during lectures when placed in a thermally comfortable environment where evaporative cooling was used [26]. In theory, conditioning the interior might produce more power than consuming power. A study investigated the minimum energy required to achieve thermal comfort relative to the ambient conditions (temperature and humidity), revealing that, at any rate, opening the window(s) was considered as an energy-free solution and can reduce energy consumption if the outdoor conditions ensure users' comfort needs [27].

Building typology plays a role in thermal sensation towards the students; in this regard, a comparison between old and new schools in Jordan was conducted to assess thermal comfort by using two methods of monitoring the classrooms; one by recording the indoor air conditions and another by simulation method to find the PMV values. The results showed both schools exceeded the thresholds of thermal comfort during the peak period, while new schools showed better performance than the old ones [28].

In the South European region, a long-term field study in four classrooms revealed that passive ventilation becomes adequate by the manual opening of windows. This provides energy sparing and adequate ventilation rate for outdoor mean temperature larger than 19 °C, while lower than 16 °C showed inappropriate results. In addition, manual-window airing provide thermal comfort recommended conditions and energy saving for the selected classrooms around a quarter of the academic year [29]. Tropical countries' weather is also close to GCC weather, which is hot-humid most of the months of the year. A study focusing on three subtropical locations in Ecuador recorded neutral temperatures for Quito (Highlands region), Guayaquil (Coastal region) and Tena (Rainforest region) as 21.8 °C, 26.3 °C and 26.9 °C, respectively, which confirms that, regardless the region, students prefer cold environment to warm environment [30].

Cross ventilation is highly recommended than single-side ventilation to achieve thermal comfort and better temperature distributions. In addition, the temperature difference that can be achieved between indoor and outdoor air temperature is higher. In this regard, a field study was carried out in Australia for two days which revealed that for prevailing wind speed up to 3.0 m/s and the mean outdoor air temperature around 26 °C, while using the cross-ventilation type showed the achievement of thermal comfort for indoor conditions 70% of the time compared with 1% in case of using single-side type [31]. Another field study conducted in Cyprus for 1 month showed, in the case of depending on cross-ventilation, the indoor conditions meet thermal comfort conditions up to 40% of the time, while single-sided ventilation achieved only about 2% of the time [32]. A review summarized and compared both types of ventilation considering many previous studies, revealed that cross ventilation provides better performance in terms of reducing the indoor air temperature compared with outdoor temperature [33].

The Olgyay brothers [34,35] developed the first attempt (1963) to define the metrics and ranges of comfort zones at different conditions of dry bulb temperature and relative humidity. The bioclimatic chart of Olgyay brothers considers various factors of outdoor conditions that affect human thermal sensation, such dry bulb temperature, mean radiant temperature, relative humidity and prevailing wind speed. The Olgyays' chart is conceptualized based on the outdoors conditions regardless of the physiological needs of the indoor conditions and are applicable only in a hot-humid climate [36].

1.4. Objectives

As shown in the previous literature, a few research studies discussed passive ventilation inside classrooms for climate conditions, such as the winter season in the GCC region. Consequently, the objective of this study is to feed this domain of research elaborated as follows:

- To check whether the applicability of the Kingdom of Bahrain's weather during the winter season provides acceptable thermal conditions inside an exposed classroom at Gulf University, Kingdom of Bahrain, as suggested by the adaptive method [37,38];
- To quantify the effect of openings (fenestration) on the windward and leeward sides to evaluate their effects on thermal comfort by carrying out a comparison between five ventilation scenarios represented in single inlet single outlet (SISO), single inlet double outlet (SIDO), double inlet single outlet (DISO), double inlet double outlet (DIDO) and single-side ventilation (SSV).
- To study the effect of occupancy load on thermal comfort.
- To compare between cross ventilation (CV) and single-side ventilation (SSV).

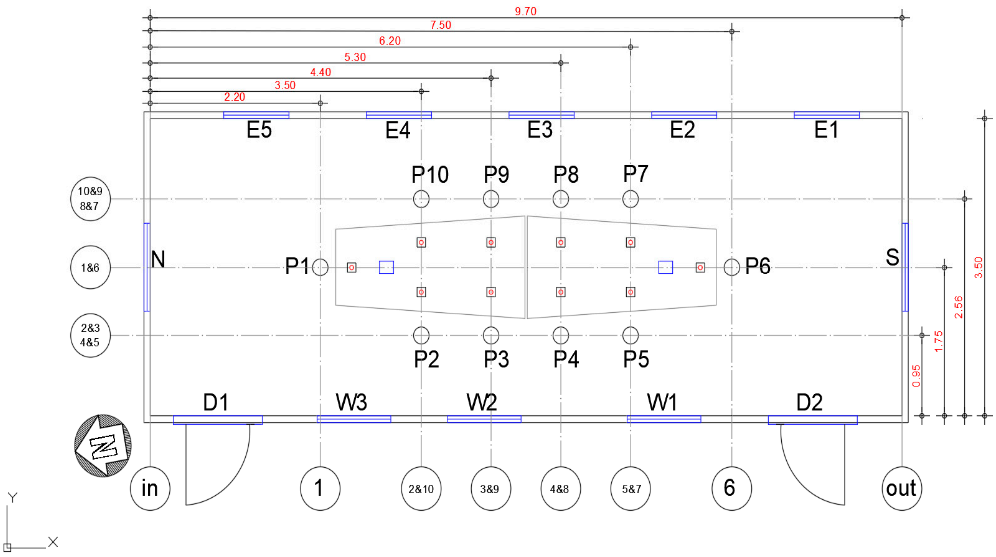
2. Materials and Methods

To experimentally evaluate the objective of this study, we selected a classroom (Fab Lab) as shown in Figure 1a–c) at Gulf University, which was monitored from 30th January to 2nd of March 2021. The following procedure of research is followed, monitoring the air conditions at the inlet(s) and outlet(s), followed by classroom setup, then recording measurements for different ventilation scenarios at ten different locations inside the classroom and, finally, analyzing the results.

(**a**)

Figure 1. *Cont.*

(**b**)



(**c**)

Figure 1. (**a**). A google map view of the classroom (Fab Lab at Gulf University, Kingdom of Bahrain where Latitude: 26°15′ N and Longitude: 50°57′ E). (**b**). 3D Shooting showing the north, west and south elevations of the classroom. (**c**). 2D Plan of the test classroom detailed with dimensions, not to scale.

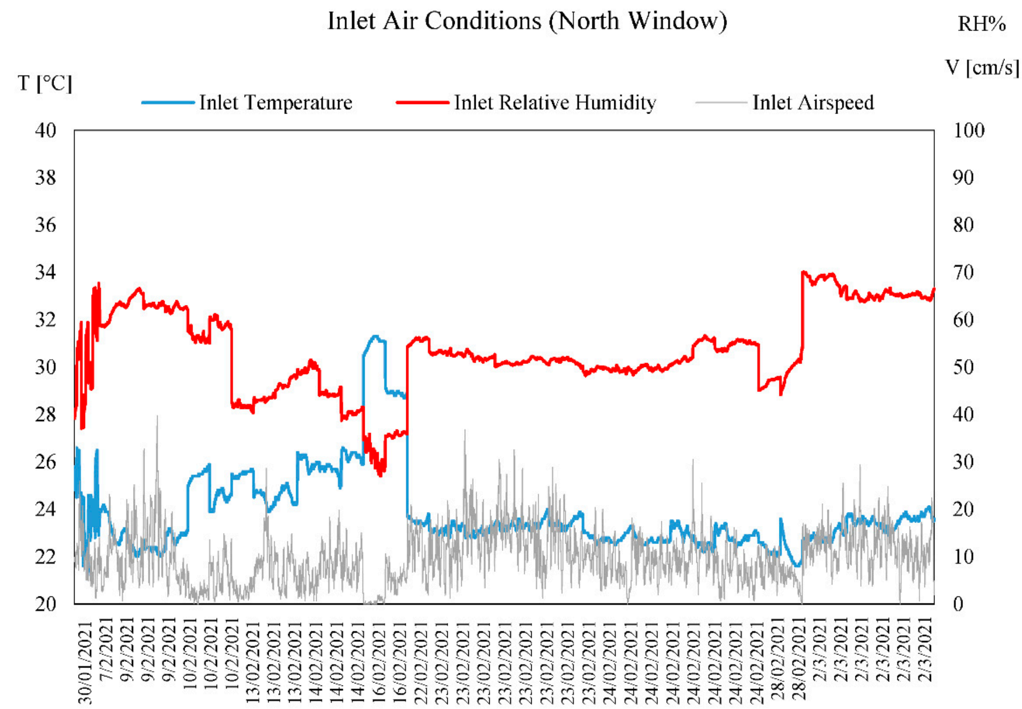
2.1. Monitoring the Air Conditions at Inlet(s) and Outlet(s)

