An Analysis of Thermal Comfort and Energy Consumption within Public Primary Schools in Egypt

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Abstract. Schools constitute the most suitable sector of building for the application of indoor thermal comfort quality as they represent a broad sector of construction. Thermal comfort plays a major role in the educational building sector, especially in hot-arid climate. It has a big impact on building interior temperature as well as on energy consumption. The present study is primarily an attempt to assess the existing indoor thermal comfort status as well as energy consumption in Egyptian public primary school building. To meet this objective, a methodological procedure has been followed; a field study was conducted in a school building that are designed based on natural ventilation and air movement through ceiling fans to assess the indoor thermal conditions based on adaptive standard comfort (ASC) model. In addition, electrical utility bills have been collected. Then, a dynamic building energy simulation model was carried out by using, DesignBuilder software for examining indoor comfort conditions as well as the energy consumption of a typical school building in Egypt. Findings revealed that lighting sources represent the largest proportion of energy consumption. In terms of indoor thermal comfort, results indicate that a higher level of thermal discomfort within the primary public school classrooms and the pupils stay more than 36.5% of their time daily in classrooms with thermal stress conditions.

Keywords: Thermal comfort; energy consumption; school building; simulation; naturally ventilated

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1. Introduction

1.1. Background

With increased global concerns on climate change caused by anthropogenic greenhouse gas emissions (Taleb and Sharples, 2011), the need for innovative spaces which can provide indoor thermal comfort and energy efficiency is also increasing.

Predictions published by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change and Working Group III, 2000) indicate an increase in global average surface temperature in different scenario ranges of 1.1–2.9℃ to 2.4–6.4℃ from a 1990s baseline towards the end of the 21st century. Across Egypt, which is the focus of this study, air temperature has already increased between 1℃ and 2℃ since 1970 and is expected to increase another 4℃ by 2100 as the special Report of Emission Scenario states, SRES, A1F (Nakicenovic and Swart, 2000). In conjunction with a raised awareness for climate change, energy consumption in buildings is taking central attention in Egypt on the public triggered by the electricity supply shortage in 2012 and 2013 as buildings sector consumes about 42% of energy (Hossein Rasazi et al., 2010). Additionally, buildings accounted for 33% of the carbon dioxide which is the primary greenhouse gas associated with global climate change (Mahmoud, 2011a).

Furthermore, thermal comfort plays a major role in buildings sector, especially in hot-arid climate. It has a big impact on building interior temperature as well as on the energy consumption. According to (Lawal and Ojo, 2011), thermal behaviour of a building is determined by the extent of thermal controls provided in the building and the existing outdoor conditions. Therefore, the thermal performance of the building envelope is one of the most important determinates of the building's energy consumption.

This study focuses on school buildings as they represent a significant part of the building stock, and also noteworthy part of total energy use (Zeiler and Boxem, 2013). Therefore, this research gives an insight into thermal comfort and energy consumption for public primary school classrooms in the Egypt through filed investigation and a series of building simulations. It is known that the primary school education system deals with pupils in such a sensitive yet promising age. This is as an important point that children are impressionable and the comfort of their environment is an important aspect of quality learning. In addition, children are more vulnerable than adults to environmental pollutants (Suk et al., 2003). Over the past several decades, research has established relationships between the classroom environment and students outcomes and identified determinates of learning environment (Puteh et al., 2012).

In Egypt, which is the focus of this study, it is reported that there are about 15600 schools all over the country with 37.6% of all pre-university education (Ministry of Education, 2012). This demand had considerably increased after the 1992 earthquake that devastated a considerable number of schools (Gado and Mohamed, 2009a). In response, the Egyptian government established the General Authority of Educational Buildings (GAEB) to design new schools around the country. These designs relied on an infiltration air of cross-ventilation with ceiling fans to achieve thermal comfort within the classrooms. GAEB uses the same prototype designs to establish schools across the various climatic conditions in many regions of Egypt without consideration to the significant variation in all climatic conditions. This led to uncomfortable interior conditions within the classrooms which span from heat stress, lack of adequate ventilation, glare to exposure to excess solar radiation.

It is evident that a large body of social science and environment-behavior research was conducted in school buildings in the 1960s and 1970s (Gado and Mohamed, 2009a). However, insufficient research has addressed indoor environmental settings with respect to thermal comfort and energy consumption conditions in school buildings. It should be pointed that thermal comfort studies typically focus primarily on occupants in residential buildings and offices where groups of occupiers often share work, which facilitates easier surveying by research investigators (Ali Ahmed, 2012; Sayed et al., 2013). Therefore, the thermal comfort is still one of the most important issues should be considered in government primary schools buildings as it has direct negative impact on teaching and learning as well as the potential for energy conservation via careful temperature control with the classrooms.

