Chapter

Computational Analysis of a Lecture Room Ventilation System

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Abstract

The level of Indoor Air Quality (IAQ) has become a big topic of research, and improving it using passive ventilation methods is imperative due to the cost saving potentials. Designing lecture buildings to use less energy or Zero Energy (ZE) has become more important, and analysing buildings before construction can save money in design changes. This research analyses the performance (thermal comfort [TC]) of a lecture room, investigate the use of passive ventilation methods and determine the energy-saving potential of the proposed passive ventilation method using Computational Fluid Dynamics (CFD). Results obtained showed that air change per hour at a wind velocity of 0.05 m/s was 3.10, which was below standards. Therefore, the lecture hall needs external passive ventilation systems (Solar Chimney [SC]) for improved indoor air quality at minimum cost. Also, it was observed that the proposed passive ventilation (SC) system with the size between 1 and 100 m^3, made an improvement upon the natural ventilation in the room. There was a 66.69% increase after 10 years in the saving of energy and cost using Solar Chimney as compared to Fans, which depicts that truly energy and cost were saved using passive ventilation systems rather than mechanical ventilation systems.

Keywords: computational fluid dynamics, indoor air quality, solar chimney, thermal comfort, zero energy

1. Introduction

Indoor Air Quality (IAQ) and energy consumption in lecture rooms is an important issue and of great concern during the last few years. For energy consumption, fossil fuels (coal, oil, and natural gas) are currently the most used form of energy resources, accounting for invariably 82% of energy consumed [1]. However, the burning of fossil fuels for our comfort emits carbon dioxide and in turn leads to the greenhouse effect, acid rain, and environment hazards [2–3]. Accordingly, a temperature analysis at NASA's Goddard Institute for Space Studies (GISS) noted that the average global Earth temperature has increased approximately by 0.8°C (1.4°F) since 1880, where most of the warming occurred in the last few decades at a rate of 0.2°C per decade since 1970 [4].

Another concern is the level of indoor air quality in lecture rooms which has been confirmed to cause discomfort among students in a class and may induce sleep and also affect learning. While considering the ventilation of lecture halls, indoor air quality is very vital. Natural ventilation has the potential to save energy costs as well as to maintain good air quality within the building, where natural ventilation is a method to deliver fresh air through buildings creating a pressure difference.

Natural ventilation could be as a result of air infiltration through various unintentional openings in the building. However, natural ventilation takes place as a result of manual control of opening of the building's doors, windows, or through other fenestration in the building. Furthermore, natural ventilation is achieved when a building is equipped with a ventilation system like natural ventilation solar chimneys and wind catchers. Air flows in and out of the building as a result of pressure differences across the openings, which is due to the combined action of wind and buoyancy-driven forces. In modern times, natural ventilation is considered not only as a simple measure of providing fresh air for the occupants and maintaining adequate indoor air quality levels, but also an excellent energy-saving means of reducing the internal cooling load of buildings located in the tropical regions. Natural ventilation system alone may achieve a good indoor thermal comfort, depending on the ambient conditions, without requiring the help of additional mechanical cooling devices.

1.1 Background of study

The high growth in population leading to high energy use globally and the accompanying increase in the fossil energy demand has resulted in detrimental effect on the environment and health of the society [5]. Among all users of fossil energy, the building industry sector has been observed to be one of the major energy consumers [6]. It is estimated that the building construction industry accounts for approximately 40% of the world's energy consumption. The industry is also accountable for the emission of pollutants of which about 70% of the total global emitted Sulphur oxides and 50% of emitted CO_2 are credited to it [7]. The total amount of energy consumed by the building industry sector are in four stages: stage one is during the process of making the materials; stage two is during transporting the materials, stage three is during the construction of the buildings and lastly during their lifetime of the buildings energy is required for operation and maintenance of the buildings [8].

