TECHNICAL ARTICLE

The Effect of Thermal Insulation on Cooling Load in Residential Buildings in Makkah, Saudi Arabia

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Buildings consume huge amounts of electrical energy in the Kingdom of Saudi Arabia, particularly during the summer months, due to the enormous air conditioning demands created by very hot outdoor temperatures. Residential buildings consume more than half of the electricity used in Saudi Arabia, with the air conditioning load making up 70% of this use. The main aim of this study is to evaluate the thermal performance of two mid-rise residential buildings in Makkah, Saudi Arabia. These buildings are five floors in height and have the same orientation, but the first building is thermally insulated, while the second building is not. To investigate the indoor thermal performance of the two buildings, physical measurements were taken during May 2019. The data gathered included indoor air temperature values as recorded every fifteen minutes for a period of sixty-eight hours in two equivalent rooms in each building. Analysis of site monitoring data was conducted, and the results obtained offer a better idea of the effectiveness of the existing building fabric characteristics, in particular external walls and rooves, in relation to indoor thermal performance. These data were calibrated with simulated results taken from thermal analysis software (TAS) to validate them and to thus quantify the cooling load in the case study buildings. The outcomes illustrate the similarity between the measured and simulated results and as well as indicating that thermal insulation can decrease cooling loads by to up to 50%.

Keywords: thermal performance; residential buildings; Saudi Arabia; insulation; cooling load; indoor air temperature

Introduction

Buildings in Saudi Arabia are characterised by a severe excess of electrical usage; buildings consume 80% of the electricity produced in Saudi Arabia, with air conditioning representing 50% of this consumption. The residential sector also consumes more than half of the electrical energy used in Saudi Arabia, with air conditioning loads representing 70% of this consumption (SEEC, 2018). Building design is one of the many ways to reduce air conditioning use in buildings (Pacheco et al., 2012); in particular, minimising the cooling load of buildings by means of effective architectural design means minimising the solar and envelope heat gain (Givoni, 1994). Nicole et al. (2012) state that poor quality building creates the most deep-rooted energy wastage problems, while Taleb and Sharples (2011) demonstrate how certain design and operational changes cab have a significant impact on the thermal performance of a building.

In terms of thermal insulation, 70% of residential buildings in Saudi Arabia lack any thermal insulation (SEEC, 2018). Kharseh and Al-Khawaja (2016) investigated the impact of various retrofitting measures in terms of reducing the cooling requirements of buildings in Qatar, using an hourly analysis program (HAP) model to simulate the cooling load for a residential house chosen as a case study. Their results show that adding less than 2 cm of polyurethane to the external walls reduced the cooling requirements of the building by 27%. Heravi and Qaemi (2014) similarly determined the most effective design and construction measures concerning building energy efficiency in Iran, simulating these measures independently using Design Builder software. The results illustrate that roof and wall thermal isolation is the most effective measure with respect to reducing building energy consumption and that improving the opaque materials of the roof and wall can reduce building energy consumption by 13.8% and 12.16%, respectively. These effects can be enhanced by adding thermal insulation materials alongside other energy efficiency measures. According to Alaidroos and Krarti (2015) maximum energy savings of up to 35% can be achieved by adding thermal insulation to both walls and roof, while according to SEEC figures thermal insulation decreases the electrical energy consumed by AC systems by 30 to 40% (2018).

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Studies dealing with the calibration of thermal models are presented in Leong and Essah (2017), Saleh (2015), and Alves et al. (2016). The aim of their monitoring was to calibrate a computational model for local climate conditions, while the current study is designed to evaluate the indoor thermal performance of mid-rise residential buildings in Saudi Arabia, using Makkah as a case study.

The case study buildings investigated are five-floor residential buildings located in a district called Shisha, to the east of Makkah in Saudi Arabia (latitude 21.4°N and longitude 39.8°E) (**Figure 1**). Makkah is surrounded by the Sarawat Mountains and is around 45 miles east of Jeddah, which is the Red Sea's main sea port. Makkah is one of the busiest cities in Saudi Arabia, and air temperatures there are warm to hot all year round. Winter temperatures are about 19°C at night and approximately 29°C in the afternoons, while summer temperatures are usually extremely hot, often exceeding 38°C in the afternoons while dipping only to about 32°C in the evenings. Makkah receives very little rainfall, and what it does get is concentrated from September to January (Nayebare et al., 2018).

