Pertanika J. Sci. & Technol. 32 (1): 45 - 66 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Effect of Natural Ventilation on Thermal Performance of Different Residential Building Forms in the Hot-dry Climate of Jordan

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ABSTRACT

This work presents a simulation study on the impact of natural ventilation on the thermal performance and thermal comfort of residential buildings of different forms in the hot-dry climate of Amman, the capital of Jordan. Three existing triple-storey residential buildings with different forms, i.e., rectangular, L-shape, and U-shape, are taken as case studies. Models with similar construction and dimensions of the buildings under investigation are designed using the OpenStudio plugin SketchUp software. Two rooms within these buildings have been considered for simulation with the aid of the EnergyPlus simulator for two cases: the basic case with no ventilation and the case with ventilation. The thermal parameters, including the air temperature, relative humidity, air speed, and mean radiant temperature of both rooms, have been extracted from the simulation. The thermal performance of these buildings is analyzed based on the indoor air temperature and mean radiant temperature, while the thermal performance is investigated via the ASHRAE-55 adaptive model. The results show that the rectangular-shaped building has the best thermal performance in unventilated conditions for the middle room on the middle floor (Room 1). In contrast, the U-shape shows better results for the west-northern room on the same floor (Room 2). On the other hand, introducing natural ventilation to the buildings reduces the indoor temperature and, subsequently, enhances the thermal performance where the buildings transform to be within the comfort zone most of the time, according to the ASHRAE-55 adaptive model. Generally, rectangular and U-shaped buildings show comparable thermal performance, while L-shaped buildings have relatively the worst performance.

Keywords: Adaptive model, ASHRAE-55, building shape, EnergyPlus simulator, ventilation

ARTICLE INFO

Article history:
Received: 09 November 2022
Accepted: 10 May 2023
Published: 06 November 2023

DOI: https://doi.org/10.47836/pjst.32.1.03

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ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

The global increase in the energy required for human life activities, especially for the building sector, consumes around 40% of the total energy worldwide. The high cost of energy production causes a big issue for communities' development (Yu et al., 2020). The residential building sector in Jordan consumes about 24% of total energy (Almuhtady et al., 2019). The large energy consumption of the residential sector in Jordan refers to the high usage of cooling systems for hot climates in summer and heating strategies for cold weather in winter. Applying passive design approaches reduces the demands of cooling and heating loads in buildings and improves their thermal performance (Ozarisoy, 2022; Elnagar & Köhler, 2020). Many effective passive approaches, such as building form, natural ventilation, and orientation, are usually considered for buildings.

Building form and its geometrical configuration directly affect energy consumption and thermal performance by enhancing the indoor climate (Lapisa, 2019; Raof, 2017). The building shape determines the percentage of exposed surface area for the building's envelope to the outdoor ambient, indicating the amount of solar radiation the building is exposed to. Minimizing the contact area for the building with the outdoor environment can be achieved by selecting a suitable shape at the early design stage, subsequently improving the thermal comfort level (Mushtaha & Helmy, 2017). A study of different shapes of traditional residential buildings in a hot-dry climate in Diyarbakır, Turkey, showed that the building form significantly impacts indoor thermal comfort and energy consumption. A courtyard in a U-shaped building can decrease 79% of cooling loads and 63% of heating loads (Kocagil & Oral, 2015). A numerical study found that the compact form greatly decreases the energy demands for cooling in a desert area (Bekkouche et al., 2013; Deng et al., 2020). Lapisa (2019) studied the influence of two building forms in different climates, i.e., tropical, Mediterranean, and Oceanic. The results show that the square building form decreases energy consumption compared to the rectangular building form for all climates in his study due to compactness. Moreover, Ali et al. (2010) presented a general study of some buildings which are built between (1900-2000) in Karak (desert climate) and Irbid (mountainous climate), where both cities are in Jordan. It shows that the rectangular form suits desert district buildings in winter, while the compact shape is more suitable in summer.

Natural ventilation enhances the thermal performance of buildings by improving the air quality for the indoor climate in the summer season, especially at nighttime since it is pulling fresh air into the indoor zones, which leads to driving hot air to move out through openings (Raji et al., 2020; Almeida et al., 2017). This process occurs because of two mechanisms: the natural movement of outdoor air around the building and the buoyancy generated due to the difference in air temperature indoors and outdoors of the building. Therefore, the designer should consider these mechanisms during the earlier building design stage to obtain maximum natural ventilation (Krarti, 2018). It is also found that the location of openings has a higher effect on natural ventilation efficiency scales than building orientation (Rodrigues et al., 2019; Yang et al., 2019). Besides, natural ventilation presents a healthy environment for residents and gives a satisfactory feeling, which raises their productivity and grants attractive results compared to mechanical methods (Nagy et al., 2019). For instance, Sick Building Syndrome (SBS) symptoms of infected occupants due to exposure to indoor air pollutants are higher for HVAC used by 30%–200% compared to natural ventilation (Chen et al., 2021).

Despite the importance of natural ventilation in improving indoor thermal performance, few studies explored its impact on thermal performance in different countries with a climate the same as Jordan's in summer. Al-Hemiddi and Al-Saud (2001) studied the impact of the natural ventilation in a courtyard house on internal thermal performance in a hot-aired climate in Riyadh, Saudi Arabia; they found that the cross ventilation through the courtyard contains a water pool can reduce the indoor air temperature by 5°C. Mastouri et al. (2019) examined the influence of night ventilation in a double-story house in a hot semi-arid climate in Marrakech, Morocco. They concluded that night ventilation gives high-efficiency results by reducing the ground floor temperature by 2°C and the first floor by 3°C. In addition, it can reduce the annual cooling loads by 27%. Only one study considers the impact of natural ventilation on thermal performance in Jordan, as Ma'bdeh et al. (2020) reported. They investigated the effect of introducing a wind tower, once at the north facade and another at the south facade, on interior thermal performance for a classroom in a building located at Jordan University for Science and Technology (JUST) in Irbid in the summer and winter. The results show that the wind tower improves indoor air efficiency in both cases, whereas the highest number of comfort hours is obtained when the tower is built on the southern side of the building. Therefore, the influence of natural ventilation and the impact of building form in Jordan on thermal performance needs to be investigated further. In this work, a simulation study using EnergyPlus software with the aid of the ASHRAE-55 adaptive model presents the impact of different building forms, i.e., rectangular, L-shaped, and U-shaped, in collaboration with the natural ventilation on the thermal performance and thermal comfort for existing residential buildings in the hot-dry climate in Jordan.

Climate Conditions and Case Studies

Jordan lies between latitude 29°–32° north and longitude 35°–38.5° east. The climate in Jordan is mostly Mediterranean type, with cold-wet winter and hot-dry summer (Nazer, 2019). Amman, the capital of Jordan, is considered a mountain area, and it has hot-dry weather in summer with an average air temperature of 8°C–25.1°C. The highest temperature reaches in summer is 39°C in July. It has cold-rainy weather in winter, with air temperature reaching 0°C or less in January. This research will focus on the summer season (hot-dry).