1.2. Climate context

In preliminary, Egypt is located between 22°N to 31° 37 ′N latitude and 24° 57′E to 35°45′E longitude with an area of approximately 1,000,000 Km^2 (Mahmoud, 2011a). Egypt has a significant variation in the climatic conditions. The Housing and Building Research Centre (HBRC) divides the country into eight different climatic design regions as reported by (Sayed et al., 2013) (see Fig. 1). According to Koeppen's climate classification (Kottek et al., 2006), Egypt experiences the 'hot desert climate type' (BWh) in the southern and central parts of the country and the 'hot steppe climate type' (BSh) along the coast. Most parts of Egypt are occupied by the Sahara desert, which represents the most extensive arid area on the planet. In general, Egypt possesses a hot-arid climate throughout the year.

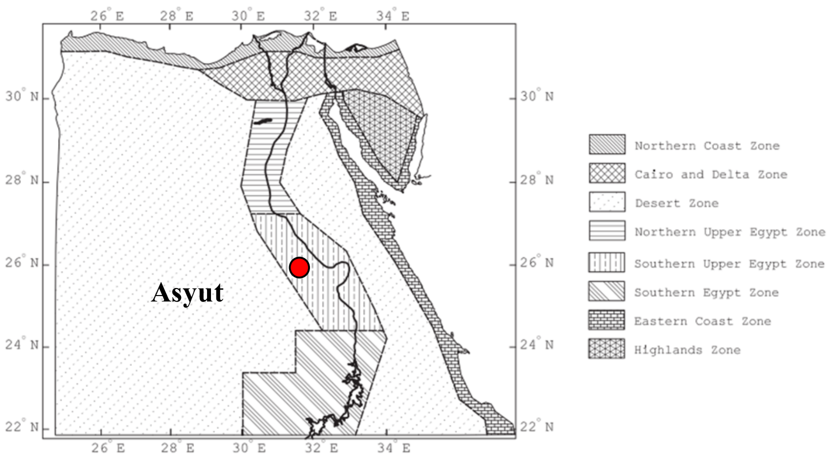


Figure 1. Classification of climatic zones in Egypt according to HBRC (Mahmoud 2011b).

3.1. Aims and objective

In the light of aforementioned, a design procedure to understand the existing situation of indoor comfort conditions in public primary school buildings is desirable. The primary objective of this study is to assess thermal comfort conditions within recent government primary schools in Egypt.

To this end, a field measurement exercise was conducted in the selected school building, followed by computer modeling work using 'DesignBuilder' software to simulate thermal performance and energy consumption of the school building. Subsequently, the calculated values from field measurement and the simulation results were compared for validation purposes.

2. Methodology

2.1. Field investigations

2.1.1. The case study (visual survey)

Experimental investigation of thermal comfort conditions within public primary schools that are designed based on natural ventilation (infiltration) and air movement within the classrooms by ceiling fans were carried in Assiut city (27°3′ N; 31°15′E) as seen in Fig. (1), which located northeast of the southern Upper Egypt zone (Ali Ahmed, 2012). The field study was conducted in three naturally ventilated classrooms from 29^{th} to 31^{th} October, 2013 at Assiut prototype distinct language school that was built in the year 2009. This school mainly belongs to the General Authority of Educational Buildings (GAEB) and has been designed according to one of the prototype architectural system that has been carbon-copied all over the country. All the studied classrooms based on natural ventilation (infiltration) and air movement within the classrooms through ceiling fans. Windows are single glazed and poorly constructed with very high levels of air permeability at both sides (1.5x1.2m), window to wall ratio reaching 32%. There is no solar protection in the windows, only the roof edge slightly mitigates the sunshine. The occupancy rate of this school is $1.1m^2$ for each pupil (the USA ratio is $2.15m^2$).

2.1.2. Measurements and data recording

In this field study, Thermal Comfort Datalogger-INNOVA 1221, shown in Fig. (2), was used for measuring and recording the classroom indoor environmental parameters such as operative temperature, relative humidity and air velocity during the school working hours when the classrooms are being fully occupied with the pupils to evaluate thermal comfort conditions. The INNOVA 1221 is a black box (138mm*285mm*300mm) built up modularly with up to four input modules. The data logger is supplied is supplied with a battery pack for use in the field Three external sensors (with measuring accuracy ±0.1 ºC) were connected to the device which was placed in front of classroom beside the board in order to not to interfere with ongoing teaching activities. The classroom furniture is arranged in three row perpendicular to the whiteboard's wall (see in Fig. 3).

The data values were measured and recorded every minute and the average of each 15 minutes was determined and is presented in the results section. While, outdoor Asyut climate data were obtained from the meteorological records of the nearest regional weather station (WMO 62392) for the same period in addition to a Mobile Weather station to measure the outdoor temperature in the school yard. Moreover, electricity utility bills has been collected from Egyptian Ministry of Electricity for the whole year 2013 as well as information about occupant density and lighting sources.