However, it is essential to maintain good indoor air quality in buildings, which is achieved by providing sufficient ventilation to ensure the removal of stale air and the supply of fresh air for the occupants using several methods. These methods include mechanical ventilation (using fans and ducts to move huge volumes of air with or without heating/cooling the air); air-conditioning (in which the temperature and humidity of the air supplied through fans and ducts are fully controlled); and natural ventilation (which makes use of the naturally occurring driving forces of wind and buoyancy). A hybrid approach has also been used in practice, which combines both natural forces and mechanical devices, usually fans, to provide adequate ventilation [9–10].

The main disadvantages of air-conditioning and fans are cost (operation and maintenance costs) and space required to house the necessary equipment.

Consequently, several architects and building design engineers are giving more attention to natural ventilation or mixed-mode systems. Predictions of ventilation scenarios are more accurately modelled for mechanically driven systems as the designer knows the flow parameters in the different components making up the system [9, 11].

From the time when more powerful, inexpensive computers were available, an additional tool has become available to designers – Computational Fluid Dynamics (CFD). This method analyses the airflow in a room by sub-dividing the space in the room into small cells and solving the equations governing the airflow and temperature distribution in each cell. This method allows changes to the geometry and operating conditions be made more easily, offering a perfect tool for the investigation of various ventilation options an early stage in the design process [9].

1.2 Statement of the problem

The electricity consumed due to the extensive usage of air conditioning units during hot weather results in increased peak electricity demand during this season. This high electrical energy demand invariably increases the consumption of fossil fuel, leading to increased atmospheric pollution and finally climate change. Therefore, using renewable energy sources such as wind and solar energy as passive ventilation methods to provide adequate indoor air quality is vital. These methods will solve direct challenges associated with building high energy usage and indirectly pollution and climate change caused by numerous mechanical ventilation systems [12–13]. As with passive ventilation, fossil dependency is eradicated and therefore natural ventilation system is a better alternative solution for indoor air quality.

1.3 Aims and objectives

The aim of the study is to develop a computational model of a lecture room to perform ventilation analysis with and without incorporating passive ventilation, and thus investigating the energy saving potential and indoor air quality improvements of the room.

The objectives were:

I. To analyse a model lecture room's thermal comfort performance without mechanical or passive ventilation devices using CFD.

II. To investigate the use of passive ventilation system to improve the natural ventilation of the room.

III. Determine the energy saving potential of the proposed passive ventilation system.

1.4 Justification of study

There is huge dependence on electricity to run mechanical devices to provide ventilation and thermal comfort in buildings located in the tropics and in temperate regions during hot seasons. Commercial and residential buildings account for 40% of the world energy demand as well as 40–50% of the global carbon emissions [14]. More than 60% of the total energy consumption in buildings are attributed to Heating Ventilation and Air Conditioning (HVAC) systems [15]. This signifies a major opportunity for reducing the total global energy consumption and greenhouse gas emissions. Naturally ventilated building designs using devices such as wind catchers and solar chimneys are progressively being used for increasing fresh air flow and reducing energy consumption in buildings. Proper natural ventilation is of necessity owing to the high cost of maintenance of mechanical ventilation systems and relative increase in electrical energy cost needed to operate such machine. It is therefore justified to apply wind and solar energy, which are renewable energy sources, to provide adequate thermal comfort, indoor air quality and solve some challenges associated with mechanical ventilation systems.

2. Literature review

2.1 Ventilation

According to Awbi [16] ventilation is the "Replacement of polluted or stale indoor air by fresh or unpolluted air from outside." The main purpose of a ventilation system, mechanical or natural, in a building is providing acceptable thermal environment and indoor air quality for its inhabitants. In summary, ventilation in a building is designed to;

1. Deliver adequate air for breathing and removing CO_2. The conventional level for the maximum concentration of CO_2 within an occupied space is 5000 parts per million, or 0.5% by volume for an exposure of 8 h as recommended in **Table 1**.