Table 1 shows the monthly average temperature during the summer season. The summer wind characteristics in Amman from June to August are shown in Figure 1. It can be noticed that the wind has different speed values and directions, but mostly during the day, it has a speed of 3.3-5.5 m/s toward the west with a frequency of 11.96%, 5.5–7.9 m/s to the west with a frequency of 9.28% and 5.5–7.9 m/s with north-west direction at a frequency of 7.79%.

This work has taken three different residential building forms, i.e., rectangular, L-shape, and U-shape, located in Amman, as case studies. The selection of these buildings is based on a field survey study for the building forms at the southern side of Alqwesmeh district, where the buildings are located, in Amman, to estimate the percentage of building forms within this area. Figure 2(a) shows a satellite view of the survey area that contains 123 buildings. Figure 2(b) illustrates a solid and void analysis of the survey area. Figure 2(b) shows that the dominant building forms in this area are rectangular buildings, with a percentage of 69.1%, followed by the L-shape, 11.38%, and the U-shape, 7.31%. Additionally, it is found that other forms of

Table 1
Monthly temperature average in the summer season in Amman, Jordan

Month	Min (°C)	Max (°C)
June	10.8	36.0
July	14.0	39.8
August	13.8	37.0

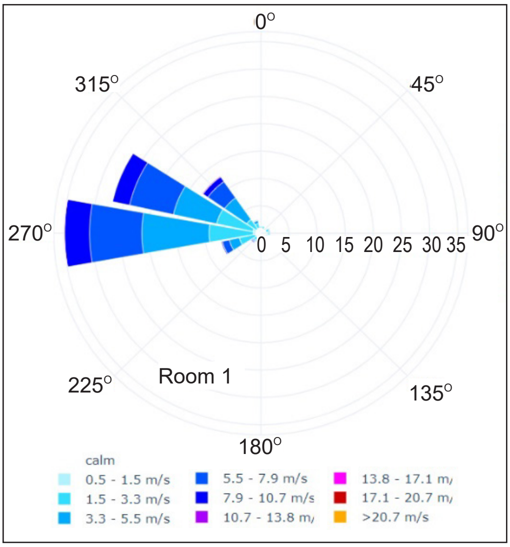
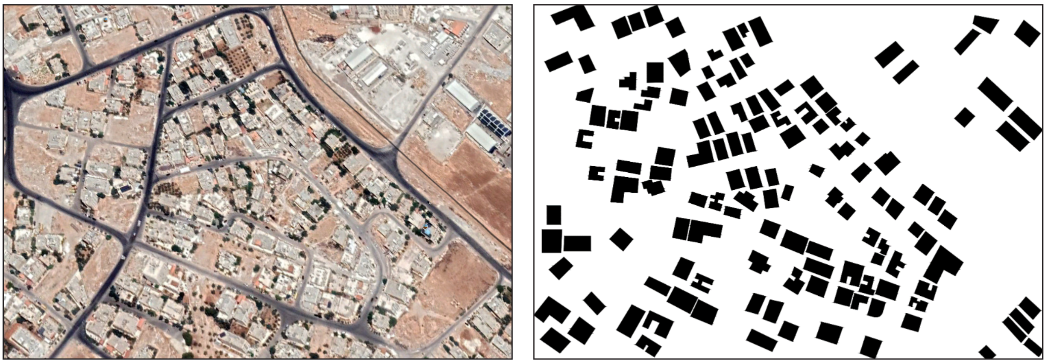


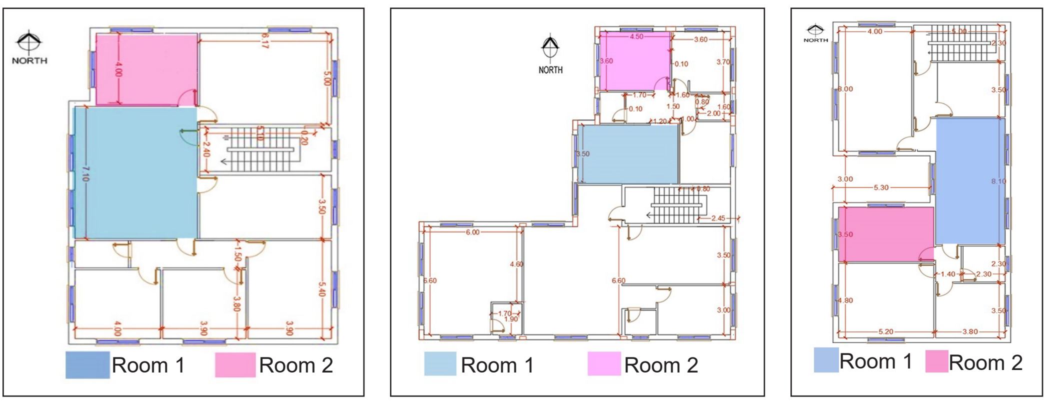
Figure 1. The wind rose from June to August for 24 hours (Betti et al., 2021)



(a) (b)

Figure 2. (a) Satellite view and (b) solid and void analysis for field survey study area at southern of Alqwesmeh district in Amman

buildings represent only 12.19%. The selected buildings have the same construction system and consist of three floors to ensure the study's accuracy. Only two rooms on the middle floor of each building are selected to investigate the effect of building shape on thermal performance by analyzing the thermal parameters (airspeed, air temperature, mean radiant temperature, and relative humidity) with and without natural ventilation. Figure 3 shows the plan of the middle floor of the buildings, where the studied rooms are named Room 1, which has only a west window, and Room 2, which has west and north windows. Figure 4 shows the main facade of the buildings directed toward the west.



(a) (b) (c)

Figure 3. Plans for residential buildings with different forms studied: (a) Rectangular; (b) L-shape; and (c) U-shape

(a) (b) (c)

Figure 4. The main facades of the studied buildings: (a) Rectangular; (b) L-shape; and (c) U-shape

METHODS

Simulation Validation

EnergyPlus is one of the most extensive simulation software validated and used for building energy and thermal performance by the research community (Muslim, 2021; González et al., 2020). It is essentially the accumulation of 65 years of experience by the US Department of Energy (DOE). It has been tested and validated under the comparative Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs BESTEST/ ASHRAE Standard 140.

A model for the rectangular building is designed to ensure the validity of EnergyPlus software in this work. The details of the design and simulation are furnished in the coming subsection. Then, a site measurement for the indoor air temperature, globe temperature, and relative humidity, under the basic conditions without ventilation (where all windows are closed, and no mechanical ventilation is used) for Room 1 in the rectangular building on 21 July. This date is selected as the design day in the current study since it represents an extreme summer day in Jordan, according to the climatic data from ASHRAE (2009). The indoor air temperature, globe temperature, and relative humidity are measured using the WBGT HI meter, which has a temperature accuracy of 0.1°C and a humidity resolution of 0.1 RH. The air velocity is measured via a high-accuracy digitally certified ST6816 anemometer with a resolution of 0.01 m/s. Figure 5 illustrates the experimental set-up of devices during the measurement. The results for site measurement are compared with the simulated results on the design day and tabulated in Table 2. The table shows that the simulated results are very close to the measured values, which confirms that the EnergyPlus simulator is valid in this work.