2.2. Modeling and simulation

The analysis of this paper is mainly concerned with assessing the current status of internal building comfort condition, according to ASHRAE standard 55 (ASHRAE, 2010a), as well as energy consumption within public primary schools, which belong to GAEB in Egypt. A typical primary school building was selected to act as a case study for this research, this school has a total land area of 3168.37 m^2, is a five-store height. Each store consists of 5 classrooms with the school total of 24 classrooms. Modelling and simulations were carried out using the dynamic thermal simulations tool, DesignBuilder (DB) in its third version (V.3.4.0.033), which is based on the state-of-the-art building performance simulation software entitled EnergyPlus. The following sections define the different configurations and parameters of the case study.

For the simulations, a model of a typical school building in Assiut was applied to address indoor thermal comfort conditions within naturally ventilated classrooms and predict energy consumption for the base model, which constitutes the most prototype architectural design that has been carbon-copied all over the country.

Figure 2. Thermal comfort INNOVA 1221.

Figure 3. Field study inside class (A) shows the disk's distribution.

2.2.1. Base model development

Geometries of the case study was constructed in DesignBuilder based on the site plan survey as well as the construction drawings supported by GAEB. A three-dimensional DesignBuilder model for the case study was firstly developed (see Fig.4). Additionally, each space in the buildings was drawn as a thermal zone according to its function and each was given a name.

The simulation is based on 'real' hourly weather data, and taking into account solar gain through windows, as well as heat conduction and convection between zones of different temperatures. For this study, the following properties were implemented in DesignBuilder:

a) *Construction material*

The construction materials used are conventional according to the Egyptian Code for Buildings. Exterior walls are made of 25 cm red brick with an interior finish of 2.5 cm thermal plaster and paint (acrylic based for contracting and expanding). Interior partitions are of 12 cm thick red brick as well as 4 to 5 cm thickness of cement plaster and paint for both sides. Floors are suspended with 10 cm finishing thickness. Slabs are made from concrete of 12 cm thick according to the spans and structure system. The specifications for construction materials used in the simulation are listed in Table 1, and the section for the aforementioned walls are shown in Fig. 5.

b) *Glazing type and lighting*

According to Mahdy and Nikolopoulou (Mahdy and Nikolopoulou, 2014), there are four main categories commonly used in Egypt, mentioned and specified in (EREC), as shown in Table 2. In simulations, windows are aluminium frames with 6 mm single clear layer glazing. The window to wall ratio (WWR) is 32 %. On the other hand, each classroom has four groups of artificial lighting with three 1200 mm T8 lamps.

c) *Activities and schedule*

According to ASHRAE standard 55 (ASHRAE, 2010a), metabolic rate of seated activity = 1 met which equal 60 w/m^2, and so metabolic rate per person = 60 x 1.8=108 W/per according to ASHRAE standard 55 (ASHRAE, 2010a). In terms of vacations and working days, a combined schedule was applied to the simulation based on The Egyptian school year which starts at 15th September and ends on 30th June.

d) *HVAC and infiltration*

All classrooms are naturally ventilated with two ceiling fans in each classroom for air movement. Windows are single glazed and poorly constructed with very high levels of air permeability at both sides (1.5x1.2m), window to wall ratio reaching 32%. There is no solar protection in the windows, only the roof edge slightly mitigates the sunshine. Windows are operable from 8:00 am till 3:00 pm so, the infiltration rate suggested to be 0.5*ach/h*.

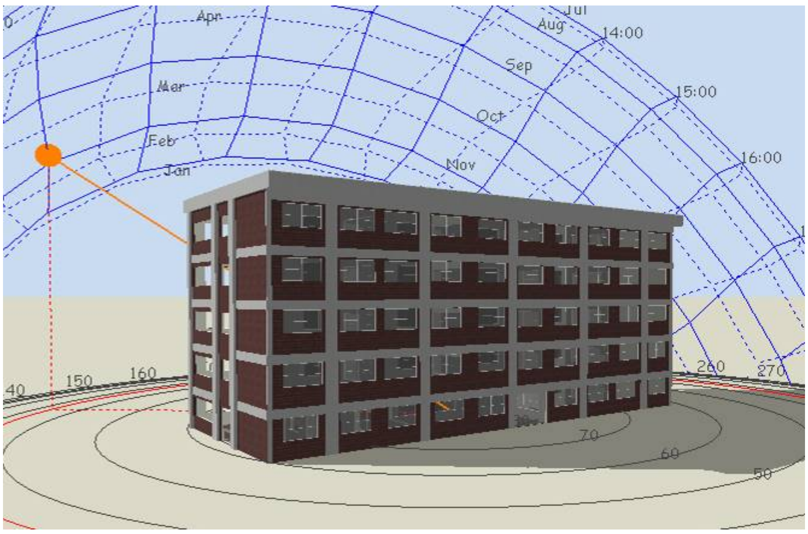


Figure 4. Reference case model in DesignBuilder.