2. Eliminate huge quantity of contaminants and airborne toxins.

3. Cool the building and its occupants in hot seasons [16–20].

2.1.1 Ventilation and thermal comfort

Ventilation systems are designed and incorporated in buildings to provide comfortable microclimates in the ventilated spaces [16]. The microclimate in this circumstance includes a thermal environment and air quality [21]. Therefore, in the design of natural ventilation systems these two factors (providing acceptable air quality and thermal comfort environment) are considered.

The human body's thermal balance are considered to be affected by four environmental factors (air temperature, mean radiant temperature, air velocity and

	Minimum ventilation required (litre/s per person)		
Activity	**0.1% CO_2**	**0.25% CO_2**	**0.5% CO_2**
At rest	5.7	1.8	0.085
Light work	8.6–18.5	2.7–5.9	1.3–2.8
Moderate work		5.9–9.1	2.8–4.2
Heavy work		9.1–11.8	4.2–5.5
Very heavy work		11.8–14.5	5.5–6.8

Table 1.
Ventilation rates required to limit CO_2 concentrations [18].

water vapour pressure in the air) [22] and three human factors (metabolism, activity and thermal insulation of clothing) [23].

2.1.2 The role of thermal comfort

There are some several reasons why thermal comfort is important in the design of buildings. These are:

- Human satisfaction is significantly affected by thermal comfort.
- There is a direct relationship between the energy consumption of a building to the temperature its occupants try to achieve in their accommodation.
- Occupants of buildings would continue to do everything possible to make themselves comfortable. Usually more energy is applied in achieving this and may be doing away with a planned low energy strategy [24].

2.1.3 Providing acceptable air quality

Ventilation in a building is designed to provide acceptable thermal environment in addition to suitable indoor air quality. However, the ventilation rate required to provide cooling and a satisfactory thermal environment is higher than that required to provide acceptable indoor air quality alone [25]. **Tables 1** and **2** show the required and recommended minimum ventilation rates necessary in buildings to provide satisfactory amount of oxygen for breathing, to dilute the metabolic CO_2 and to dilute odour. It is noted that the amount of ventilation required in a building is highly affected by the activity.

Figure 1 shows the ventilation rates for fresh air control, provided by the Chartered Institute of Building Services Engineers (CIBSE), the minimum amount of required airflow rate is also greatly affected by the amount of smoking, and by minimising smoking in the indoor area, the required airflow rate decreases as considerably.

2.2 Natural ventilation in educational buildings

Educational buildings are usually segmented into rooms with a number of people involved in various activities when in use. Thermal comfort in these buildings is important for the convenience of the occupants. Ventilation designs of educational buildings are based on factors such as the projected number of

Source	Purpose of ventilation	Minimum recommended value (1/s/p)
CIBSE (1989)	oxygen for breathing	0.3
HSE Guidance Note EH22 (1988)	oxygen for breathing	0.5
CIBSE (1986: B2–3)	dilution of metabolic CO_2	5
HSE Guidance Note EH22 (1988)	dilution of metabolic CO_2	2
CIBSE (1986: B2–3)	dilution of odour	8
HSE Guidance Note EH22 (1988)	dilution of odour	9

Table 2.
Recommended amount of air to provide acceptable indoor air quality.