Figure 5. Experimental set-up during data collection

Table 2
Comparison between measured and simulated results for simulator validation

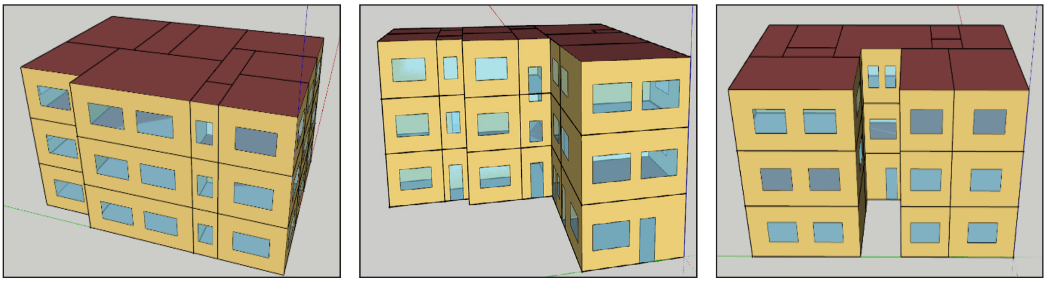
Time (H)	Measured temperature (°C)	Simulated temperature (°C)	Measured mean radiant temperature (°C)	Simulated mean radiant temperature (°C)	Measured relative humidity (%)	Simulated relative humidity (%)
1:00	32.30	32.88	33.06	33.91	35.15	35.53
2:00	32.00	32.19	33.40	33.32	36.14	36.18
3:00	31.89	31.61	33.30	32.75	36.12	36.80
4:00	31.15	31.08	32.60	32.24	37.25	37.88
5:00	30.94	30.82	32.10	31.76	37.84	38.64
6:00	30.91	30.85	31.80	31.45	39.66	39.79
7:00	31.21	30.98	31.90	31.33	41.07	41.80
8:00	31.25	31.28	31.60	31.39	42.63	42.51
9:00	31.33	31.36	31.80	31.55	43.52	42.48
10:00	31.40	31.55	31.90	31.69	43.50	42.10

Table 2 *(continue)*

Time (H)	Measured temperature (°C)	Simulated temperature (°C)	Measured mean radiant temperature (°C)	Simulated mean radiant temperature (°C)	Measured relative humidity (%)	Simulated relative humidity (%)
11:00	31.59	31.97	31.80	31.87	42.12	40.63
12:00	31.68	32.32	31.70	32.06	41.32	38.63
13:00	32.05	32.78	32.10	32.57	38.54	35.75
14:00	33.00	33.65	33.20	33.59	36.72	33.11
15:00	34.23	34.81	34.60	34.87	33.38	31.57
16:00	35.27	36.12	35.40	35.98	31.22	30.43
17:00	36.20	37.23	35.80	36.53	30.80	29.30
18:00	36.60	37.55	35.70	36.33	32.67	29.50
19:00	36.30	37.18	35.20	35.78	33.57	31.85
20:00	35.47	36.87	34.30	35.38	35.45	33.36
21:00	35.00	36.48	33.90	35.09	38.03	34.02
22:00	33.84	35.35	33.50	34.68	38.38	37.08
23:00	32.38	33.93	32.90	34.17	41.45	40.18
24:00	31.71	32.82	32.80	33.60	42.19	41.67

Simulation Procedures

Using AutoCAD, the simulation for the buildings under investigation starts with drawing two-dimensional plans for three residential buildings, i.e., rectangular, L-shaped, and U-shaped. Three-dimensional models of the buildings have been built using the OpenStudio plugin SketchUp software, as shown in Figure 6. The existing buildings' models are constructed with three layers: a 3cm-thick stone block, 10cm-thick concrete, and a 10cm-thick hollow block. After that, the loads for the electrical equipment, people, and lights are calculated and included in the simulation. The load definitions used in the simulation are summarized in Table 3. Here, every building room is set as a thermal zone to evaluate each room's internal thermal performance individually. The weather file for Amman in



(a) (b) (c)

Figure 6. 3D building drawings using SketchUp Plugin OpenStudio: (a) Rectangular; (b) L-shape; and (c) U-shape

Table 3
Loads definition for the current work

Definition	People	Lighting	Electrical equipment
Loads	6 persons	12 w/m^2	Living room: 190 w Bedroom: 80 w Kitchen: 6010 w

EPW format is uploaded to the simulator to set the climatic parameters. In addition, the summer design day is set as 21 July 2022 and is imported in DDY format. Then, the output variables, particularly the air speed, air temperature, mean radiant temperature, and relative humidity, are measured every 15 minutes. The four readings taken per hour are averaged for high-accuracy measurement. The overall protocol for the simulation in this work is depicted in Figure 7. The thermal parameters for each building are analyzed for the unventilated case, as all openings of the middle floor are closed, and compared with output parameters for the naturally ventilated situation, as all openings of the same floor are opened. Finally, the thermal parameters for the buildings are used to analyze the results through the ASHRAE-55 adaptive model to find the comfort hours during the day.

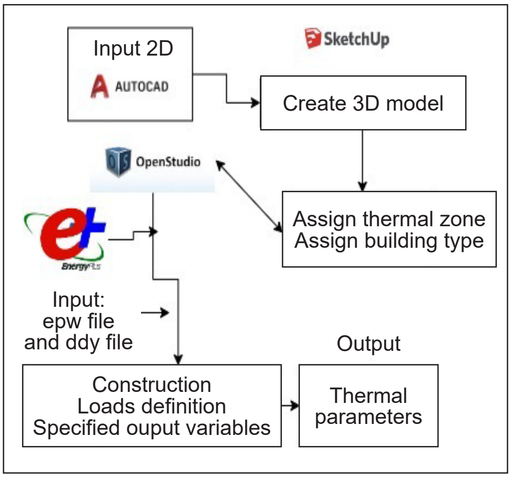


Figure 7. Summary of the simulation protocol

RESULTS AND ANALYSIS

Thermal Performance

Figure 8 shows the indoor air temperature comparison for the unventilated situation for the three buildings, while all openings are closed for Room 1 and Room 2. From Figure 8(a), the rectangular building has a better result in the daytime from 7:00 a.m. until 5:00 p.m., which is correlated to the compact rectangular shape; thus, it has less exposed surfaces' area to direct solar radiation. The U-shape building shows a minimum air temperature after 5:00 p.m. since it creates self-shading that blocks the direct solar radiation at the peak time for the west façade at 5:00 p.m., which reduces the heat stored inside the building during nighttime. However, the U-shape building shows the worst result between 7:00 a.m. and 5:00 p.m. since Room 1 has an additional east window that allows the solar heat to enter from early morning into the building and be stored inside. The L-shape building shows the highest indoor air temperature most of the time among the other buildings, except for the

U-shape between 7:00 a.m. to 5:00 p.m., since it has a larger surface/volume ratio compared to the rectangular, as can be seen in Table 4, and less self-shading effective compared to U-shape case. It is reported that increasing the surface/volume ratio increases solar radiation exposure while self-shading for buildings enhances thermal parameters value (Muhaisen & Abed, 2015; Mohsenzadeh et al., 2021). An almost similar trend for the mean radiant temperature for Room 1 is observed, as shown in Figure 9(a).