2.2.2. Simulation & validation of the base model

Model validation is an essential task to ensure that the architectural, mechanical and electrical systems. (Oberkampf and Trucano, 2002) defined the verification and validation of computer simulation as below: "*Validation is the assessment of the accuracy of a computational simulation by comparison with experimental data*". Kaplan and Canner (Rahman et al., 2010) made recommendations for the allowable difference between predicted and measured (actual) data. For instance, the prediction of energy use is considered satisfactory when the difference is within 5% on a monthly basis for internal loads such as lighting, appliances or domestic hot water system. However, the acceptable difference may increase up to 15–25% monthly and 25–35% daily for the simulation of environmental parameters. In this computational simulation process, three parameters were considered for base model validation. They are internal average hourly temperature, average hourly relative humidity and monthly energy consumption.

Table 1. Physical characteristics of base model building.

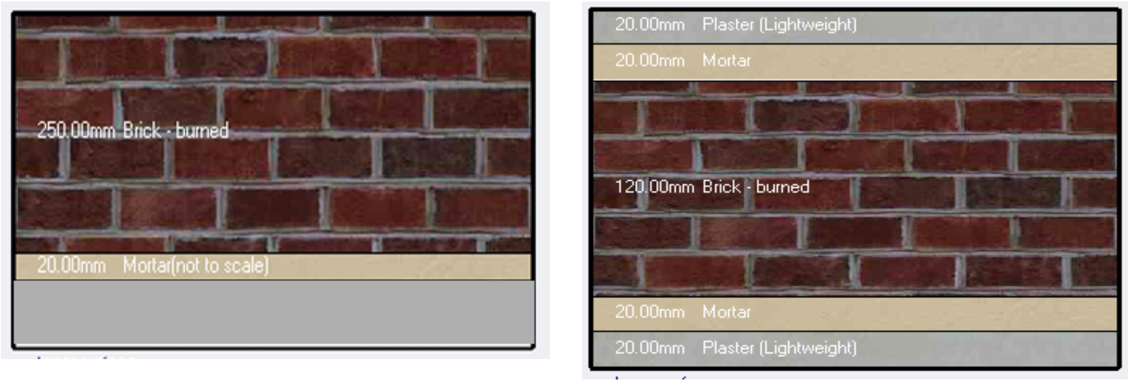
Material	Thick. mm	Density kg/m^3	Conductivity W/m.K	Specific heat J/kg.K
External wall from outside to inside (*U-value=1.58 W/m^2.K*)				
Plaster (light)	25	2300	1.3	840
Mortar	20	2800	0.88	896
Brick	250	1500	0.85	840
Internal partitions (*U-value= 1.64 W/m^2.K*)				
Plaster (light)	25	2300	1.3	840
Mortar	20	2800	0.88	896
Brick	120	1500	0.85	840
Mortar	20	2800	0.88	896
Plaster (light)	25	2300	1.3	840
Intermediate floors (*U-value= 1.14 W/m^2.K*)				
Ceramic tiles	25			
Mortar	20	2800	0.88	896
Sand brick	60	2200	1.83	712
Reinforced concrete	120	2300	1.9	840
Mortar	20	2800	0.88	896
Plaster (light)	25	2300	1.3	840
Roof (*U-value= 1.92 W/m^2.K*)				
Mosaic tiles	30	2100	1.4	800
Mortar	20	2800	0.88	896
Sand brick	60	2200	1.83	712
Reinforced concrete	120	2300	1.9	840
Mortar	20	2800	0.88	896
Plaster (light)	25	2300	1.3	840

Table 2. Used glass specifications.

Name	**Category**	**SHGC***	**LT****	**U-value *W/m^2.K***
Clear 6.4mm	Single	0.71	0.65	5.76
Clear reflective 6.4mm-(stainless steel cover 8%)	Single reflective	0.18	0.06	5.36
Clear 3.2mm Transparent/Transparent (6.0mmair)	Double	0.66	0.59	3.71
Clear reflective 6.4mm Transparent (stainless steel cover 8%)/ transparent-(6.0mmair)	Double reflective	0.13	0.05	2.66

*Solar heat gain coefficient

** Light transmission



a) Outer surface b) Inner surface

Figure 5. Wall sections used, (a) exterior wall and (b) internal wall/partitions.

3. Results and discussion

3.1. Measured thermal condition

The thermal comfort evaluation stage in the presented study is determined by three methods which are:

- Using the PMV and PPD values inside the classrooms in accordance with ISO 7730 (ISO Standard 7730, 2005) specifications which was originally developed by Fanger in 1970 on the basic of climate chamber experiments
- Using the Adaptive Comfort Standard (ACS) for naturally ventilated buildings which were employed by ASHRAE standard 55 (ASHRAE, 2010b).