Cooling load is the energy needed to cool a building to a comfortable temperature (Nicol et al., 2012). There are many studies examining cooling load and ways to decrease this in residential buildings, with many adopting surveys and computer models. However, the current study is the first paper to deal with physical measurements, calibrated with a computer model, in mid-rise residential buildings in Saudi Arabia in order to evaluate the use of insulation, along with the effects of its lack in old buildings, in relation to cooling load.

Methods

Evaluating the thermal performance of a non-air-conditioned building involves calculation of temperature variation inside the building over a specified time

Figure 1: The location of Makkah (Maps Saudi Arabia, 2019).

period and the estimation of the duration of uncomfortable periods. For an air-conditioned building, this also involves the estimation of its heating and cooling loads, energy demand, and the size and specification of HVAC equipment. The quantification of these aspects determines the performance of a building design and helps with evolving improved designs to achieve comfortable indoor conditions (Nayak and Prajapati, 2006).

Indoor air temperature refers to is the dry bulb temperature of the air in the space. It is usually the most important thermal environmental variable affecting thermal comfort which as a result affect the energy used to heat or cool a building (CIBSE, 2015). Cooling is often required depending on the climate, and to cool people in indoor environments, convection is generally the most important mechanism. Slight air currents resulting either from natural convection, wind, or mechanical cooling are thus required, but too much ventilation greatly increases energy use, as incoming air must be heated or cooled (Smith and Parmenter, 2016). In the case of Makkah, where outdoor temperatures are usually higher than indoor requirements, active mechanical cooling must thus be utilised.

The two case study buildings are very similar; both are on the same main street, with the same orientation. After an initial site visit, these two buildings were chosen for the evaluation of their indoor thermal performance as the first case study building complies with new Saudi building standards regarding the use of thermal insulation in the external walls, roof, and windows, while the second case study building was built in the late 1990s and has no insulation at all (**Figure 2**).

The rooms chosen for the two case studies have different orientations. The 4th floor room has one external wall orientated north-east, with one window, while the 5th floor (top) room has one external wall orientated south-west, again with one window. The middle floor room in the first building is a bedroom 12.5 m² in size, while the bedroom on the top floor is 14.8 m² (**Figure 3**). The middle floor room in the second building is a bedroom of 22.2 m², while the bedroom on the top floor is 27.2 m² (**Figure 4**).

The instruments used for the fieldwork were four data loggers (Elitech UK) used for temperature recording, which were placed in the four different rooms in the two buildings to assess the buildings' performance conditions simultaneously for 68 hours, from 4 May 2019 to 6 May 2019 (**Table 1**) (Elitech, 2019).

The case study buildings were also modelled using thermal analysis software (EDSL TAS version 9.4.4). TAS was developed by Environmental Design Solutions Limited, and it offers a building thermal analysis software programme that can be used to simulate the thermal performance of buildings.