Figure 8(b) shows that for Room 2, the L-shape shows the highest indoor air temperature, followed by the U-shape and then the rectangular one. It can be explained using the same theory discussed in Figure 8(a), where the L-shape building has a high surface-to-volume ratio while the U-shape has self-shading, which reduces direct solar radiation. Figure 8 shows that Room 1 is hotter than Room 2 for the unventilated situation because Room 2 has two windows at the north and west facade, as shown in Figure 2. The northern window is not exposed to direct sun during daytime; thus, the outdoor temperature from the north facade is expected to be lower than the indoor temperature for Room 2. This temperature gradient may cause some loss through window glass from the room toward the outside. A similar trend for the mean radiant temperature for Room 2 is also observed, as shown in Figure 9(b).

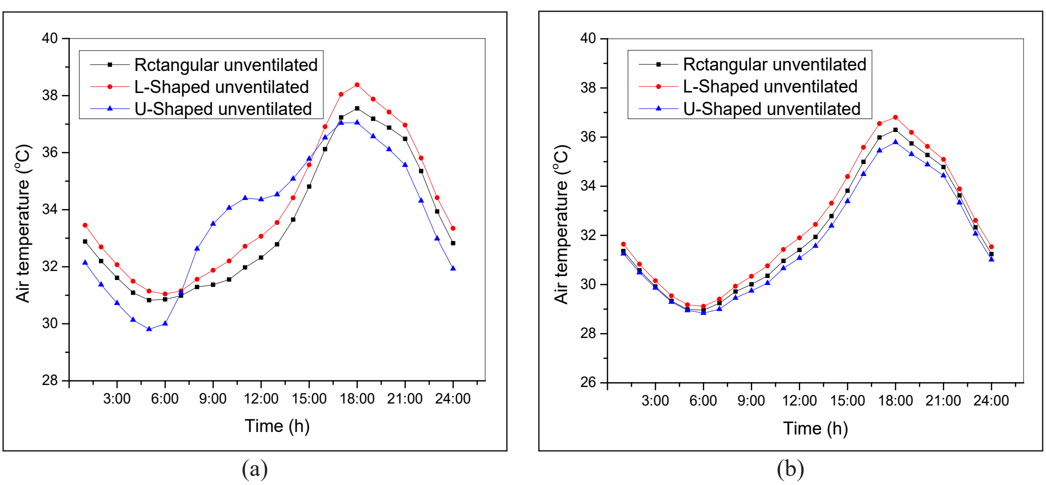
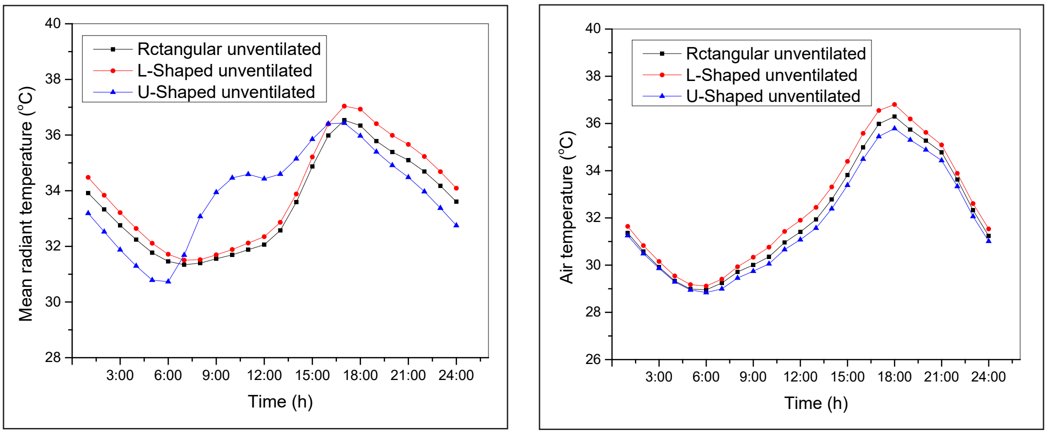


Figure 8. Air temperature comparison for the unventilated situation of different building shapes: (a) Room 1; and (b) Room 2

Table 4
Shape parameters for the buildings in the study

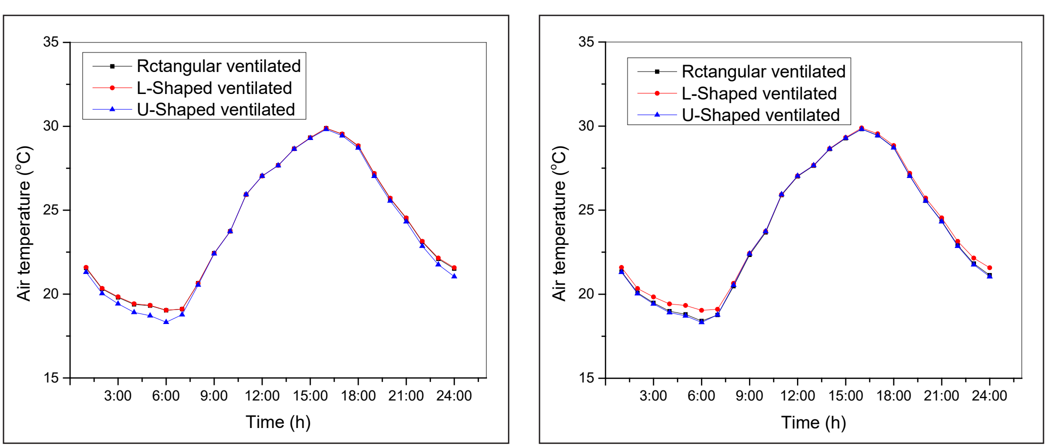
	Rectangle	L-shape	U-shape
Surface area	576.00 m^2	668.23 m^2	582.38 m^2
Volume	604.80 m^3	666.51 m^3	552.99 m^3
S/V ratio	0.9524	1.0025	1.0531



(a) (b)

Figure 9. Mean radiant temperature comparison for the unventilated situation of different building shapes: (a) Room 1; and (b) Room 2

Figure 10 shows the indoor air temperature for the ventilated case while all windows are opened. Comparable to the unventilated case, the results show a considerable drop in indoor air temperature by almost 10°C at nighttime due to the cold outdoor climate. In comparison, it reduces by 4–8°C during the daytime. Table 5 summarizes the results of the optimum reduction in the indoor air temperature for both rooms in all building forms for the ventilation case compared to the unventilated case. This drop is attributed to the natural ventilation through the buildings that leads to renewed air and discharges the heat, which enhances indoor air quality (Hughes et al., 2012). Similar results for indoor temperature drop are reported by Yu et al. (2018), Al-Hemiddi and Al-Saud (2001), and Ma'bdeh et al. (2020). From Figure 10(a), one can notice that Room 1 in the U-shaped building shows the lowest temperature at night compared to other forms.