Based on observations taken between June 2005 until January 2021 from 7 AM to 7 PM local time, the yearly average daytime and nighttime mean outdoor air temperature are 29 °C and 26 °C respectively, while the average prevailing windspeed about 5 m/s from NNW. Moreover, the average daytime temperature during the experiment's period is 20 °C and the average prevailing windspeed about 5 m/s [18]. Nevertheless, we prefer to record more accurate conditions relevant to the tested classroom, so the inlet(s) and outlet(s) openings were monitored during all experiments. The air temperature, airspeed and relative humidity were recorded as shown in Figure 2a,b. These recorded conditions during the experiment period are shown in Figure 3a,b. It can be observed that the average inlet temperature equals 24 °C, average inlet airspeed equals 10 cm/s, average inlet relative humidity equals 53%, measured at the north window inside the classroom, while the outlet air conditions at the south window are 29 °C, 3.0 cm/s and 42%, respectively.

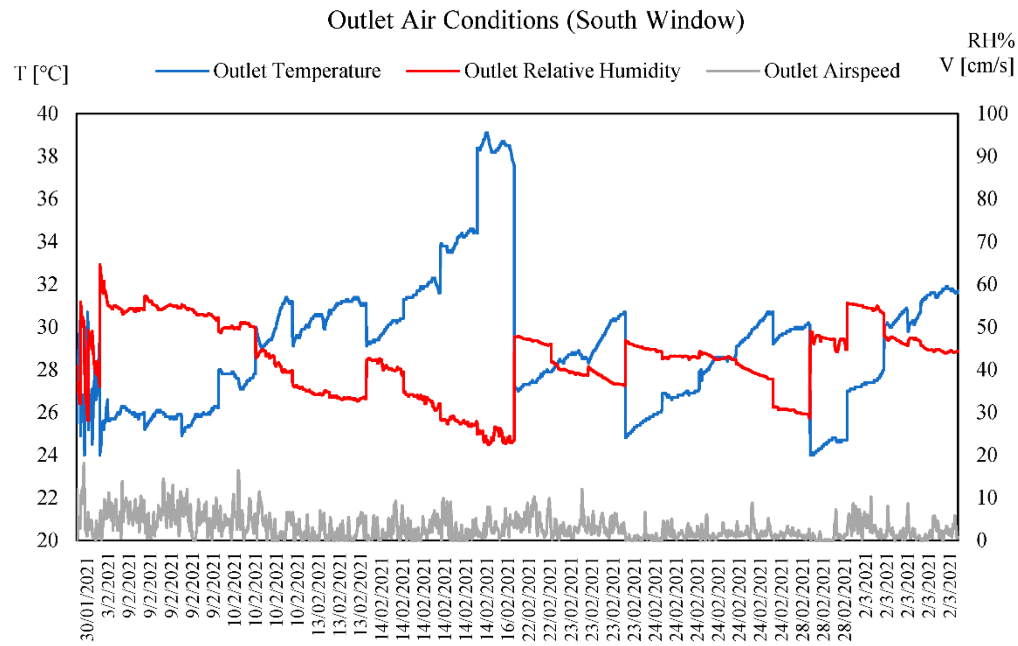
(**a**)

(**b**)

Figure 2. (**a**). Monitoring air conditions at inlet window opening in the north direction. (**b**). Monitoring air conditions at outlet window opening in the south direction.



(**a**)



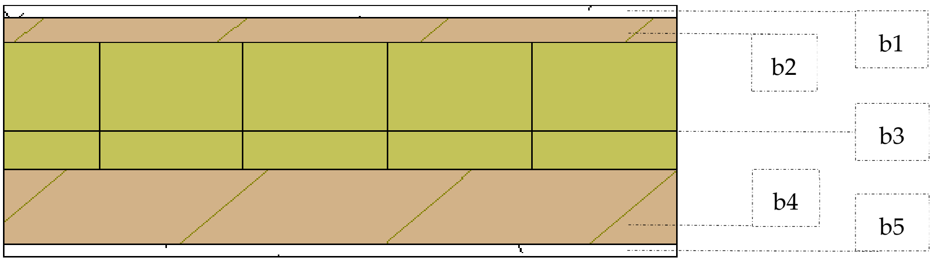
(**b**)

Figure 3. (**a**). Inlet air conditions of the north window during the experiments period. (**b**). Outlet air conditions of the south window during the experiment period.

2.2. Classroom Setup

The classroom used in this study is in the Kingdom of Bahrain where the latitude: 26°15′ N and longitude: 50°57′ E. The geometry is rectangular shape with inner dimensions 9.7 × 3.5 × 2.3 m (L × W × H), with 10 windows around the periphery as shown in Figure 1b. North and west windows are windward while the south and east windows are leeward during all experiments of this study. Instructor and students sit all around the two tables to interact, the capacity considered as ten occupants. Therefore, ten lamps (100 W per each) are located all around the two tables to be used as a source of sensible heat which covered by opaque material and two ultrasonic humidifiers used as a source of humidity allocated as shown in Figure 4a.

(**a**)



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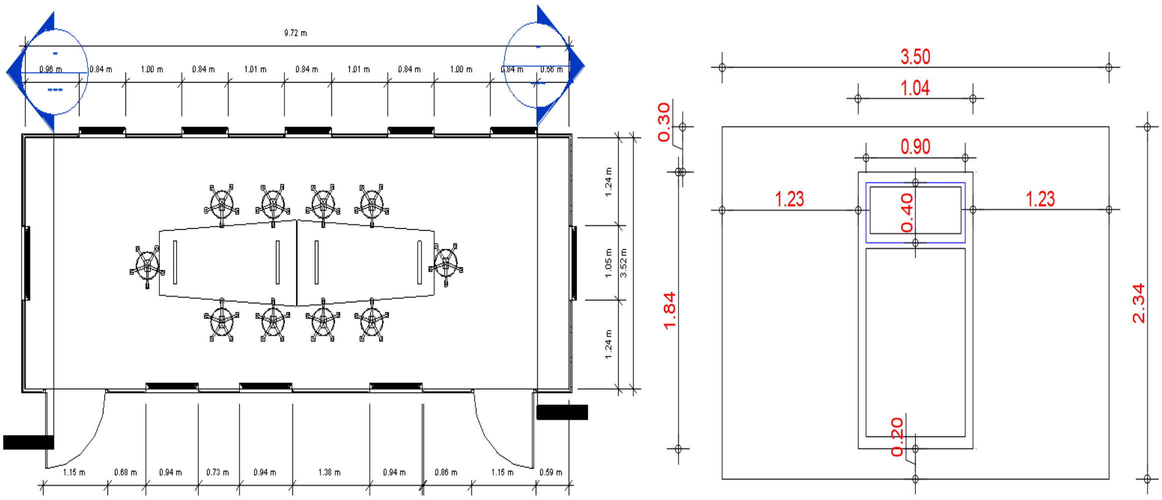
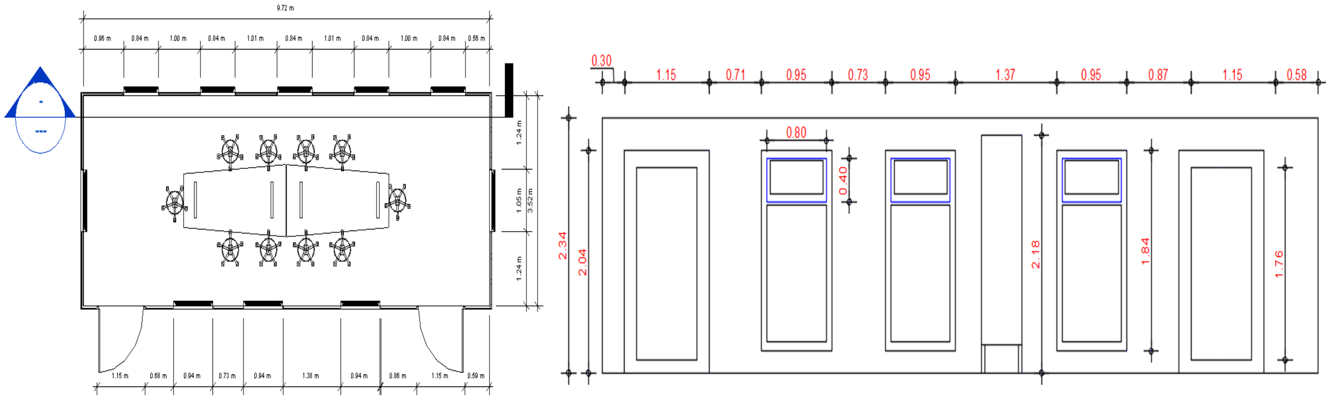