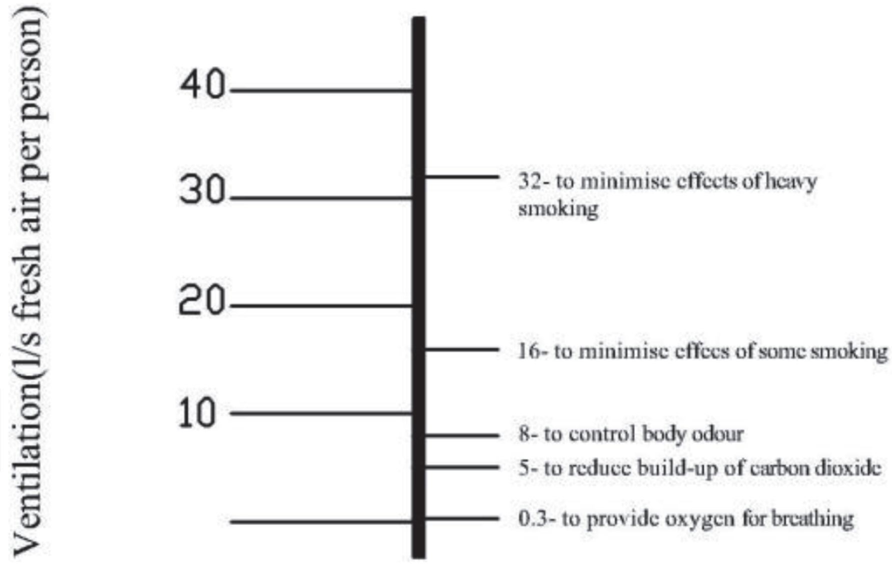

Figure 1.
Ventilation rates for fresh air control [26].

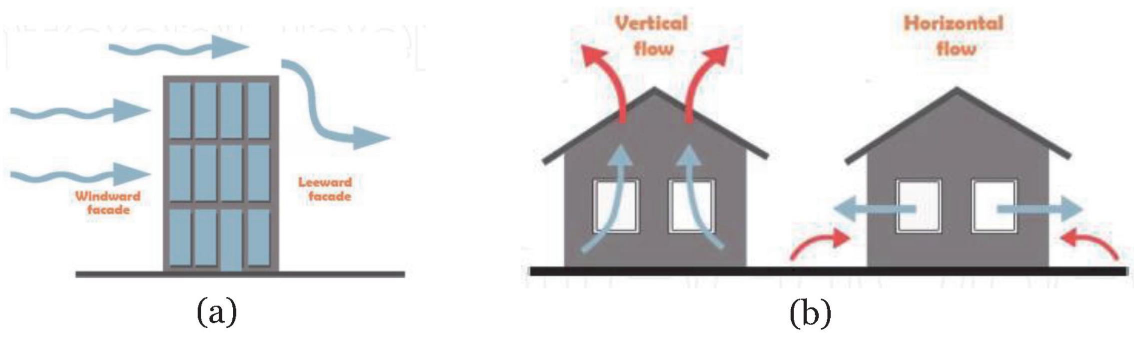

Figure 2.
Mode of natural ventilation: (a) natural ventilation due to pressure difference. (b) Natural ventilation due to temperature difference [27].

occupants and ambient conditions such as average temperature and relative humidity. In many places like Nigeria, power considerations require that energy consumption in these buildings should also be kept as low as possible. This may require the use of natural or passive ventilation which is strongly dependent on the airflow circulation pattern within room spaces, which can be achieved by temperature differences (buoyancy forces) or pressure differential between two points (**Figure 2**) [27]. Adequate ventilation in educational facilities is of great importance as reviews of previous studies in school environments [28–29] shows that there are inadequacies in the indoor air quality (IAQ) in many classrooms leading to higher risk of health-related issues especially in preschool environments. It was also noted that this problem is predominant in developed countries. However, the same challenges are encountered in developing countries especially during the hot season where classrooms are mostly overcrowded (**Figure 3**). In a study in China to improve the ventilation design of school buildings [30], it was noted that despite the fact that school buildings are actually designed for natural or mechanical ventilation, inadequate ventilation occurs. Furthermore, during hot season and due to crowded classrooms the ventilation system becomes inadequate thus affecting learning. It is therefore inferred that in tropical regions and developing countries where natural ventilation is being used, the number of students in a classroom, the outdoor temperature and the activities in the lecture hall affects the ventilation performance of the lecture hall.

Figure 3.
Selected (overcrowded) lecture hall.