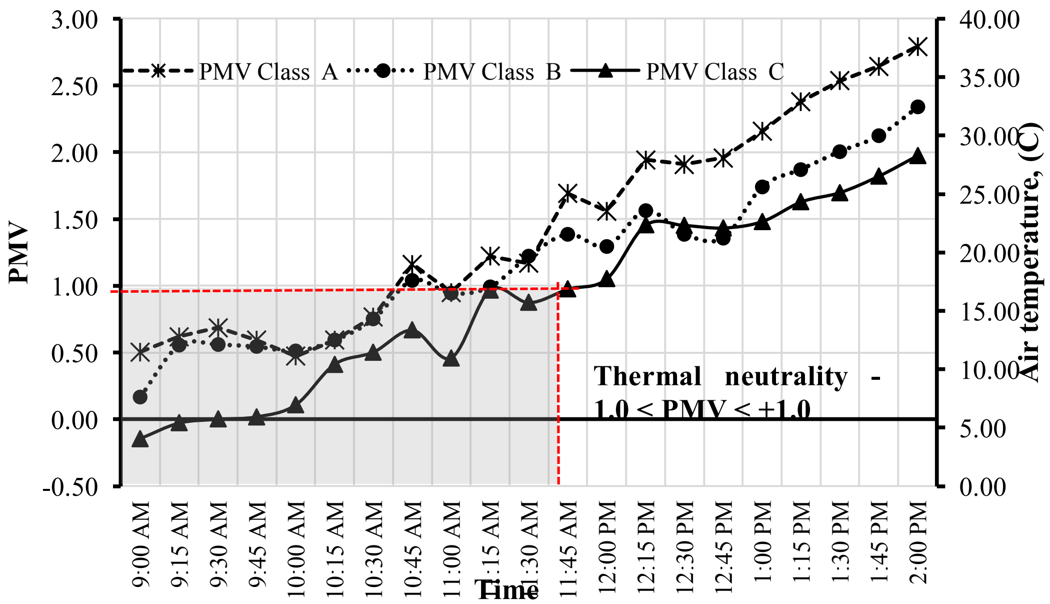


Figure 6. Indoor air temperature against PMV.

According to ISO 7730 (ISO Standard 7730, 2005) specifications, the acceptable thermal environment for a PMV lies between -1 and +1 and the PPD is below 20%. The PPD is related to the PMV and it is based on the assumption that people voting -3,-2, +2 or +3 are dissatisfied. PMV for case studies started at -0.14 value and raised until 2.8 value at the end of school day, further analysis showed at the afternoon the PMV value increases the comfort limit as shown in Fig. 6. The average PMV and PPD across the classrooms were 1.17 and 38.86%, respectively which indicate a high level of thermal discomfort in the classrooms. The same trend that was predicted by Gado and Mohamed (Gado and Mohamed, 2009b).

In the ACS, the mean monthly outdoor air temperature determines the acceptable indoor air temperature. This relationship is expressed by the following formula:

$$T_{com} = 0.31\ (T_{out}) + 17.8$$

Where T_{com} is the optimum comfort operative temperature in °C and T_{out} is the mean monthly outdoor air temperature in °C. Thus, in this context the acceptability ratio of thermal environment decreases less than 80% when the indoor operative temperature exceeds 29.5°C. The measured data clearly show that there has been a steady increase of operative temperature in the measurement within the classrooms ranged from 25.5ºC to 34.5ºC during that day time. As depicted from Fig. 7, the internal classroom temperature is raised by 7 ºC. According to the results of (Humphreys, 1977) this level of increase well led to discomfort condition for the pupils. This might be due to the fact that children are sent to the schools wearing relatively warm clothes in the relatively cool morning than required for the range of temperature variation during the school day. Clearly from the figure, the internal air temperature profiles across the three cases studied are within the comfort limit until noon time. While afternoon time, the results indicate that the internal air operative temperature across the three classrooms exceeded the comfort limit which means that pupils are in discomfort for about 39.86% of the time they spent in school.