(**c**)

Figure 4. *Cont.*



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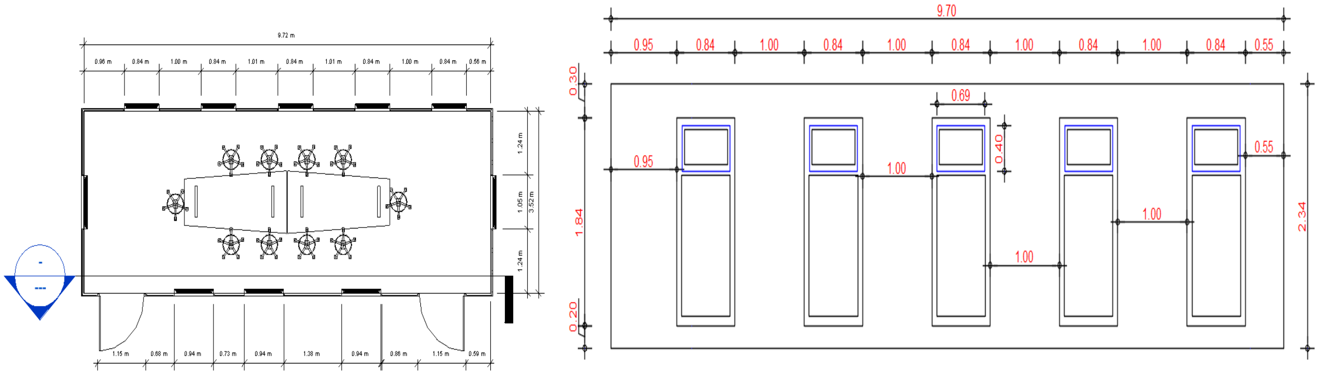


(**e**)

Figure 4. (**a**). Sample of monitoring inside the test classroom at location (2). (**b**). Walls and ceiling construction detailing: (b1) 13 mm Gypsum plaster; (b2) 10 mm Plywood; (b3) 32 mm Batt insulation; (b4) 16 mm Plywood; (b5) 19 mm Gypsum plaster. (**c**). North and south section view of the studied classroom; window opening (900 mm × 400 mm). (**d**). East section view of the studied classroom; windows opening (690 mm × 400 mm). (**e**). West section view of the studied classroom; windows opening (800 mm × 400 mm).

The walls and ceiling construction of the studied classroom are indicated in Figure 4b with a low thermal mass of total thickness equals 90 mm and overall heat transfer coefficient equals 0.138 W/m^{2}K. In addition to the previous construction, the roof is coated with a 22-gauge steel deck painted with white plastering. Figure 4c–e represent the four section views that may help to fully understand the interior of the space, where the size of openings, dimensions of windows and doors are described.

2.3. Recording Measurements

The indoor air conditions were recorded at ten positions (P1–P10) corresponding to sitting positions around the tables as shown in Figure 1c. In addition, inlet and outlet opening were monitored during all experiments; all recorded data gathered by Testo 400 apparatus connected to globe thermometer, temperature sensor, humidity sensor and turbulence probe which accuracy is according to standard EN 60584-2, the accuracy of Class 1, ±0.5 °C, ±2%RH and ±0.03 m/s, respectively [39]. Every experiment was carried for half an hour with time averaging of three minutes at each location to record the average airspeed, average air temperature, globe temperature and relative humidity for waist level (1.1 m) of the seated occupant as recommended by ANSI/ASHRAE 55 [40]. After completing each experiment, a set of calculations were carried to obtain the values of mean radiant temperature [41], operative temperature [40] and humidity ratio [42], as per the following equations:

$$T_{mrt} = [(T_g + 273.15)^4 + (((1.1 \times 10^8 \times {V_a}^{0.6})/(\varepsilon_g \times D^{0.4})) \times (T_g - T_a)^{0.25})] - 273.15 \quad (1)$$

$$T_{op} = (T_a/2) + (T_{mrt}/2) \quad (2)$$

$$\mathrm{Log}_{10}\, P = A - (B/(C + T)) \quad (3)$$

$$\omega = 0.622\ (P_v/(P - P_V)) \quad (4)$$

where T_{mrt} is the mean radiant temperature (°C); T_g is the globe temperature (°C); T_a is the air temperature (°C); V_a is the air speed (ms^{-1}); D is the globe thermometer diameter (150 mm); ε_g is the emissivity of the sphere (0.95 for black thermometer); T_{op} is the operative temperature (°C); P is the vapor pressure (mmHg); ω is the humidity ratio ($Kg_{H2o}/Kg_{dry\ air}$); T is the air temperature (°C); A, B and C are Antoine's constants equal 8.07131,1730.63 and 233.426, respectively.

2.4. Five Ventilation Scenarios

Twenty-eight experiments were carried from 30th January until 2nd of March 2021 around noontime, with a different inlet(s) and outlet(s) window manual openings, with different conditions of prevailing air temperature, airspeed magnitude and vector, relative humidity and sky condition. These 28 experiments are grouped into five ventilation scenarios, namely: "single inlet single outlet" SISO, "single inlet double outlet" SIDO, "double inlet single outlet" DISO, "double inlet double outlet" DIDO and "single side ventilation" SSV. In each scenario, the experiments were filtered according to the air change per hour (ACH), which is calculated based on the airspeed at the inlet(s).

We compared the experiments' results regardless of the outdoor conditions; therefore, we considered dimensionless comparison by using the temperature difference between inlet temperature and each location temperature, similarly considering airspeed and humidity ratio difference comparison. In addition, we aimed to introduce a trusted study with accurate results, so we excluded twelve experiments' results from this study during the analysis of the results due to sky condition and solar radiation effect, rapid fluctuating in outdoor conditions, different prevailing wind direction and human error during the insufficient transition to another experiment after conducting single-sided ventilation experiment. The methodology of this study represented in five researching points as follows:

2.4.1. Experiments' Repeatability

The objective of experiments' repeatability to obtain accurate results with an acceptable level of confidence for the measurements' devices in this study. For this purpose, a cross ventilation scenario (1) [CV-N-S] or [SISO] was repeated two times at noontime with very similar conditions at inlet and outlet as shown in Table 1. Similarly, single-side ventilation scenario (2) [SSV-N] was repeated two times with conditions shown in Table 2.

Table 1. Inlet and outlet conditions during repeated experiments of Scenario (1) [CV-N-S].

Recorded Parameter	Experiment (1)	Experiment (2)
	23 February 2021	**24 February 2021**
T_{in} [°C]	23.40	23.20
V_{in} [m/s]	0.12	0.10
$\%RH_{in}$	51.20	51.40
T_{out} [°C]	28.3	27.5
V_{out} [m/s]	0.03	0.02
$\%RH_{out}$	40.7	43.2

CV-N-S represents cross ventilation from the north window (inlet) to the south window (outlet). T_{in} and T_{out} are the inlet and outlet air temperatures. V_{in} and V_{out} are the inlet and outlet air speed. $\%RH_{in}$ and $\%RH_{out}$ are the inlet and outlet relative humidity.

Table 2. Inlet conditions during repeated experiments of Scenario (2) [SSV-N].