Figure 4.
Denmark study classrooms: (a) classroom with automatically operable windows and exhaust fan; (b) mechanically ventilated classroom [31].

In a study carried out in Denmark to measure indoor climatic conditions in classrooms [31], a comparison of different ventilation systems was done (**Figure 4**). The results obtained revealed that mechanical ventilation and natural ventilation with added exhaust fan performed better than the other systems. This indicates that the basic passive ventilation using window may not be adequate for educational buildings and may require the aid of other systems.

From other studies it has been observed that 30 students in a classroom would produce about 2.3 and 2.7 kWh of heat per hour and 500 litres of CO_2. These are indoor loads that need to be removed to improve the thermal comfort and IAQ of the classroom. Adequate classroom ventilation will solve these issues [32].

3. Methodology

3.1 Study area

The research was conducted at Olabisi Onabanjo University, College of Engineering and Environmental Studies, Ibogun Campus, Ifo, Ogun State, Nigeria located 240°SW on the Longitude 3.0990 and latitude 6.8080. The location has an annual average temperature of about 28.5°C and wind speed of about 4 m/s. The average relative humidity is about 63%. The study was performed in the selected lecture room where ventilation is normally achieved through opening of doors, windows and Mechanical ventilation system (ceiling fans). This lecture hall is representative of lecture halls in many Nigerian higher institutions especially in the southwestern region of Nigeria.

3.2 CFD model

The pseudo steady-state incompressible Reynolds-averaged Navier–Stokes (RANS) method is applied due to the computational cost and modelling accuracy. The standard $k - \varepsilon$ two-equation turbulence model has been modelled for this study. All room simulation scenarios modelled only considered wind-driven ventilation in isothermal conditions. The model equations are as follows.

3.2.1 Flow and energy equations

The general classical equations describing the flow in a room are represented as follows.

i. Continuity equation:

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x_1}(pU_1) = 0 \quad (1)$$

ii. Momentum (Navier-Stokes) equation:

$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial X_i}(\rho U_i U_j) = -\frac{\partial p}{\partial X_i} + \frac{\partial}{\partial X_j}\left(-\rho\overline{u_i u_j}\right) + \frac{\partial}{\partial X_j}\left[\mu\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial Xi}\right)\right] + g_i(\rho - \rho_r) \quad (2)$$

iii. Thermal energy equation:

$$\frac{\partial}{\partial t}(\rho T) + \frac{\partial}{\partial X_j}(\rho U_j T) = \frac{\partial}{\partial X_i}\left(-\rho\overline{u_i T'}\right) \quad (3)$$

It is noted that for the computational model used in this study that Eq. (3) has no effect on the airflow in the room as isothermal conditions were considered. However, Eq. (3) is considered for the solar chimney model. U_i represents the time-mean velocity component in the X_i direction while u is the fluctuating velocity components in the x_i direction. For turbulent flows, the viscous stress term on the right hand side of Eq. (2) is neglected as it is usually much smaller than the Reynolds stress term in the equation. For a case of steady incompressible flow and fluctuating velocities described by a suitable turbulence model, the effect of a fluctuating flow is represented by means of time-independent flow equations as shown below

$$\frac{\partial}{\partial X_j}(\rho U_i) = 0 \quad (4)$$

$$\frac{\partial}{\partial X_j}(\rho U_i U_j) = -\frac{\partial p}{\partial X_i} + \frac{\partial}{\partial X_j}\left(\rho\overline{u_i u_j}\right) + g_i(\rho - \rho_i) \quad (5)$$

$$\frac{\partial}{\partial X_j}(\rho U_j T) = \frac{\partial}{\partial X_i}\left(-\rho\overline{u_i T}\right) \quad (6)$$

3.2.2 Turbulence model

In Vector forms,
Turbulent kinetic energy (TKE, k)

$$\frac{\partial k\overline{u_i}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{v_t}{\sigma_k}\frac{\partial k}{\partial xi}\right) + v\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{7}$$