The main applications of the software include the assessment of environmental performance and energy consumption. To simulate the thermal performance of buildings, TAS uses a fundamental approach based on dynamic simulation. With this method, the thermal state of the building is traced through a series of hourly snapshots, providing the user with a detailed picture of how the building will perform across a typical year. This approach allows for greater clarity in the modelling process, as the user can account for the numerous thermal processes that occur in the building model. TAS software is split
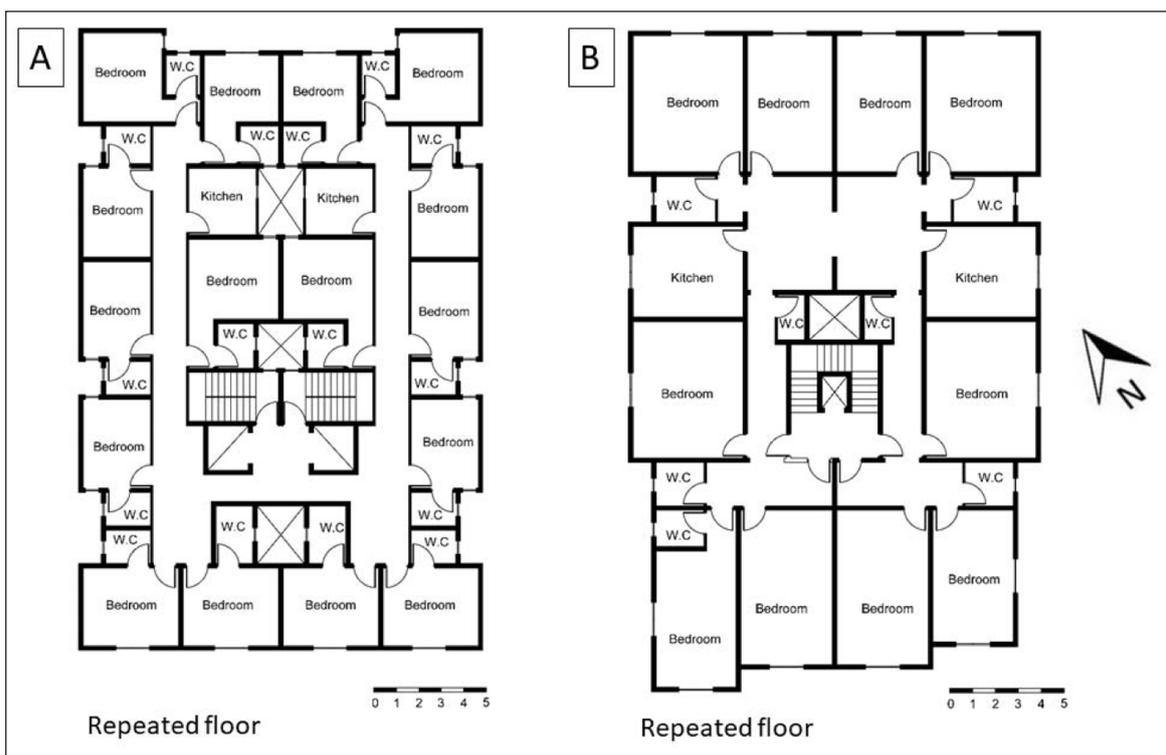
Figure 2: A. Architectural drawing of the repeated floor in the first case study building. **B.** Architectural drawing of the repeated floor in the second case study building.

Figure 3: A. Room chosen for fieldwork on the middle floor of the first case study building. **B.** Room chosen for fieldwork on top floor of the first case study building.

Figure 4: A. Room chosen for fieldwork on the middle floor of the second case study building. **B.** Room chosen for fieldwork on top floor of the second case study building.

Table 1: Instrument data.

Name	Type	Parameter	Range	Accuracy	Note
Temperature data logger	Elitech URC5	Indoor air temperature	−30°C~+70°C	±0.5°C (−20°C ~+40°C); others, +1°C	Continuous test

into three different modules: a 3D modeller, a building simulator and the results viewer. The 3D modeller is used for creating the building models for the building simulator module, while in the building simulator module, the model is simulated by assessing the effects of conduction, convection, advection, long-wave radiation, solar radiation, casual gains and plants with radiative and convection portions. The results from the simulation process can be examined using the results viewer, where a user-selected combination of parameters from any zone or surface can be displayed and compared with those from other areas. The results can also be exported from TAS to a third-party programmes such as Microsoft Excel to facilitate further user-defined analysis (EDSL TAS, 2019).

By modelling the two buildings in TAS, recorded indoor temperature data were calibrated to the simulated result to verify the methods chosen. This was followed by adding and removing thermal insulation on the external walls and roof to compare the case studies and to find the optimum values for such insulation through parametric analysis. In the modelling process, only the three top floors were modelled, as the rooms in this study were on the 4th and 5th floors. Additionally, the nearby buildings were modelled, but no lighting gain or internal gain was presented.

The external temperature for the simulation was based on historical data obtained from Meteonorm (Meteonorm, 2019), while the other external temperature used in this study were obtained from the nearest weather station to the site, which is located in small airport east of Makkah (World Weather Online, 2019).

Building fabrics assessed in the case study buildings are presented in **Tables 2** and **3**. The first case study building

is new, and it complies with the standards regarding thermal insulation on external walls and rooves, while the second case study building was built in the late 1990s and does not have any thermal insulation.