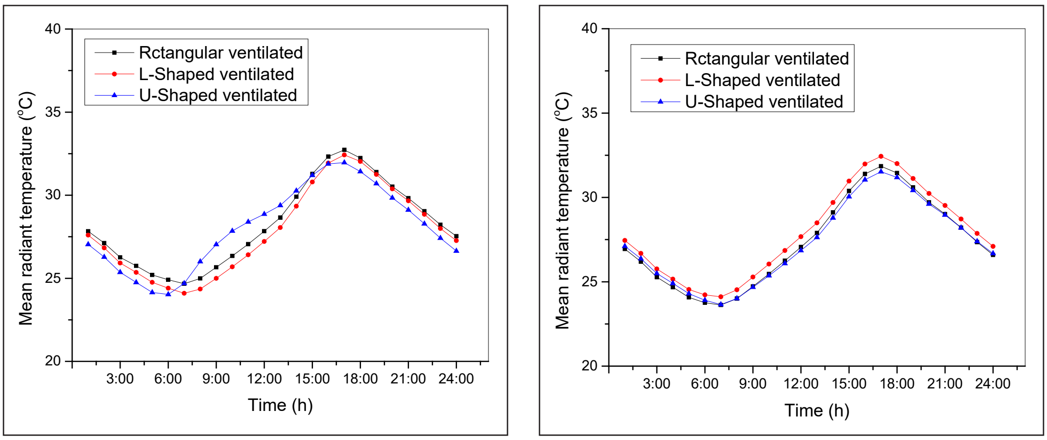
(a) (b)

Figure 10. Air temperature comparison for different ventilated building shapes for: (a) Room 1; and (b) Room 2

Table 5
Average air temperature reduction after natural ventilation compared to the basic situation

Rectangular Shape		L-Shape		U-Shape	
Room 1	Room 2	Room 1	Room 2	Room 1	Room 2
4.99–12.24°C	4.14–10.71°C	5.70–12.60°C	4.79–10.97°C	6.43–12.31°C	3.76–10.42°C

Furthermore, from Figure 10 (b), one can notice that Room 2 in the L-shaped building shows a slightly higher temperature at nighttime than other buildings. Since the air temperature does not differ much between the buildings throughout the day, the mean radiant temperature has been plotted for Room 1 and Room 2, as shown in Figure 11. The results show good agreement with the discussion for air temperature variation with more details for the temperature throughout the day. For Room 1 in Figure 11(a), the U-shaped building shows a higher temperature from 7:00 a.m. to 5:00 p.m., possibly due to the east window's exposure to solar radiation; obviously, a higher difference is observed during early morning hours. From Figure 11(b), the L-shape building shows the highest temperature all day long for room Room 2, while the U-shaped building still has the lowest temperature most of the time among all buildings because of the self-shading effect.



(a) (b)

Figure 11. Mean radiant temperature comparison for the ventilated situation of different building shapes: (a) Room 1; and (b) Room 2

Thermal Comfort

ASHRAE-55 adaptive model is a widely certified standard to evaluate thermal comfort, where there are continual revisions and updates for standard documents that mirror the latest results regarding thermal comfort zones from field experiments. ASHRAE-55 (2020) is the newest version after a long line of editions and publications from 1966 until the previous version, ASHRAE (2017). The newest version of the adaptive model shows a graphical method for Occupant-Controlled Naturally ventilated spaces, representing the operative temperature versus the adopted prevailing mean outdoor air temperature, as shown in Figure 12(a). The prevailing mean outdoor air temperature is the arithmetic average of daily outdoor temperatures. It is usually evaluated not less than seven days and not more than 30 days before the day under investigation, and it is given by Equation 1 (Kim et al., 2019; Saif et al., 2021):

$$\overline{t_{pma\,(out)}} = (1-\alpha)\left[t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^2 t_{e(d-3)} + \alpha^3 t_{e(d-4)} + \cdots\right] \quad [1]$$

where α is an exponential constant, its value ranging from 0 to 1, and the recommended value for α is 0.8, $t_{e(d-1)}$ is the mean external air temperature for the previous day, $t_{e(d-2)}$ is the mean external air temperature for the previous 2 days.

The upper and lower limits for 80% acceptability limit and 90% acceptability limit for comfort area usually follow Equations 2 to 5 (Saif et al., 2021).

The upper limit of 90% acceptability:

$$= 0.31 \times \overline{t_{pma\,(out)}} + 20.3\ [°C]\ (10 \le \overline{t_{pma\,(out)}} \le 33.5) \quad [2]$$

The lower limit of 90% acceptability:

$$= 0.31 \times \overline{t_{pma\,(out)}} + 15.3\ [°C]\ (10 \le \overline{t_{pma\,(out)}} \le 33.5) \quad [3]$$

The upper limit of 80% acceptability:

$$= 0.31 \times \overline{t_{pma\,(out)}} + 21.3\ [°C]\ (10 \le \overline{t_{pma\,(out)}} \le 33.5) \quad [4]$$

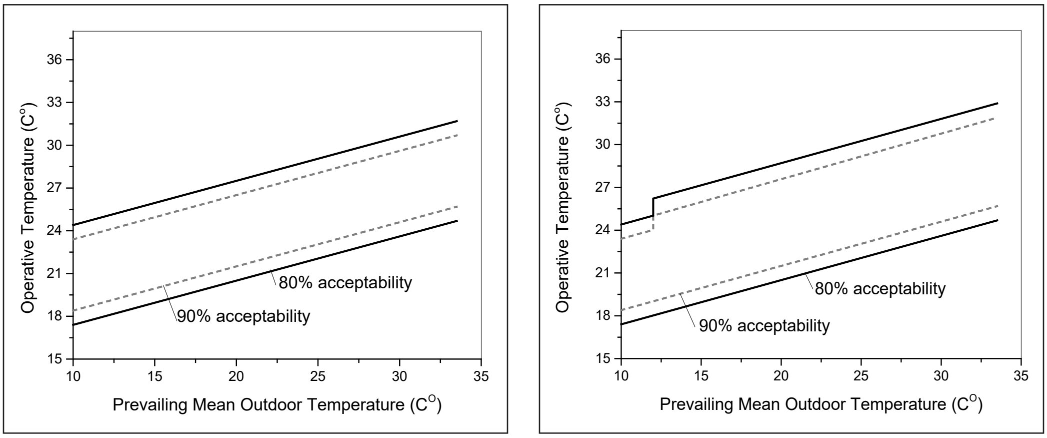
The lower limit of 80% acceptability:

$$= 0.31 \times \overline{t_{pma\,(out)}} + 14.3\ [°C]\ (10 \le \overline{t_{pma\,(out)}} \le 33.5) \quad [5]$$

where $t_{pma\,(out)}$ is the prevailing mean outdoor air temperature.