Recorded Parameter	Experiment (1)	Experiment (2)
	10 February 2021	**13 February 2021**
T_{in} [°C]	25.50	25.50
V_{in} [m/s]	0.02	0.03
$\%RH_{in}$	56.4	41.8

SSV-N represents single-side ventilation from the north window (inlet). T_{in} is the inlet air temperature. V_{in} is the inlet air speed. $\%RH_{in}$ is the inlet relative humidity.

2.4.2. Climate Applicability

Twenty-eight experiments were conducted and assessed to check the applicability of a climate such in the Gulf region during the winter season. If satisfying the recommended thresholds of thermal comfort as per adaptive method, experiments were carried at different conditions to give clear findings. In this regard, substantial factors were investigated and their influence on the indoor air conditions in the studied classroom. The operative temperature for all experiments calculated and checked as per the adaptive method [18], we considered this parameter as a key of performance for each experiment.

2.4.3. Inlets and Outlets Effect

To quantify the effect of inlets and outlets on a naturally ventilated environment, five scenarios were tested SISO, SIDO, DISO, DIDO and SSV, as shown in Figure 5. The comparison investigated which of these scenarios provided the minimum temperature difference between location and inlet air temperature. We present a consistent comparison between these different scenarios, while comparing double inlet with single inlet, we considered to reference the air change inside the environment based on the cross-sectional area and inlet airspeed for each window opening.

2.4.4. Occupancy Effect

In this research, occupancy load is characterized by two sources, source of sensible load represented in 10 lamps (100 W per each) and source of humidity represented in two humidifiers. We studied the effect of occupancy on adaptive comfort through three modes of cross ventilation Scenario (5) [CV-N-W3-S-E1] or [DIDO]. Mode (1) when all lamps and humidifiers turned off named as "no occupancy" or "0% of occupancy load", mode (2) when five lamps and one humidifier turned on named as "50% of occupancy load" and, finally, mode (3) when all lamps and humidifiers are turned on named as "100% of occupancy load". Therefore, we carried an experiment three times on the 2nd of February 2021.

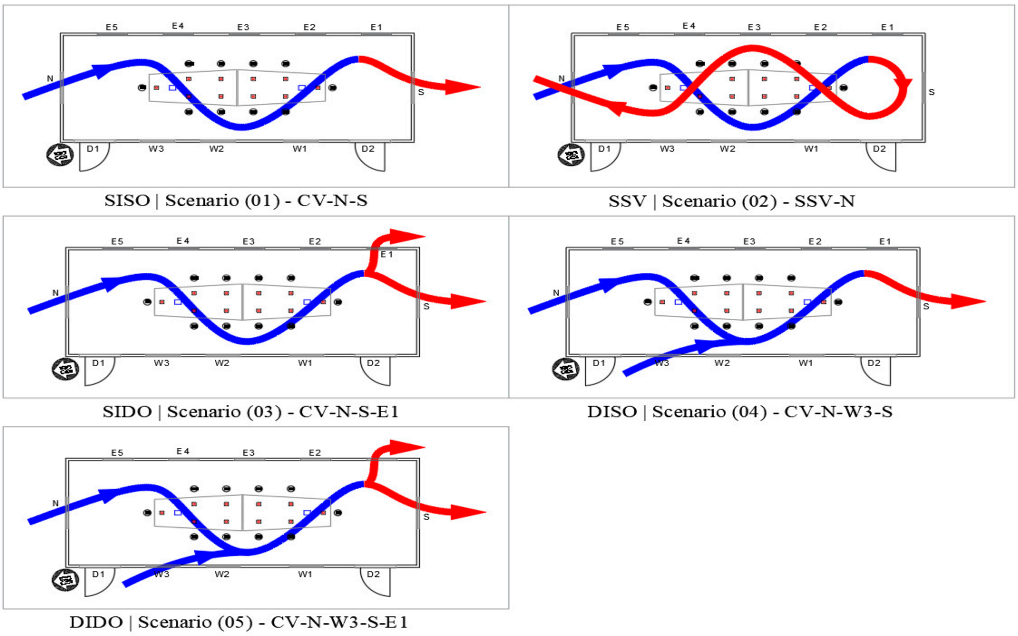


Figure 5. Graphical representation of the five ventilation scenarios.

2.4.5. Cross Ventilation versus Singe-Side Ventilation

As clarified in the literature [17–19], it has been revealed all previous research recommended cross-ventilation than single-side ventilation. In this regard, we conducted a comparison between these two ventilation modes to obtain how much temperature and airspeed difference by using any of them in such a climate. Consequently, a comparison between scenario (1) [CV-N-S] or [SISO] and scenario (2) [SSV-N] was carried.

3. Results and Discussion

3.1. Repeatability Analysis

Based on results carried for cross ventilation mode as shown in Figure 6a,b which compared two repeated experiments at 23th and 24th February 2021 of scenario (1) [CV-N-S] or [SISO], the maximum difference of temperature (ΔT) was 0.45 °C at position (4), while the maximum difference of airspeed (ΔV) was 0.02 ms^{-1} at position (7) as shown in Figure 6a,c, the maximum difference of humidity ratio ($\Delta \omega$) was 0.0005 $Kg_{H2O}/Kg_{dry\ air}$ at position (4) as shown in Figure 6d.

In single-side ventilation mode, the results of the two repeated experiments that carried on 10th and 13th February 2021 of scenario (2) [SSV-N] as shown in Figure 7a,b, the maximum difference of temperature (ΔT) was 0.62 °C at position (10), while the maximum difference of airspeed (ΔV) was 0.02 ms^{-1} at position (9) as shown in Figure 7a,c, the maximum difference of humidity ratio ($\Delta \omega$) was 0.0012 $Kg_{H2O}/Kg_{dry\ air}$ at position (1) as shown in Figure 7d. The small difference between experiments for both scenarios due to the difference in inlet conditions which can be observed in Tables 1 and 2.