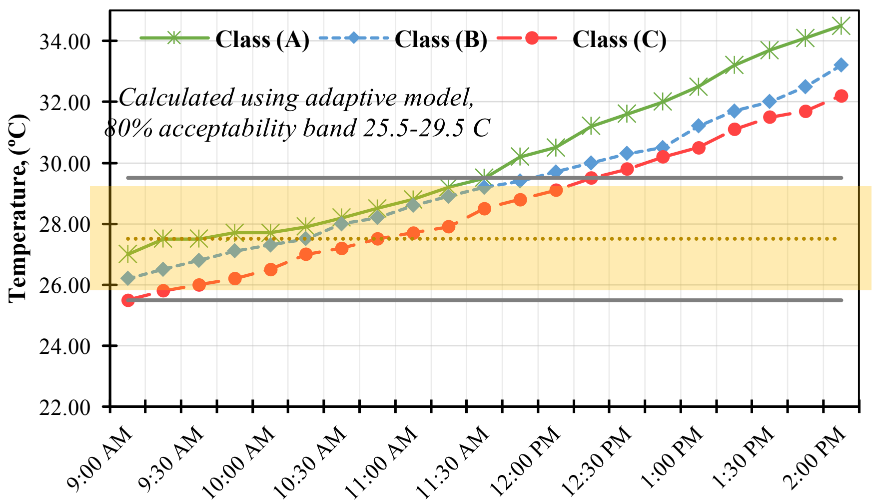


Figure 7. Indoor operative temperature profiles with (ACS) comfort zone limit.

3.2. Calibration test

As mentioned earlier, in this computational simulation process, three parameters were considered for base model validation. They are internal average hourly temperature, average hourly relative humidity and monthly energy consumption. Figure 8 shows detailed comparisons of the indoor air temperature, outdoor air temperature during selected day from field study.

It can be clearly seen that the predictive simulated results tend to be underestimated the experimental results. As Fig. 7 displays the highest indoor air temperature during the three days was recorded as 32.2°C and the lowest indoor temperature as 25.5°C, while DesignBuilder simulation showed the highest indoor air temperature as 32.5°C and the lowest indoor temperature as 24.8°C. On the other hand, the highest outdoor air temperature during field study was 34.5°C, while DB simulation showed the highest outdoor air temperature was 35.2°C. In conclusion, the measured data varies within 6.7% of the simulated data. The discrepancies between the measured and predicted results might be due to that, in the real building, there were numerous infiltration airflows paths which allow the indoor heat to dissipated. However, in DB model the infiltration rate was fixed and the values could be lower than that of the real buildings. Hence, less heat dissipation in the DB model led to higher prediction of the indoor heat gain.

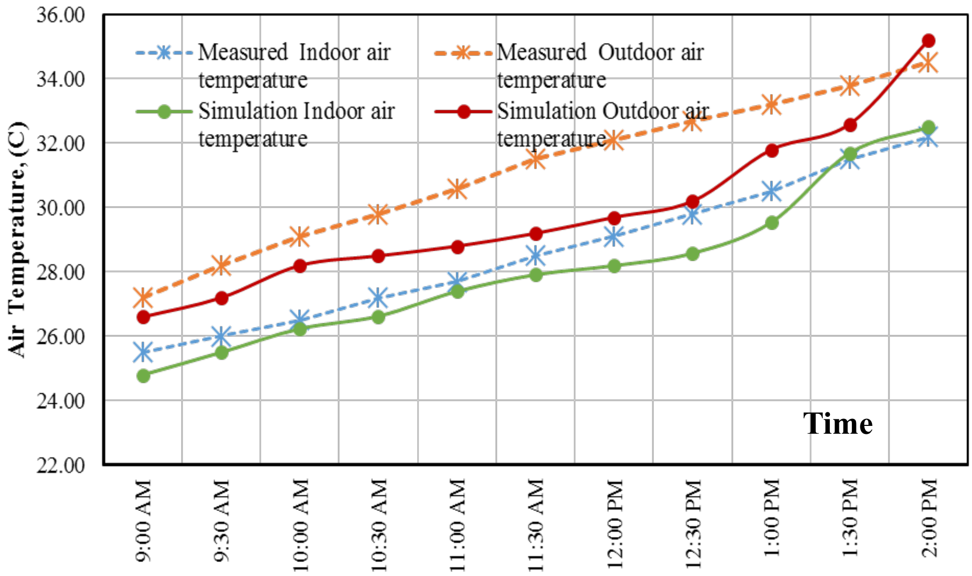


Figure 8. Measured vs. simulated internal average hourly indoor air temperature and average hourly outdoor air temperature.

3.3. Energy use

Each zone of the building was physically investigated with the assistance of the building's operation in order to obtain information and data on the building lighting, equipment and occupancy for the purpose of knowing details of thermal characteristics of building envelope. Moreover, electricity utility bills for the whole year 2013 has been collected. For the financial analysis, the cost of the energy consumption was calculated in Egyptian pound (EGP), using the electricity tariff by the Egyptian Ministry of Electricity and Energy for the governmental sector, which is referred to as operation cost. Next, the energy use within the building was simulated for a whole year, using real climatic data. It is found from Fig. 8 that the collected data of energy is within 9% of the simulated energy consumption. This demonstrates that the DB predictions are in good agreement with the data collected.