The increment in the average air speed increases the operative temperature, which widens the upper limit of the thermal comfort zone, as shown in Figure 12(b) (ASHRAE, 2017; ASHRAE, 2020; Bienvenido-Huertas et al., 2022). For example, as the average air speed increases from 0.3 m/s to 0.6 m/s, the operative temperature increases by 1.2°C, as the average air speed becomes 0.9 m/s, the operative temperature increases by 1.8°C, and when the average air speed reaches 1.2 m/s, the operative temperature increases by 2.2°C (ASHRAE, 2017; ASHRAE, 2020).

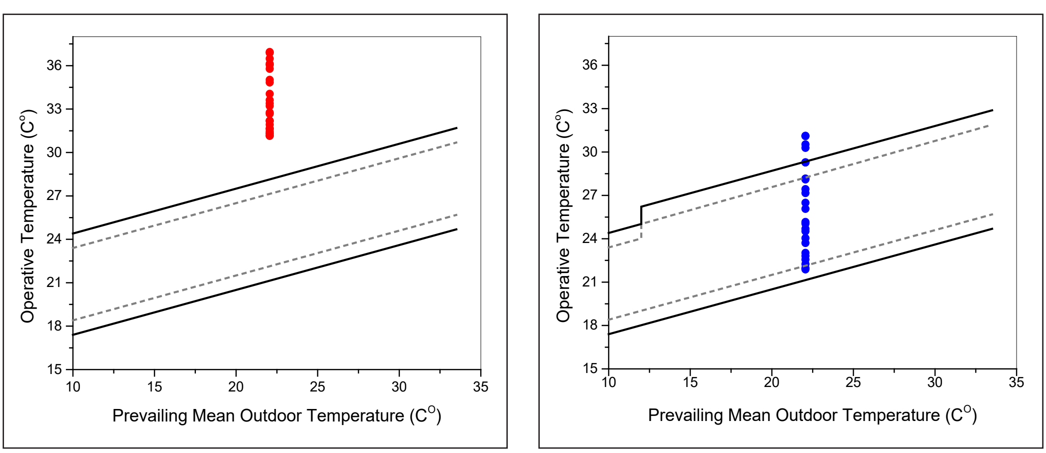
In order to find out the comfort zone for the rooms in all building forms, the adaptive comfort graphs have been plotted using the CBE thermal comfort tool, in which the air temperature, relative humidity, mean radiant temperature, average air speed, prevailing mean outdoor air temperature, metabolic rate, and clothing parameters are inserted to the tool for each hour individually. The metabolic rate is set as 1.2 met, and clothing is set as



(a) (b)

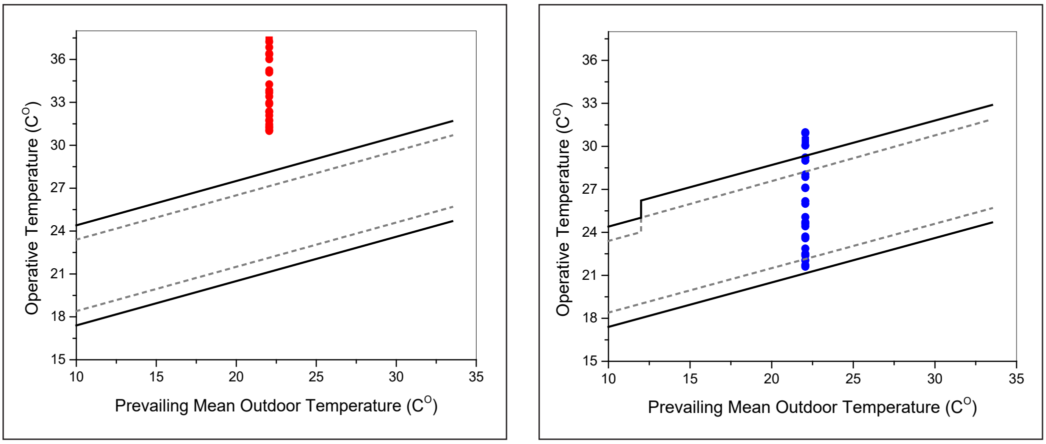
Figure 12. Modulation of the upper limit for thermal comfort zone according to the criteria established by ASHRAE-55: (a) Average air speed 0.3 m/s; and (b) average air speed 0.6 m/s

0.5 clo. Figures 13, 14, and 15 show the ASHRAE-55 adaptive models for Room 1 in all building forms with and without natural ventilation. The results show that Room 1, under basic conditions in all building forms, is out of thermal comfort zones, i.e., 80% and 90% acceptability. However, in the ventilation case, it can be noticed that a notable shift of most of the day hours to be within the comfort zone; the same observation is reported by Heracleous and Michael (2018) and Kumar et al. (2018). Room 1 in the rectangular shape building recorded 66.67% of the total hours during the day within 90% acceptability, while 16.67% of the total time within 80% acceptability and 16.67% of the day hours still within the uncomfortable status, specifically, the non-acceptable time is recorded between



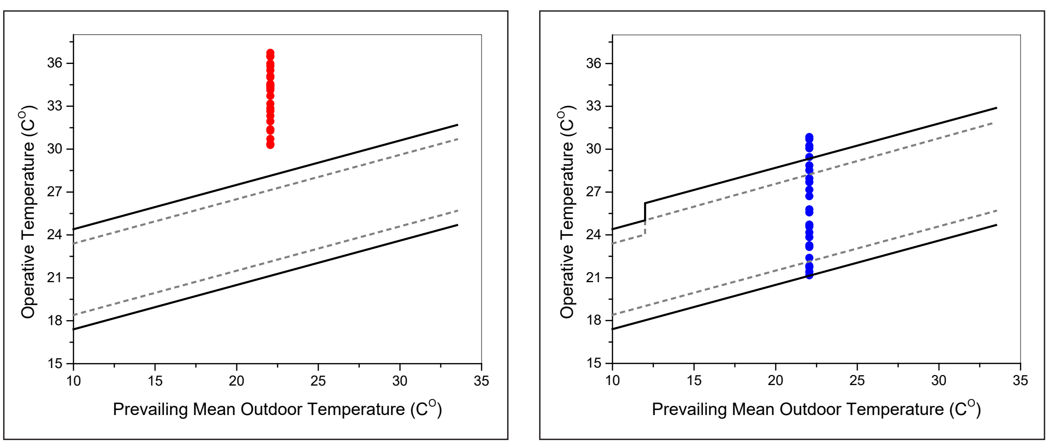
(a) (b)

Figure 13. ASHRAE-55 adaptive model: (a) Unventilated; and (b) ventilated situation for Room 1 in the rectangular building



(a) (b)

Figure 14. ASHRAE-55 adaptive model: (a) unventilated; and (b) ventilated situation for Room 1 in the L-shape building