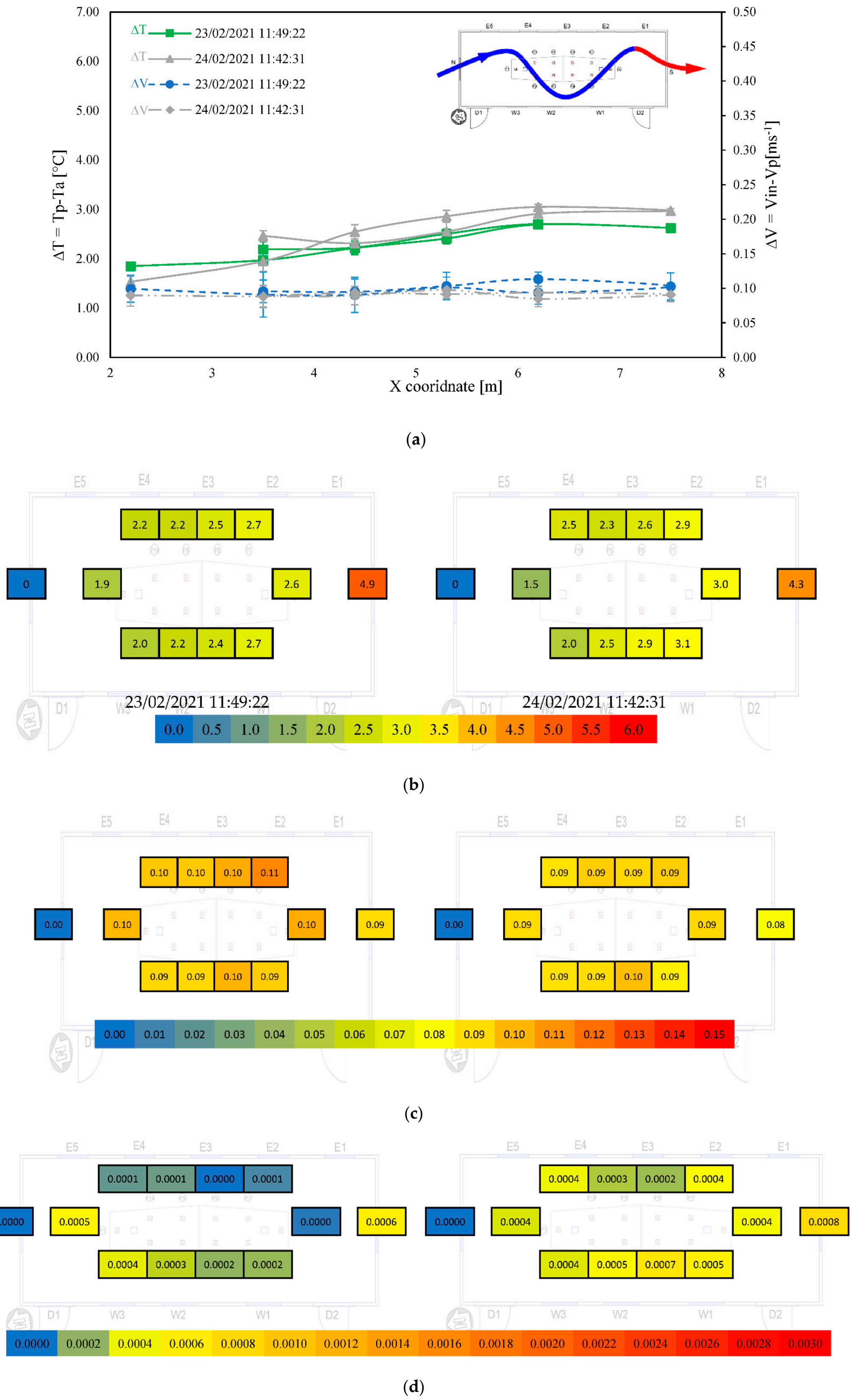


Figure 6. (**a**). Repeated Experiments of Scenario (1); [CV-N-S] or [SISO]. (**b**). Temperature difference between locations and inlet $\Delta T = Tp - Ta$ [°C] of Scenario (1); [CV-N-S] or [SISO]. (**c**). Velocity difference between location and inlet $\Delta V = Vin - Vp$ [ms^{-1}] of Scenario (1); [CV-N-S] or [SISO]. (**d**). Humidity ratio difference between locations and inlet $\Delta\omega = \omega p - \omega i$, [KgH2O/Kgdry air] of Scenario (1) [CV-N-S] or [SISO].

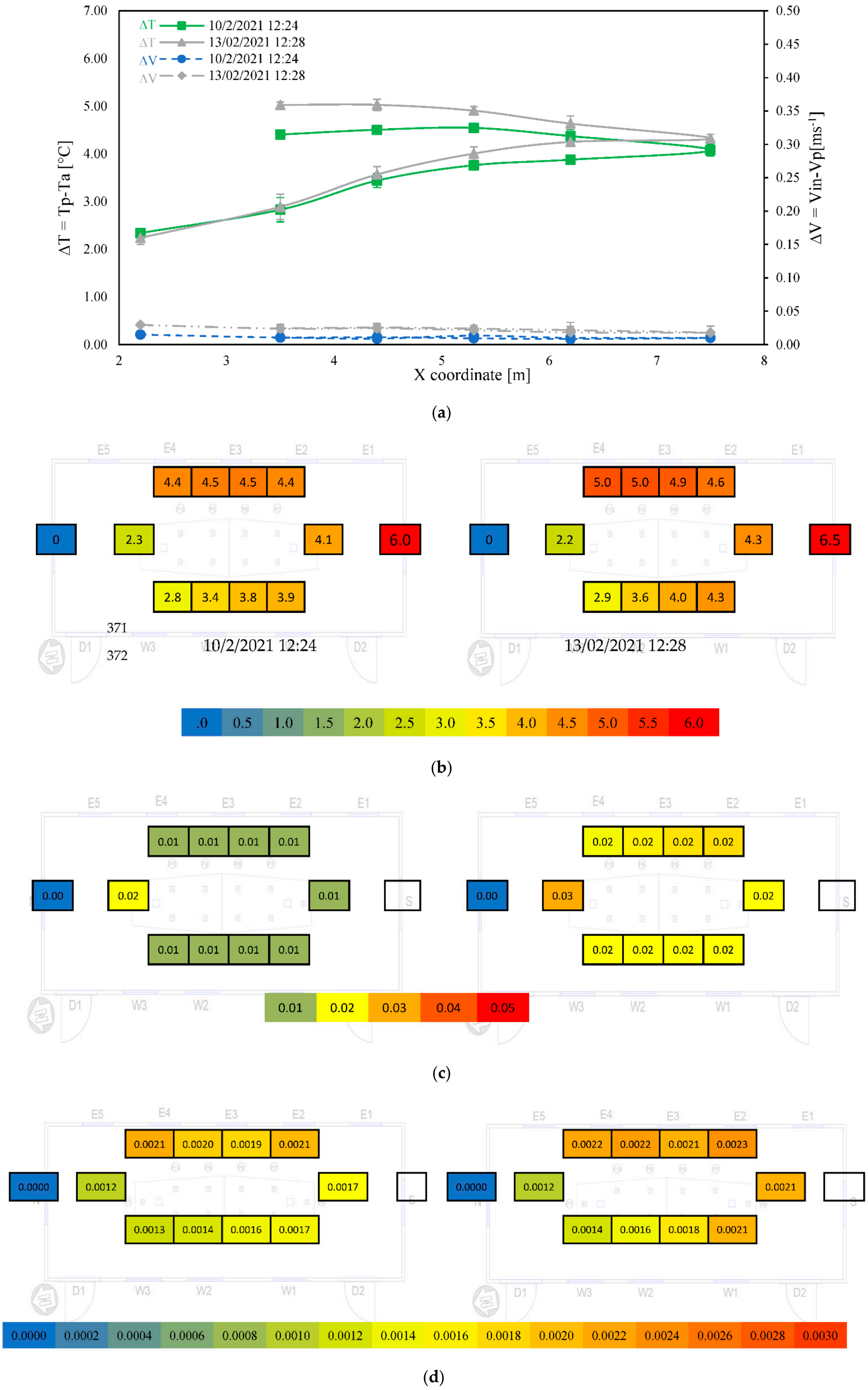


Figure 7. (**a**). Repeated Experiments of Scenario (2) [SSV-N]. (**b**): Temperature difference between locations and inlet ΔT = Tp − Ta [°C] of Scenario (2) [SSV-N]. (**c**): Velocity difference between location and inlet ΔV = Vin − Vp [ms^{-1}] of Scenario (2) [SSV-N]. (**d**): Humidity ratio difference between locations and inlet Δω = ωp − ωi, [KgH2O/Kgdry air] of Scenario (2) [SSV-N].

3.2. Comfort Assessment

For both cross ventilation and single-side ventilation modes during this research, we found the range of prevailing mean outdoor temperature was between 21.8 to 31.6 °C. We concluded that the minimum, average and maximum temperature differences between location and inlet air temperature (ΔT) were 1.8, 3.5 and 5.3 °C, respectively. Shaded cells in Table 3 not complied with 90% acceptability limits of ASHRAE Standard 55. Figure 8a–c indicate that prevailing mean outdoor temperature between 21.8 and 26.8 °C provided the accepted operative temperature inside the studied classroom considering maximum temperature difference (ΔT) of 1.8 °C for maximum prevailing outdoor temperature, so the threshold operative temperature was 28.6 °C inside the studied environment. This conclusion is based on the carried experiments for different manual opening as per the adaptive method, under limitations of inlet airspeed less than 0.2 ms^{-1}, with representing occupant metabolic rate ranging from 1.0 to 1.3 met, while feeling free to adapt their clothing to depend on the results.

3.3. Inlets and Outlets Effect

The comparison between SISO, SIDO, DISO and DIDO ventilation scenarios presented in Figure 9a–d) shows the difference between location and inlet air temperature inversely proportional with the number of air change per hour inside the classroom. The SIDO scenario does not affect temperature difference if compared with the SISO scenario for similar air change, which can be observed if we compared the SISO with ACH equals 1.14 and SIDO with the same ACH as shown in Figure 9a,b. Using the DISO scenario instead of SISO increased the air change, consequently decreasing the temperature difference; in addition, the temperature difference of positions (2) and (3) adjacent to the window (W3) decreased, as shown in Figure 9a,c. The DIDO scenario showed a lower temperature difference than SISO as shown in Figure 9a,d. When the DISO scenario is compared with SISO, SIDO and DIDO ventilation scenarios, it shows the lowest temperature difference at all positions.