According to the simulation and collected results the annual electricity consumption for the building was 13019 kW per year (9227.27 EGP per year). This means that the building is consuming 1.5 kWh/m^2/year of electrical energy. Based on simulations, lighting sources consume the largest amount of total consumption. Fig. 9 shows that the electricity consumption in summer months is slightly higher than the winter months, because of appliances auxiliary system (two ceiling fans in each classroom as they are operating all over the school day).

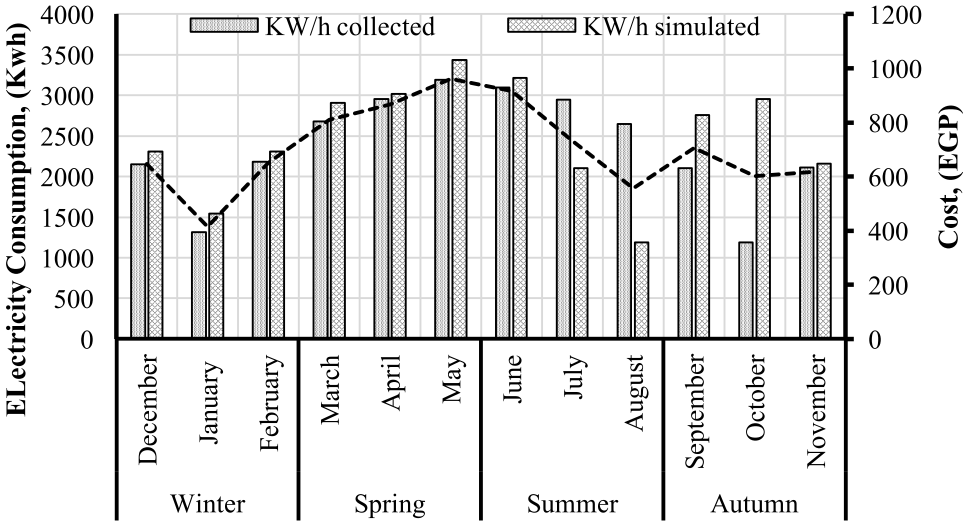


Figure 9. Comparison between averaged electricity bills and energy simulation.

3.4. Comfort analysis

As a result of model validation, a simulation using DB software was applied to get values of indoor air temperature within school day and outside air temperature of Assiut climate zone through the school year. Consequently, comfort limit conditions were determined based on ACS model which were employed by ASHRAE standard 55. All material and construction details, as discussed previously, have been applied to the simulation model. On analysing the hourly climatic data of Asyut city, it is clearly seen from the displayed Fig. 10 that that the predictive indoor air temperature exceed the adequate level of comfort during October (the first of 20 days and the rest of month after noon time), the last half of April and May entirely represent about of 32.29% of school year contrary of 7.98% of discomfort conditions during morning hours as indoor air temperature declined the minimum limit of adequate comfort in last December and January. On the other hand, 59.73% of occupied time the predictive indoor air temperature expected to fall within comfort limit.

In terms of heat gains which refer to flows through the fabric due to the air temperature difference between inside and outside. Fig. 11 displays the main sources of heat gain within classroom during school day. As depicted from the figure, solar gains from exterior windows, which increased around noon hours as a result of increasing of solar radiation incident amount, are the largest source of heat followed by the occupants and lighting. While, ceiling and internal walls represent a small proportion of total heat gain of the building.