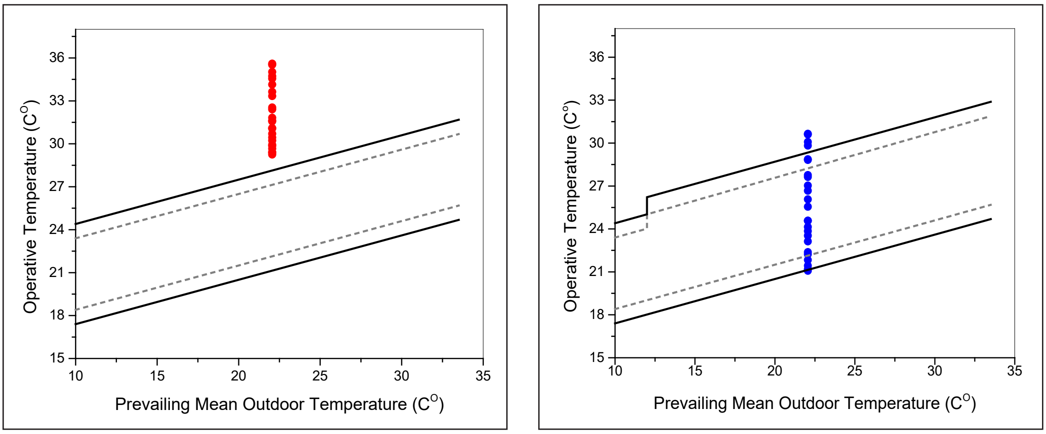
(a) (b)

Figure 15. ASHRAE-55 adaptive model: (a) unventilated; and (b) ventilated situation for Room 1 in the U-shape building

4:00–6:00 p.m. Room 1 in the L-shape building shows that the comfort time within 90% acceptability reduced to 62.5% of total day hours. At the same time, the comfortable time for 80% acceptability increases to 20.83% of total day hours.

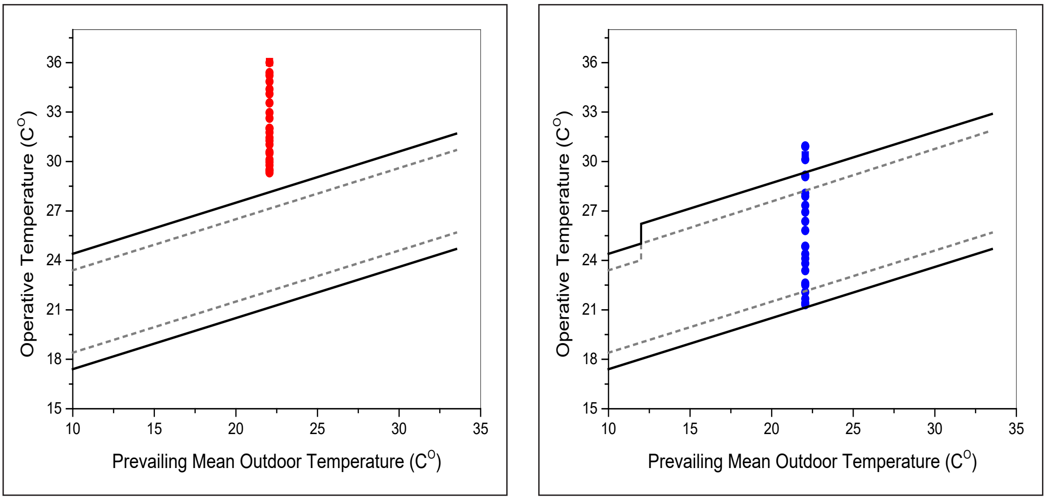
However, the uncomfortable status within the peak hours (4:00–6:00 p.m.) remains at 16.67% of day hours. For Room 1 in the U-shape building, the 90% acceptability, 80% acceptability, and uncomfortable status records 58.33%, 20.83%, and 20.83% of hours during the day, respectively. 83.33% of the uncomfortable time is between 2:00–6:00 p.m. and 3:00–6:00 p.m. for other buildings. Thus, it can be concluded that the rectangular-shaped building records the best performance compared to the other building shapes since it usually presents high acceptability. At the same time, the U-shape shows a higher percentage of uncomfortable situations and less acceptability time. The uncomfortable high percentage of the U-shaped building is attributed to the eastern and western windows; thus, Room 1 will face direct sun radiation for longer, especially in the morning. Subsequently, the mean radiant temperature (MRT) for Room 1 in the U-shaped building records 1.5°C higher during morning hours than the other buildings, as illustrated in Figure 9(a). Furthermore, it is noticed that some of the 80% acceptability hours of the rectangular shape building are recorded in the early morning between 6:00–7:00 a.m. and show a slightly cool sensation, which might be shifted toward 90% acceptability by minimizing the number of opening windows at this time, thus reduces the ventilation effect.

Figures 16, 17, and 18 show the adaptive model for Room 2 performance in both cases with and without ventilation for all building forms. The results show that Room 2 in all buildings under ventilation conditions is out of the thermal comfort zone. On the other hand, for the ventilation case, Room 2 in all building forms records 58.33%, 25%, and 16.67% of day hours for the 90% acceptability, 80% acceptability, and uncomfortable status, respectively. The unacceptability time in Room 2 for all shapes has a warm sensation recorded between 3:00–6:00 p.m. Interestingly, it is noticed that the number of uncomfortable hours close to the 80% acceptability zone in the rectangular and the U-shape building relatively are more than for L-shape; this attributed to the compactness in rectangular shape and self-shading in U-shape, which indicates that their performance is relatively better than L-shaped building. Table 6 summarizes the comfort hours percentage for Room 1 and Room 2 in different building forms under ventilation conditions according to ASHRAE-55.



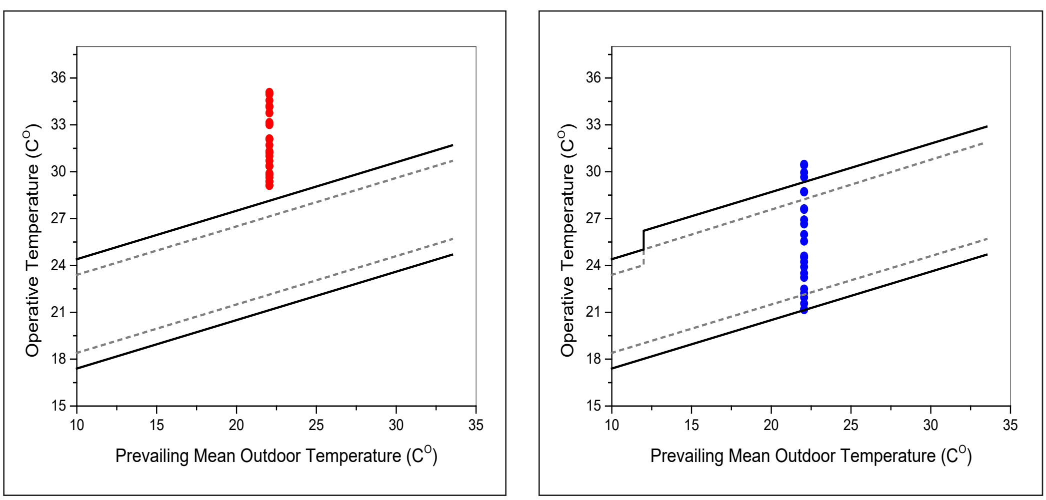
(a) (b)