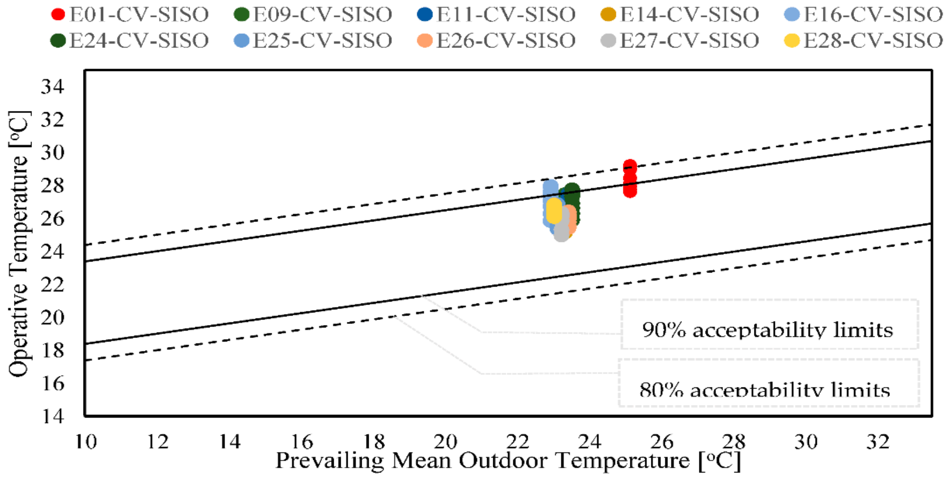
3.4. Occupancy Effect

We studied the relation between operative temperature and inlet air temperature for three modes (1), (2) and (3) at 0%, 50% and 100% of occupancy load. Figure 10 shows the difference between the three modes as expected. We concluded that as much as the occupancy load increased, the temperature difference increased for similar inlet conditions. The record of minimum, average and maximum temperature difference between inlet air and all ten locations showed 1.8, 2.3 and 2.7 °C for 0% occupancy load, 2.6, 3.4 and 4.2 °C for 50% occupancy load, 3.2, 4.2 and 5.1 °C for 100% occupancy load of Scenario (5) [CV-N-W3-S-E1] or [DIDO], while the minimum, average and maximum airspeed difference between inlet airspeed and all ten locations' airspeed showed similar results 0.06, 0.07 and 0.08 ms^{-1}, respectively.

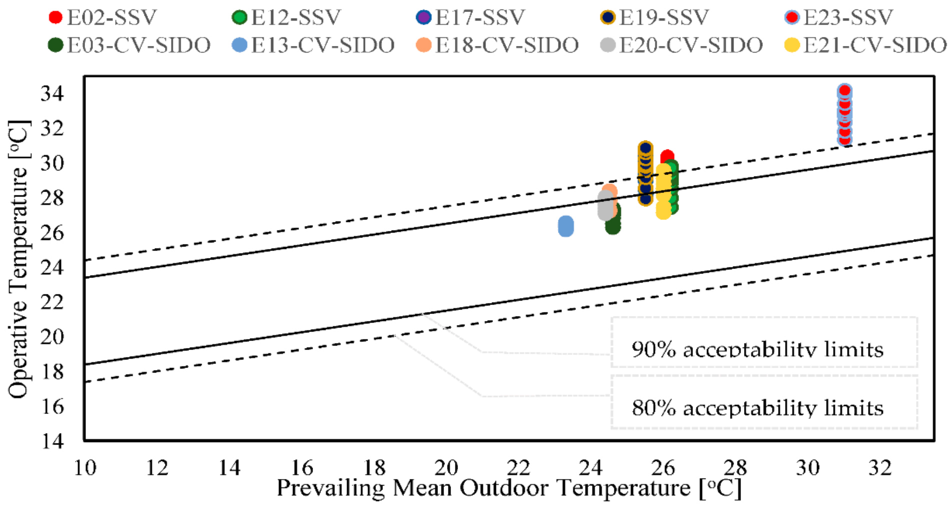
Table 3. Inlet and operative temperatures of carried experiments.

Experiment ^{Mode} Scenario	**E01 ^{CV} SISO**	**E02 ^{SSV} SSV**	**E03 ^{CV} SIDO**	**E04 ^{CV} DISO**	**E05 ^{CV} DIDO**	**E06 ^{CV} DIDO**	**E07 ^{CV} DIDO**	**E08 ^{CV} DIDO**	**E09 ^{CV} SISO**	**E10 ^{CV} DIDO**
Ta	25.1	26.1	24.6	23.5	22.9	22.3	22.3	21.8	23.3	24.3
T_{op} @ P_1	27.6	28.2	26.3	24.3	24.9	24.1	24.4	25.0	25.8	26.5
T_{op} @ P_2	27.9	28.8	26.5	24.4	25.1	23.9	24.5	25.2	26.0	26.4
T_{op} @ P_3	28.1	29.4	26.8	24.5	25.4	23.7	24.6	25.3	26.5	26.8
T_{op} @ P_4	27.7	29.8	27.0	25.0	25.7	23.6	24.7	25.6	26.7	27.1
T_{op} @ P_5	27.9	30.1	27.2	25.5	25.5	23.6	24.9	25.9	26.9	27.3
T_{op} @ P_6	28.4	30.1	27.0	25.8	25.2	24.0	25.1	26.1	27.1	27.4
T_{op} @ P_7	29.0	30.3	27.2	25.9	25.6	24.3	25.5	26.6	27.4	27.7
T_{op} @ P_8	29.2	30.4	27.3	25.6	25.7	24.4	25.9	26.9	27.4	27.9
T_{op} @ P_9	29.2	30.1	27.3	25.5	25.7	24.5	26.0	26.7	27.3	28.0
T_{op} @ P_{10}	29.0	29.8	27.1	25.3	25.0	24.5	26.0	26.6	27.4	27.8
Mode	**E11 ^{CV} SISO**	**E12 ^{SSV} SSV**	**E13 ^{CV} SIDO**	**E14 ^{CV} SISO**	**E15 ^{CV} DIDO**	**E16 ^{CV} SISO**	**E17 SSV**	**E18 ^{CV} SIDO**	**E19 ^{SSV} SSV**	**E20 ^{CV} SIDO**
Ta	23.4	26.2	23.3	23.3	22.5	22.9	25.5	24.5	25.5	24.4
T_{op} @ P_1	25.6	27.4	26.5	25.1	24.7	25.8	28.0	27.2	27.9	27.1
T_{op} @ P_2	25.6	28.0	26.4	25.3	24.9	26.3	28.5	27.3	28.5	27.2
T_{op} @ P_3	25.8	28.5	26.1	25.6	25.2	26.7	29.0	27.8	29.1	27.4
T_{op} @ P_4	26.1	28.8	26.3	26.0	25.3	27.0	29.4	28.3	29.5	27.8
T_{op} @ P_5	26.4	29.1	26.3	26.2	25.3	27.3	29.5	28.3	29.8	27.9
T_{op} @ P_6	26.7	29.2	26.3	26.3	25.5	27.2	29.7	28.4	29.9	28.0
T_{op} @ P_7	27.1	29.3	26.4	26.5	25.6	27.6	30.0	28.4	30.2	27.9
T_{op} @ P_8	27.4	29.6	26.5	26.6	25.6	27.9	30.2	28.2	30.6	27.9
T_{op} @ P_9	27.5	29.8	26.4	26.6	25.7	27.9	30.3	28.3	30.8	27.6
T_{op} @ P_{10}	27.3	29.7	26.4	26.3	25.8	27.9	30.3	27.9	30.8	27.6
Mode	**E21 ^{CV} SIDO**	**E22 ^{CV} DIDO**	**E23 ^{SSV} SSV**	**E24 ^{CV} SISO**	**E25 ^{CV} SISO**	**E26 ^{CV} SISO**	**E27 ^{CV} SISO**	**E28 ^{CV} SISO**		
Ta	26.0	25.6	31.0	23.5	23.1	23.4	23.2	23.0		
T_{op} @ P_1	27.1	28.1	31.3	25.9	25.4	25.4	25.0	26.1		
T_{op} @ P_2	27.4	28.3	31.8	25.9	25.3	25.6	25.3	26.3		
T_{op} @ P_3	28.1	28.5	32.3	26.3	25.7	25.8	25.8	26.5		
T_{op} @ P_4	28.5	29.0	32.7	26.6	26.1	25.9	26.1	26.7		
T_{op} @ P_5	28.5	29.1	32.9	26.9	26.1	26.2	26.3	26.8		
T_{op} @ P_6	28.8	29.2	33.0	27.3	26.3	26.2	26.2	26.8		
T_{op} @ P_7	29.1	29.3	33.4	27.6	26.5	26.4	26.2	26.8		
T_{op} @ P_8	29.4	29.5	33.9	27.7	26.8	26.3	26.1	26.7		
T_{op} @ P_9	29.6	29.4	34.1	27.6	26.8	26.2	25.9	26.6		
T_{op} @ P_{10}	29.3	29.2	34.2	27.4	26.6	26.0	25.9	26.7		