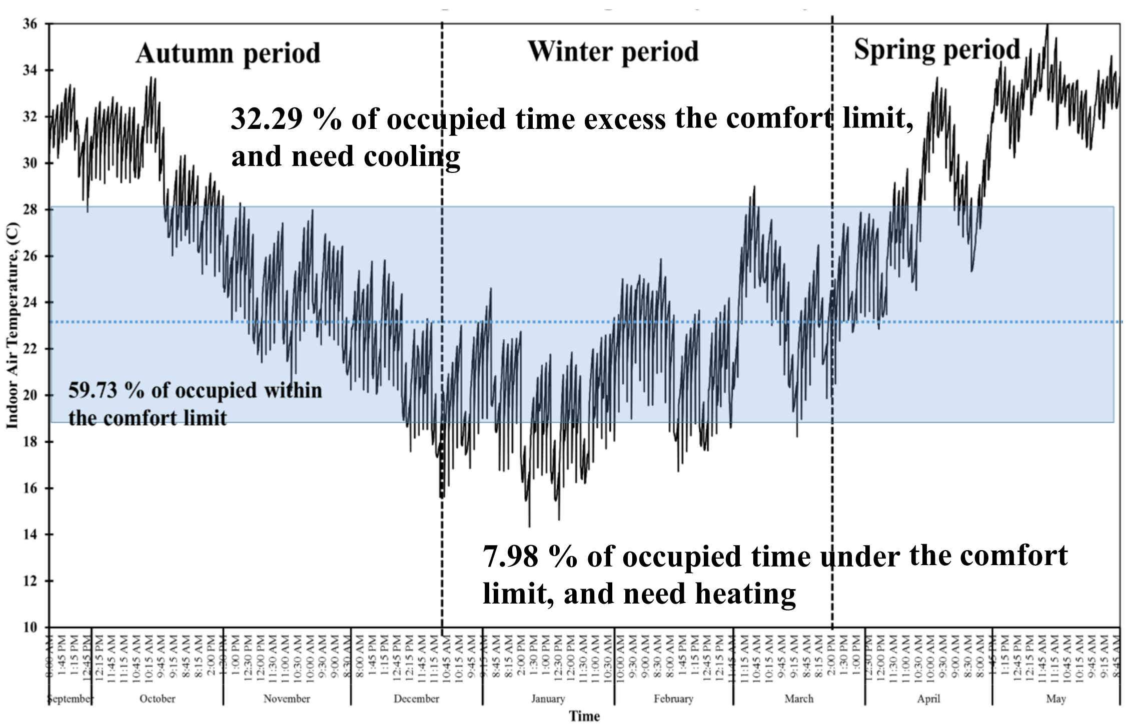


Figure 10. Indoor air during school year in occupied time in Asyut.

4. Conclusion

This study investigated the thermal comfort conditions as well as energy consumption within public primary schools that are designed based on natural ventilation (infiltration) and air movement within the classrooms by ceiling fans. The output results may assist school building designers and stakeholders in the future to improve the thermal environment conditions within the classrooms of such schools. The main achievements of this study are as follows:

- It is reasonable to conclude from this study that DesignBuilder is a satisfactory simulation package with which to assess thermal comfort conditions and predict energy consumption for public school buildings in Egypt.
- The acceptability ratio of thermal comfort calculated by (ACS) model ranges from 25.5ºC to 29.5ºC. It is expected that students spent about 59.73% within comfort conditions. In contrast, 32.29% of occupied time excess the comfort limit and fall within under-heated area. However, 7.98% fall within overheated area and need cooling.
- According to the simulation and collected results the annual electricity consumption for the building was 13019 kW per year (9227.27 EGP per year). This means that the building is consuming 1.5 kWh/m^2/year of electrical energy.

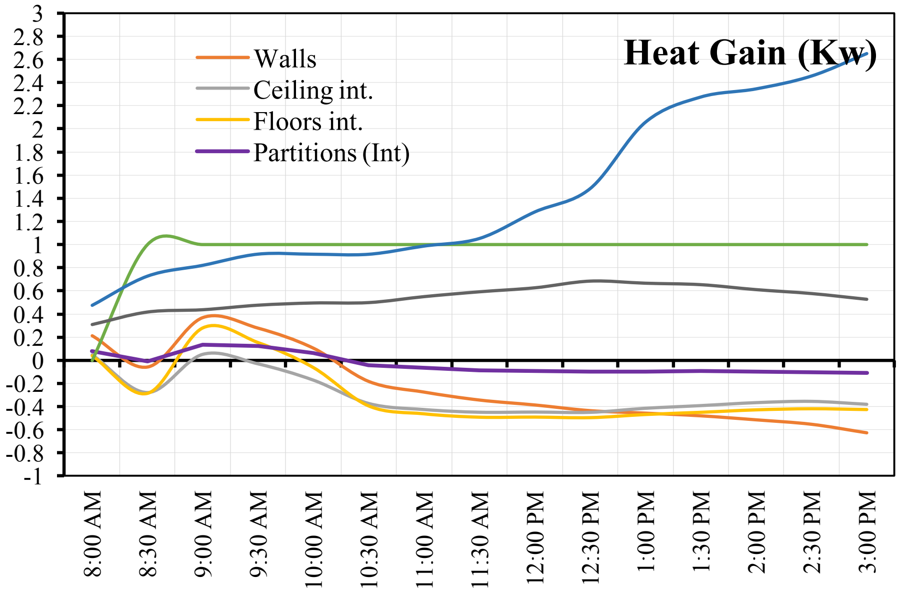


Figure 11. Heat balances in the classroom for 15 October.

In order to rehabilitate the existing government school buildings, thermal comfort wise, the study has derived the following recommendations:

- The necessity to develop new designs and guidelines to adapt the variation in climate conditions all over the country, and provide comfort conditions for occupants.
- Increase thermal efficiency of the building envelope by the use of external insulation.
- Protect all the exposed openings from direct solar continues shade on those openings.
- Support further researches on insulation materials and its behavior in local constructions.

Acknowledgment

The first author would like to acknowledge Ministry of Higher Education (MoHE) of Egypt for providing a scholarship to conduct this study as well as the Egypt Japan University of Science and Technology (E-JUST) for offering the facility and tools needed to conduct this work.

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Received: 29 September 2014 • **Revised**: 26 March 2015 • **Accepted**: 14 May 2015