Figure 16. ASHRAE-55 adaptive model: (a) unventilated; and (b) ventilated situation for Room 2 in the rectangular building



(a) (b)

Figure 17. ASHRAE-55 adaptive model: (a) unventilated; and (b) ventilated situation for Room 2 in the L-shape building



(a) (b)

Figure 18. ASHRAE-55 adaptive model: (a) unventilated; and (b) ventilated situation for Room 2 in the U-shape building

Table 6
Comfort hours percentage for Room 1 and Room 2 under ventilation conditions

Comfort percentage	**Rectangular Shape**		**L-Shape**		**U-Shape**	
	Room 1	**Room 2**	**Room 1**	**Room 2**	**Room 1**	**Room 2**
90% acceptability	66.67%	58.33%	62.50%	58.33%	58.33%	58.33%
80% acceptability	16.67%	25.00%	20.83%	25.00%	20.83%	25.00%
Out of ASHRAE comfort zone	16.67%	16.67%	16.67%	16.67%	20.83%	16.67%

DISCUSSION

The impact of natural ventilation on different building forms is investigated in two situations: with and without ventilation. The thermal behavior has been examined for basic (all windows are closed) and natural ventilation cases (all windows are opened). The building form is more effective on the thermal performance when the windows are closed, with no ventilation case, since it depends on many factors such as surface-to-volume ratio, building compactness, and self-shading.

Rectangular shape building recorded the best results in the daytime for Room 1 since the compact shape minimizes exposed solar radiation. However, the L-shape shows second-ranked results because of the large surface/volume ratio; conversely, the U-shape has the worst results due to the opposite side opening. Thus, it is facing the sunrise and sunset times.

Unventilated Room 2 in the U-shape building shows better performance as compared with other forms since the maximum temperature recorded is 35°C, and the worst thermal performance for the same room is obtained for the L-shape building regarding larger surface-to-wall ratio for the building as compared to rectangular case and no self-shading as compared to U-shape case.

Natural ventilation enhances the thermal behavior of all buildings in the hot-dry climate, where it remarkably reduces the indoor air temperature and mean radiant temperature; as a result, it improves the indoor thermal performance as the buildings transform from non-comfort zone to acceptable comfort situations in most of the time according to the ASHRAE-55 adaptive model.

Room 1 in the rectangular building shows the best thermal performance according to ASHRAE-55 adaptive model as compared to the other shapes since it is recorded 66.67% of the time within 90% acceptability, 16.67% of the time within 80% acceptability, and 16.67% of the time within the uncomfortable status. For Room 2 under ventilation conditions, all building forms record the same hour percentage of comfortability according to the ASHRAE-55 adaptive model. L-shape building presents relatively less thermal performance since it records fewer hours within the uncomfortable zone, close to 80% acceptability comfort zone.

Table 7 compares natural ventilation's impact on improving indoor air temperature and comfort hours between the current work and the previous research.

Table 7
Comparison of the impact of natural ventilation between current work and the previous research

Reference	Climate	Approach	Findings
Al-Hemiddi and Al-Saud, 2001	Hot–arid	Experimental	Cross-ventilation provides cool indoor air.
Omrani et al., 2017	Warm-humid summers and mild to cool winters	Experimental	- Cross ventilation maintains comfortable thermal conditions 70% of the time. - Indoor condition in single-sided ventilation has an average of 3°C hotter than cross ventilation.

Table 7 *(continue)*

Reference	Climate	Approach	Findings
Kumar et al., 2018	Hot semi-arid	Experimental	- Natural ventilation reduces 40% and 98% of discomfort time in summer and winter, respectively.
Heracleous & Michael, 2018	Mediterranean	Simulation.	- Natural ventilation reduces operative temperature.
Mastouri et al., 2019	Hot Semi-Arid	Simulation.	- Night ventilation reduces the operative temperature of the ground floor by 2°C and 3°C on the first floor.
Ma'bdeh et al., 2020	Dry-hot	Simulation.	- Ventilation improves indoor air quality. - The comfort hours increased by 106 h during February and 170 h during August.
Current work	Hot-dry summer	Simulation	-Natural ventilation reduces indoor air temperature by almost 10°C at nighttime and 4–8°C during the daytime. - Ventilation increases comfort hours percentage (90% acceptability) from 58.33% to 66.67%.

CONCLUSION

A simulation experiment using the EnergyPlus simulator is conducted in this paper to investigate the impact of ventilation on the thermal performance and thermal comfort of three residential buildings of different forms, namely rectangular, L-shape, and U-shape, which are in Amman, the capital of Jordan, that is characterized with a hot-dry climate in the summer season. Models for the proposed buildings according to their actual constructions are designed using the OpenStudio plugin SketchUp software. After defining the loads and the design day, they are simulated with the aid of the EnergyPlus simulator. As a preliminary step, the simulator is validated by comparing the simulated data with the site-measured results for Room 1 within the rectangular building, which shows good matching. The simulation results show that natural ventilation greatly reduces the indoor thermal temperature of the rooms under investigation. It drops by almost 10°C at nighttime due to the cold outdoor climate, while during the daytime, it reduces by 4–8°C. This reduction in air temperature is correlated to the influence of natural ventilation to refresh the indoor air and discharge the heat, subsequently improving indoor air quality. Comparably, Room 1 in the U-shaped building shows a lower temperature at night compared to other forms, and Room 2 in the L-shaped building shows a relatively higher temperature than the other buildings. The thermal comfort for the rooms has been evaluated using the ASHRAE-55 adaptive model to find out that the natural ventilation has a remarkable impact on shifting the 100% out-of-comfort rooms to less than 20% of the total design day hours. Comparably, Room 1 in the rectangular building records 66.67% of total hours during the day within the 90% comfort acceptability according to ASHRAE-55, which is the highest among the other forms. Room 2 in all building forms records the exact acceptability percentages of 58.33%, 25%, and 16.67% of day hours for the 90% acceptability, 80% acceptability, and uncomfortable status, respectively. Based on these results, it can be concluded that natural ventilation through windows in the hot-dry climate significantly improves indoor thermal performance, especially for the rectangular and U-shape forms. For further understanding of the influence of natural ventilation, it is highly recommended to consider investigating parameters such as type of ventilation and window-to-wall ratio and correlate them to the building form.

ACKNOWLEDGEMENT

The authors thank the houses' owners, Mr. Ahmad Saif, Mrs. Kholoud Altartir, and Mr. Shehadeh Hussein, for providing the sketch plans and facilitating the site measurements.

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