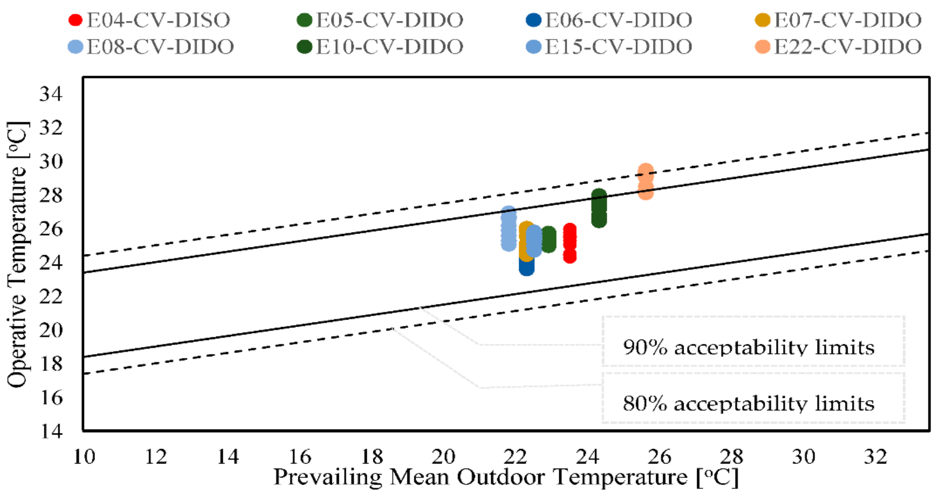
E01–E28	Twenty-eight experiments carried by authors
P_1–P_{10}	Ten Locations monitored in the studied classroom
CV	Cross Ventilation
SSV	Single-Side Ventilation
SISO	Single Inlet Single Outlet
SIDO	Single Inlet double Outlet
DISO	Double Inlet single Outlet
DIDO	Double Inlet double Outlet
T_a	Inlet Air Temperature
T_{op}	Operative Temperature
	Shaded cells not complied with 90% acceptability limits of ASHRAE Standard 55



(**a**)



(**b**)



(**c**)

Figure 8. (**a**). Plotting of SISO ventilation' experiments on adaptive method chart. (**b**). Plotting of SSV and SIDO ventilations' experiments on adaptive method chart. (**c**). Plotting of DISO and DIDO ventilations' experiments on adaptive method chart.

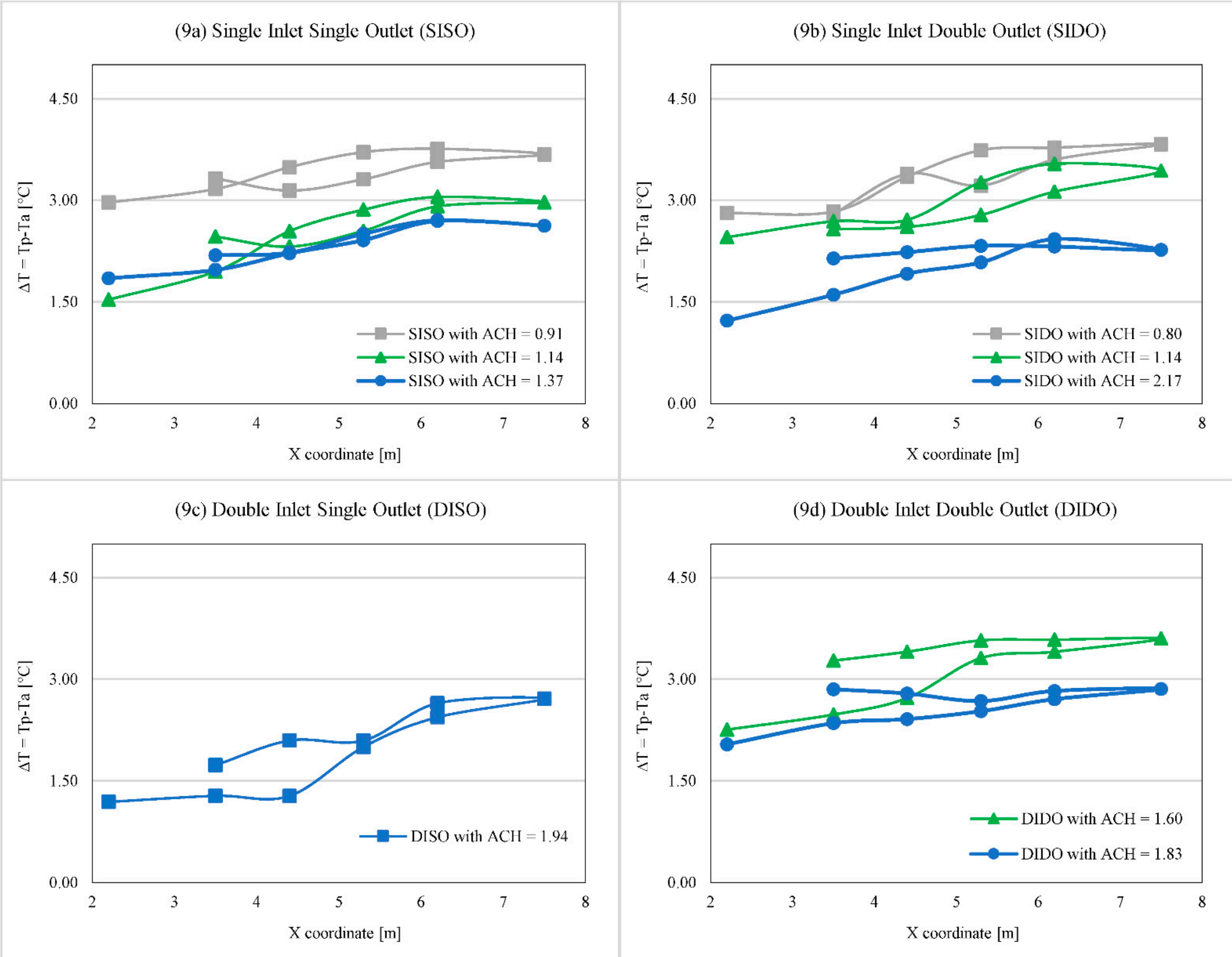


Figure 9. Temperature difference between locations and inlet ΔT = Tp − Ta [°C] for different ACH: (**a**) Scenario (1) [CV-N-S] or [SISO]; (**b**): Scenario (3) [CV-N-S-E1] or [SIDO]; (**c**): Scenario (4) [CV-N-W3-S] or [DISO]; (**d**) Scenario (5) [CV-N-W3-S-E1] or [DIDO].

3.5. Cross Ventilation versus Singe-Side Ventilation Analysis

Figure 11 shows a comparison between temperature and airspeed difference of scenario (1) [CV-N-S] or [SISO] and scenario (2) [SSV-N]. The findings show as much as moving away from the window opening (inlet) the temperature difference increased. The adjacent locations of the inlet opening revealed the lowest temperature and airspeed difference.