The Saudi building code suggests that indoor air condition be set at 21.9°C and 23.9°C in winter and summer, respectively (SBC, 2019). However, the Saudi Energy Efficiency Centre recommends the set thermostat point of air conditioning be between 23 and 25°C (SEEC, 2018). In this study, a 25°C set thermostat point was chosen due to the implied saving in cooling load compared to any lower indoor air conditioning temperature. Cooling is assumed to be available all year around, mainly to quantify the effect of thermal insulation on cooling load in both buildings.

Results and discussion

An analysis of the fieldwork results was undertaken in order to develop insight into the existing building states with regard to thermal performance. In-site monitoring of indoor air temperatures was conducted in order to assess the thermal performance of the two building in Makkah. Indoor air temperature values were recorded every 15 minutes for nearly three days (4 May to 6 May 2019). This data was then used to analyse indoor air temperatures as affected by external building fabrics.

The analysis of indoor air temperatures is given in terms of the indoor thermal performance of the case study buildings (**Figures 5** and **6**). Outdoor air temperature (OAT) values were between 30°C and 41°C during the recording period, with OAT peaking during the day (11:00 to 17:00), and the lowest temperature values occurring in the very

Table 2: Building fabrics for the first case study building.

Element	Description	Thickness(mm)	U-value (W/m².K)
External wall (SW elevation)	Marble stone, cement mortar, insulated red hollow brick, cement mortar, white paint	280	0.52
External walls	Beige paint, cement mortar, insulated red hollow brick, cement mortar, white paint	250	0.53
Internal walls	White paint, cement mortar, red hollow brick, cement mortar, white paint	250	2.30
Internal floors	Carpet, tile, soil, reinforced concrete, air cavity, gypsum board	987	1.0
Roof	Tile, soil, insulation, reinforced concrete, air cavity, gypsum board	1027	0.26
Windows	Double glazing	22	1.6

Table 3: Building fabrics for the second case study building.

Element	Description	Thickness(mm)	U-value (W/m².K)
External walls and internal walls	Beige paint, cement mortar, concrete block, cement mortar, white paint	250	3
Roof and internal floors	Tiles, soil, reinforced concrete, cement mortar, white paint	355	2.23
Windows	Single glazing	10	5.5
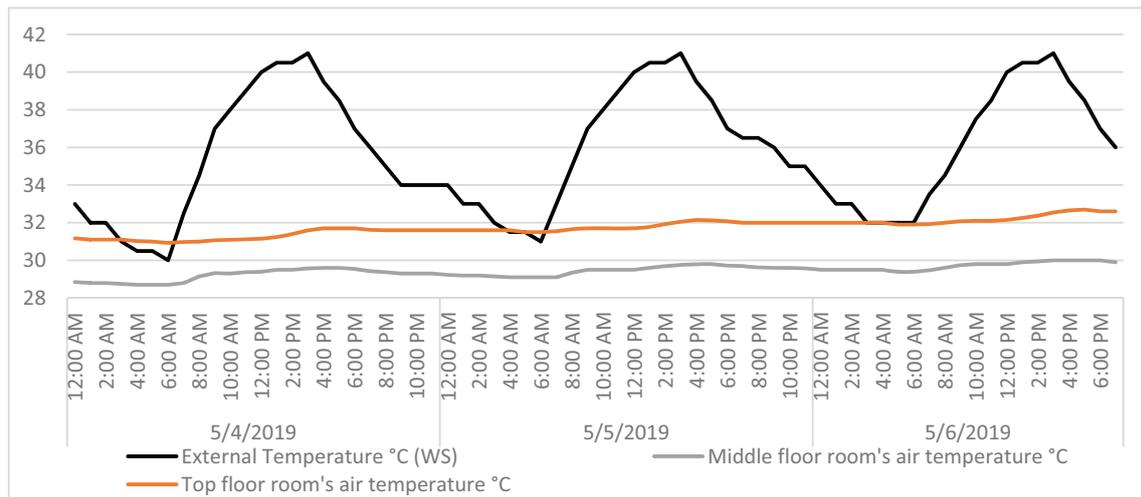
Figure 5: Outdoor and indoor temperature profiles for the two rooms on the middle floor and the top floor in the first case study building.
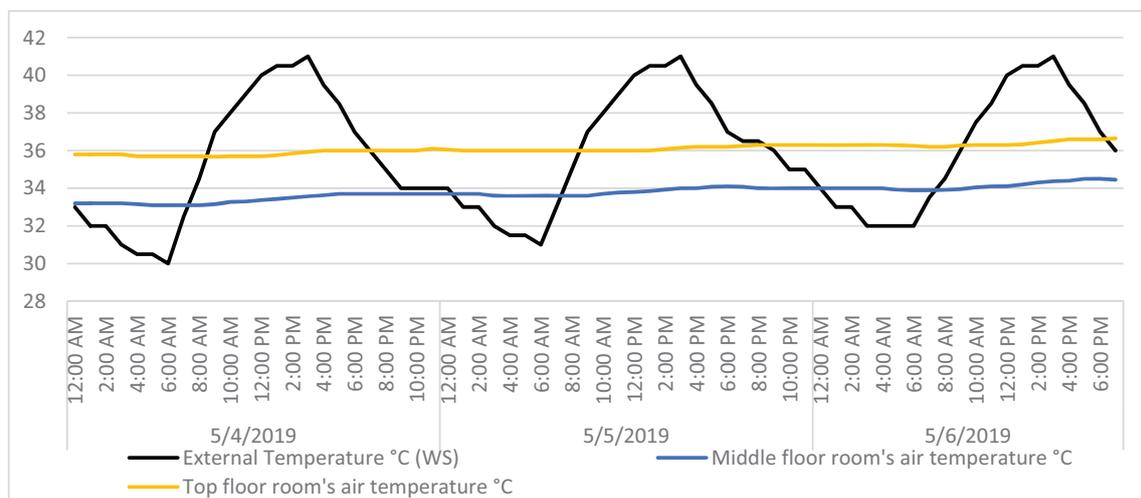
Figure 6: Outdoor and indoor temperature profiles for the two rooms on the middle floor and the top floor in the second case study building.