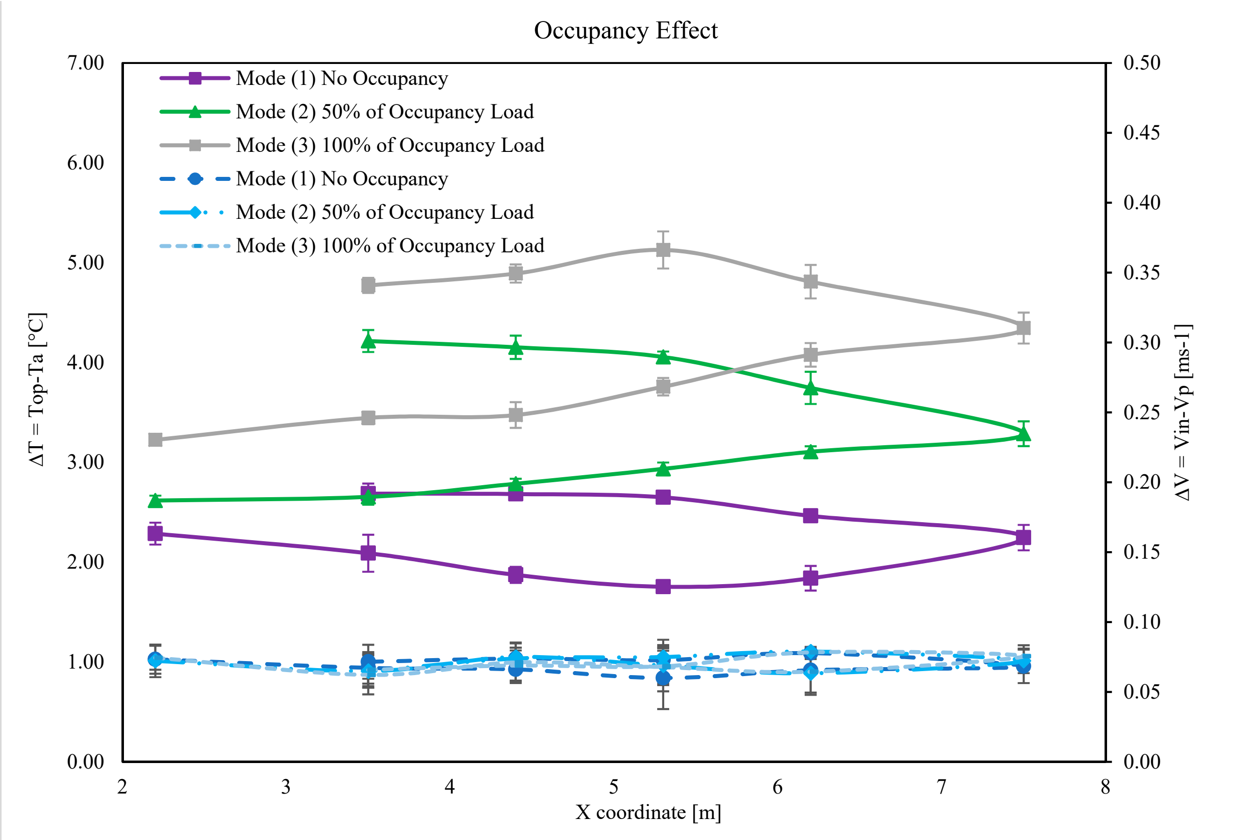


Figure 10. Occupancy Effect of Scenario (5) [CV-N-W3-S-E1] or [DIDO] at 0, 50 and 100% occupancy load.

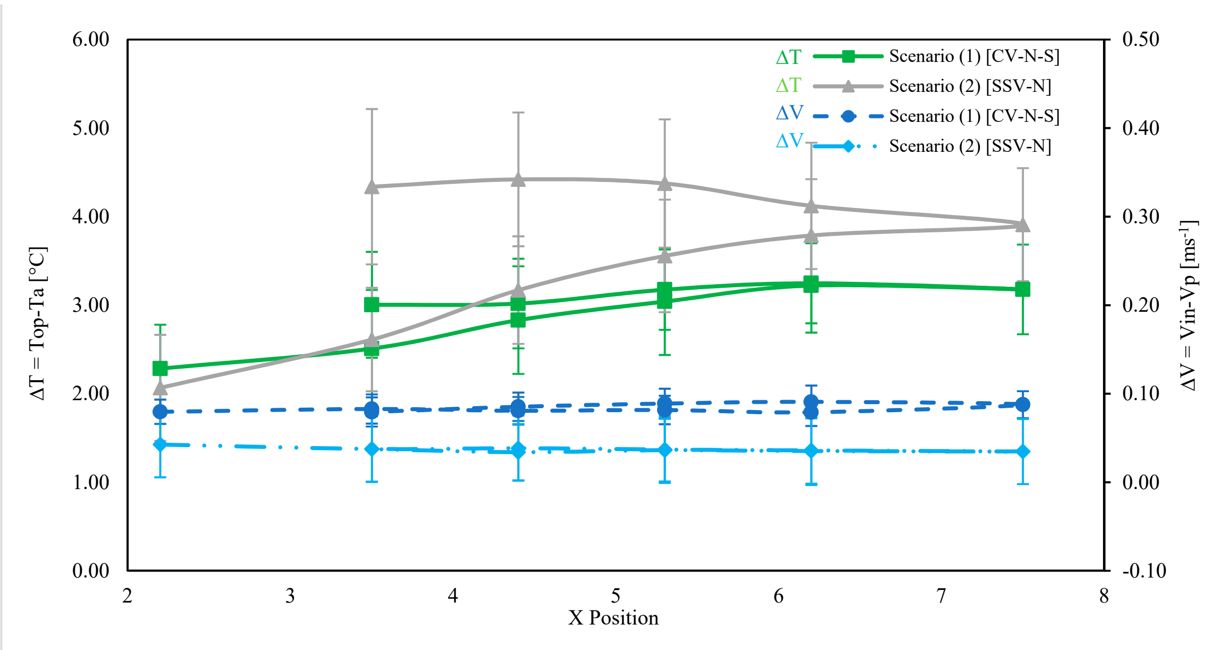


Figure 11. Comparison between cross ventilation and single-side ventilation of Scenario (1) [CV-N-S] and Scenario (2) [SSV-N].

4. Conclusions

In this study, five passive ventilation scenarios were evaluated to indicate the effect of openings on thermal comfort inside an exposed classroom at Gulf University campus, the Kingdom of Bahrain, during the winter season to reduce the dramatic energy consumed in air conditioning systems and released emissions from mechanical equipment. The purpose of this comparison is to draw sustainable solutions that mimic natural ventilation systems and adapted to climatic variation locally and beyond. Hence, we checked the applicability of this gulf climate in winter (or similar) to examine whether it provides acceptable thermal conditions as suggested by the adaptive method. In addition, to quantify the effect of the inlet(s) and outlet(s) on thermal comfort by carrying a comparison between these scenarios namely: single inlet single outlet (SISO), single inlet double outlet (SIDO), double inlet single outlet (DISO), double inlet double outlet (DIDO) and single-side ventilation (SSV). Furthermore, we studied the effect of occupancy load on thermal comfort and eventually compared cross ventilation (CV) and single-side ventilation (SSV). The measured findings are elaborated as follows:

- The repeatability of experiments showed accurate results with an acceptable level of confidence by using the measurement devices of this study, while recording the indoor parameters of dry air temperature, humidity, globe temperature and airspeed for the repeated experiments, either it was cross-ventilation (CV) or single-side ventilation (SSV).
- Single-side ventilation cannot offer thermal comfort except at high airspeed (ACH > 1.14), while comfort is attained by cross-ventilation at ambient outdoor temperature ranged between 21.8 °C to 26.8 °C, considering the maximum temperature difference of 1.8 °C for maximum prevailing outdoor temperature when the inlet airspeed less than 0.2 ms^{-1}.
- The increase in inlet temperature for measured locations ranged between 1.8–5.3 °C.
- The difference between monitored locations and inlet air temperature is inversely proportional to the number of air change per hour inside the classroom.
- The double inlet single outlet "DISO" scenario achieves the lowest temperature difference compared with the other scenarios at the same ACH.
- The difference between location and inlet air temperature is directly proportional to occupancy load.
- Using cross-ventilation instead of single-side ventilation reduces the temperature differences in all locations between 0.5 to 2.5 °C. Cross ventilation increases the entrained air causing the airspeed for all locations to increase up to three folds.
- On the extent of saving energy consumed inside mechanically ventilated buildings, it is recommended to depend on the passive ventilation either it is cross ventilation or single-sided mode. The measured findings indicate up to 85% of climate outdoor conditions provide full and partial thermal satisfaction for occupants, while 15% offer dissatisfaction due to the low airspeed associated with occupants are free to adapt their clothing.

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