early mornings (3:00 to 7:00). Diurnal OAT ranges were found to vary by up to 11°C.

For the first case study building, the temperatures indoor ranged between 28.7°C and 32.7°C (**Figure 5**). A constant status was noticed in both rooms, which had daily temperature fluctuations of less than 1°C. The monitored temperature results suggest that the air temperature on the middle floor room was 2.5°C less than that of the top floor room, possibly because the top floor room is exposed to solar radiation from the roof and also because its external wall is orientated to the south-west. It can be seen that the indoor air temperature in both rooms was generally less than the OAT.

For the second case study building, the temperatures indoor ranged between 33.1°C and 36.6°C (**Figure 6**). A constant status was noticed in both rooms, which had daily temperature fluctuations of less than 1°C. The monitored temperature results showed that the air temperature on the middle floor room was around 2°C less than that of the top floor room, again mainly because the top floor room is exposed to solar radiation from the roof, and

also because its external wall is orientated to the south-west. The indoor air temperature in both rooms in the second case study building was 4 to 5°C higher than the rooms in the first case study building, probably because the first case study building is well insulated externally.

The simulated results for the two case studies show very similar indoor air temperature results to the measured results for the two chosen rooms (**Figures 7** and **8**). The reason for plotting the simulated results in this way was to verify and calibrate the analytic work. The simulated temperatures closely followed the recorded temperatures in the middle floor rooms, while for the top floor rooms, the difference was around 2K for both buildings. For a simulated energy model to be acceptable based on ASHRAE guidelines (ASHRAE, 2002), the calculated normalised mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE) should be 10% and 30%, respectively, for a model that deals with hourly figures. This study monitored hourly temperature, and both the NMBE and the CVRMSE were thus calculated based on the values of the entire recorded temperature set
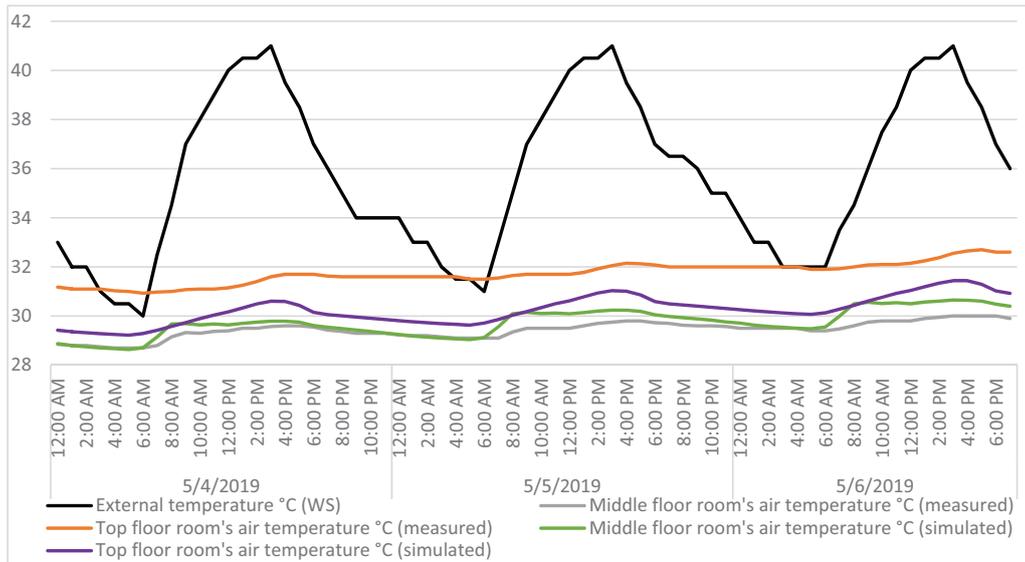
Figure 7: Measured and simulated data for outdoor and indoor temperature profiles for the two rooms on the middle floor and the top floor in the first case study building.
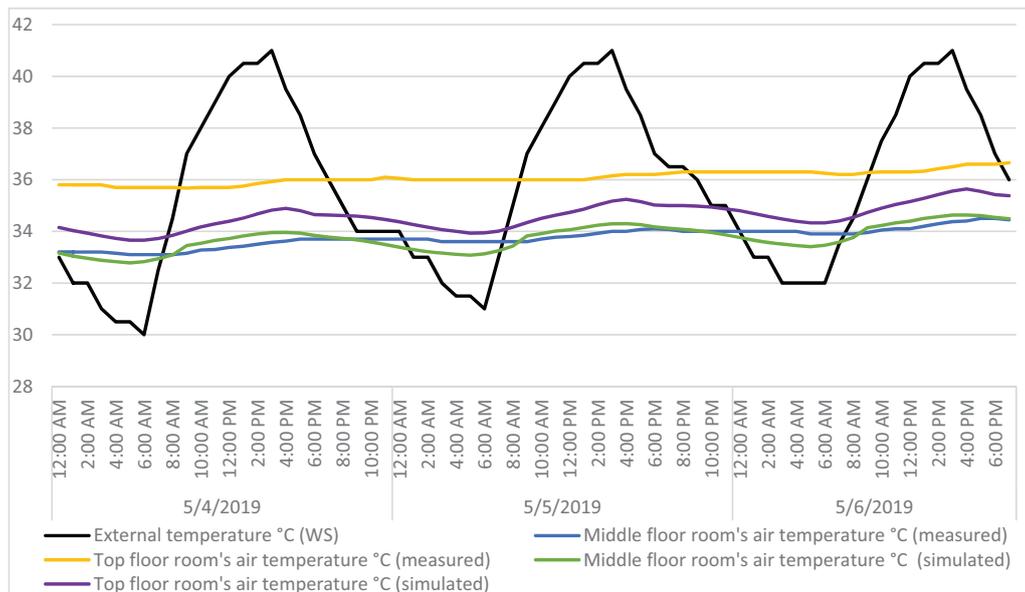
Figure 8: Measured and simulated data for outdoor and indoor temperature profiles for the two rooms on the middle floor and the top floor in the second case study building.

Table 4: Calibration results for the measured and simulated values.

Case studies	Selected rooms	NMBE	CVRMSE
First building	Middle floor room	−0.6	2.4
	Top floor room	3.1	12.2
Second building	Middle floor room	0.04	0.1
	Top floor room	2.8	12.3

during the 68 monitored hours (**Table 4**). This means that the NMBE was lower than the 10% limit and the CVRMSE was lower than the 30% limit set by ASHRAE. It is thus safe to assume that the simulated results are within the acceptable range.

For the first building, to highlight the importance of the thermal insulation, the effects of partial insulation, such as roof only or only external walls, and the building with and without thermal insulation are shown in **Figure 9**. The cases used are shown in more detail in **Table 5**.

The base case refers to only cooling being used, with no change in the current state of the building insulation.

The first case removes the insulation board from the roof in the top floor room. The change for the middle floor room is minimal, as nothing is changed there, but the increase in cooling load in the top floor room as result of this is 23.3%.

The second case removes the insulation from the external walls in both rooms. The change for both rooms is thus similar, an increase of around 45% in cooling as compared to the base case.
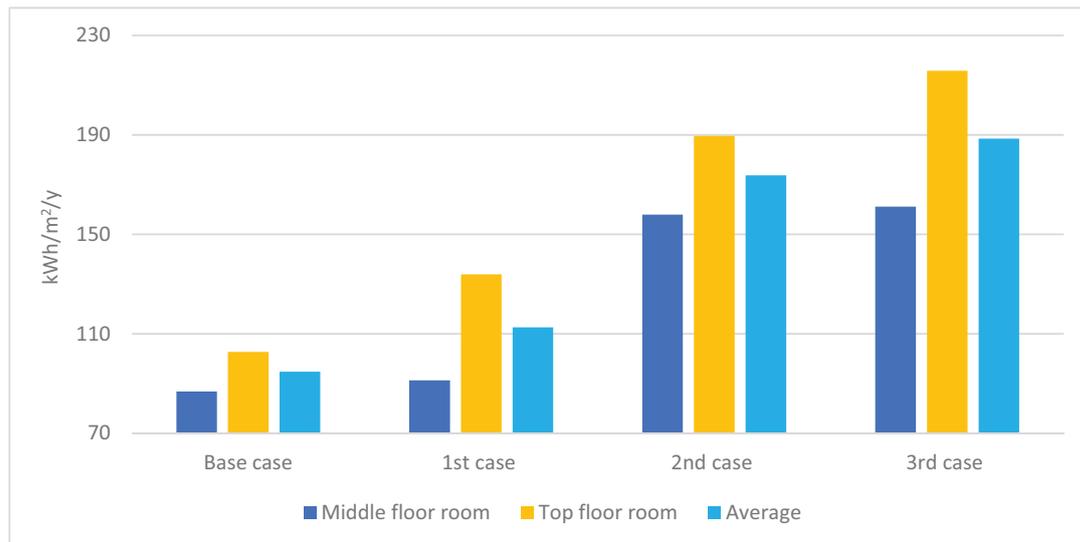
Figure 9: Annual cooling load profiles for the middle and top floor rooms in the first case study building.

Table 5: Description of the cases used in the first building.

Cases	Description	Average increase of cooling load (%)
Base case	25°C	–
1st case	Base case + 50 mm of expanded polystyrene insulation board is removed only from the roof in top floor room	15.8
2nd case	Base case + expanded polystyrene insulation is removed to the external walls in both rooms	45.4
3rd case	Base case + 1st case + 2nd case	49.7

The third case removes the insulation board from the top floor room as well as removing the insulation from the external walls in both rooms. The change for the middle floor room is minimal as compared to the second case, but for the top floor room, an increase of a further 7% in cooling load compared to the second case, creating an over 50% increase of cooling loads compared to the base case, was observed.

For the second building, to show the importance of thermal insulation, the effects of partial insulations such as only the roof or only the external walls are compared to adding full thermal insulation, as shown in **Figure 10**. The cases used are shown in more detail in **Table 6**.

The base case is with only cooling used, without changing the current state of the building.

The first case adds insulation board to the roof in the top floor room. The change for the middle floor room is minimal, as nothing there is changed, but the reduction of the cooling load in the top floor room as result of this is 17.7%.

The second case adds insulation to the external walls in both rooms. The change for the rooms is thus similar, with increases of 25% and 19% respectively in cooling compared to the base case.

The third case both adds insulation board to the top floor room and also adds insulation to the external walls of both rooms. The change for the middle floor room is

minimal as compared to the second case, but for the top floor room, an 20% reduction of the cooling load compared to the previous case, creating an approximately 40% reduction in cooling loads compared to the base case, ensued.

The middle floor room and top floor room in the first case study building have annual cooling loads of 86 and 102 kWh/m²/y, respectively, while the middle floor room and top floor room in the second case study building have annual cooling loads of 148 and 201 kWh/m²/y, respectively.

The average cooling load in the first case study building is 45.8% less than for the second case study building. The top floor room in the first building consumes only a little over half of the cooling load of the top floor room of the second building.

That is mainly because the top floor room in the second building lacks thermal insulation in the external walls and roof. The middle floor rooms in both buildings have the same orientation (NE) and neither are exposed to solar radiation from the roof, while the top floor rooms in both buildings have the same orientation (SW) and are exposed to solar radiation from the roof.

Comparing the base case of the first building to the third case in the second building, which is the optimum case to reduce cooling load based on adding insulation to the external walls and roof, the average
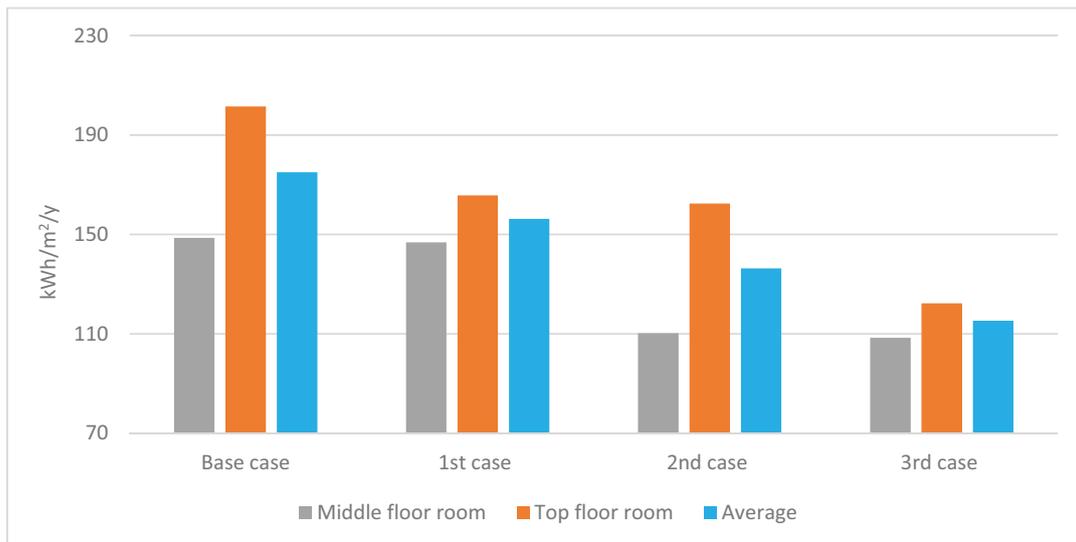
Figure 10: Annual cooling load profiles for the middle and top floor rooms in the 2nd case study building.

Table 6: Description of the cases used in the second building.

Cases	Description	Average reduction of cooling load (%)
Base case	25°C	–
1st case	Base case + 50 mm of expanded polystyrene insulation board is added only to the roof in top floor room	10.7
2nd case	Base case + expanded polystyrene insulation is added to the external walls in both rooms room	22
3rd case	Base case + 1st case + 2nd case	34.1

cooling load for the third case for the second building is 115 kWh/m²/year while the average for the base case of the first building is 94 kWh/m²/year. The second building figure can clearly be improved by reducing the ceiling height to match that of the first building, which has fake ceilings used to hide electrical, lighting, and A/C. Additionally, the room sizes in the 2nd case study building are around double those of the rooms in the first building, which may have an additional effect.

Conclusion

The paper covered fieldwork data collection, conducted in May 2019, to investigate the indoor thermal performance of two mid-rise residential buildings in Makkah, Saudi Arabia. Indoor air temperature values were calculated for 68 hours in two zones in each building; then, to verify and calibrate the ensuing analytic work, thermal analysis software (TAS) was used to create simulations of these rooms. The simulated results were compared to the measured results and were found to be in an appropriate range for the model to be acceptable. The results show that building envelopes have a significant effect on indoor air temperatures. In particular, the cooling load in the first case study building was almost half that of the second case study building, mainly because of a lack of thermal insulation in the external walls and roof in the latter.

Competing Interests

The authors have no competing interests to declare.

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