Energy dissipation rate (ε)

$$\frac{\partial \varepsilon\overline{u_i}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{v_t}{\sigma_k}\frac{\partial k}{\partial xi}\right) + c_{1\varepsilon}\frac{\varepsilon}{k}v\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\frac{\partial u_j}{\partial x_i} - c_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{8}$$

The solutions to Eqs. (5) and (6) require that the fluctuating velocity term in Eq. (5) and the fluctuating temperature term in Eq. (6) be represented by "equivalent" time-mean terms. All available turbulence models are semi-empirical and do not produce the same results. The two equation kinetic energy, k, and its dissipation rate, ε model is one of the most popularly used turbulence models applied by most researchers who studied the numerical solution of air flow in rooms and cavities [33–34] and is also used for the present study.

3.2.3 Setting up a CFD model

Computational fluid dynamics can be set up using the chart below in **Figure 5**.

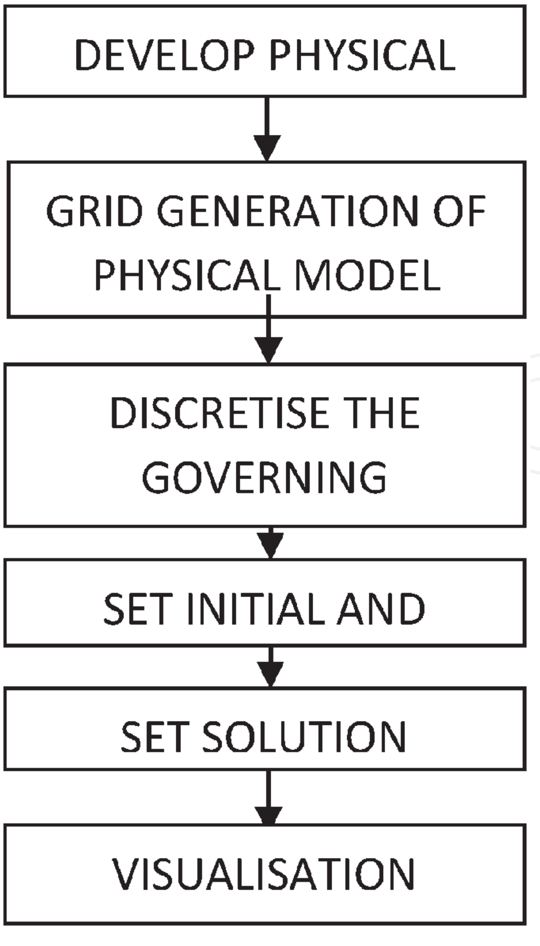

Figure 5.
CFD model chart.

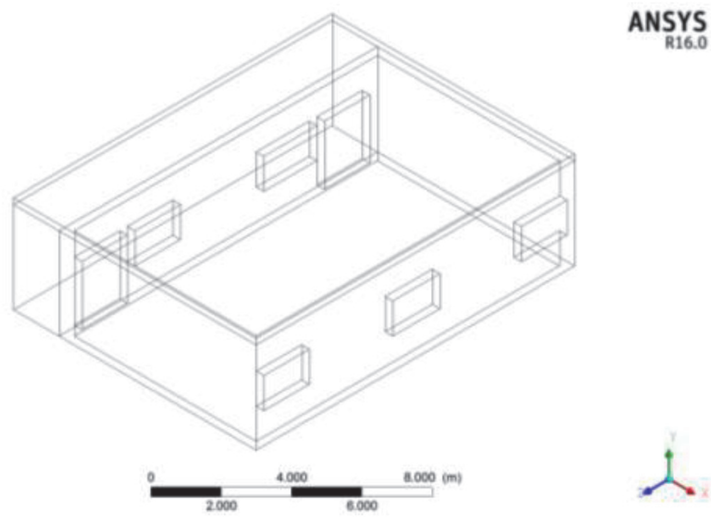

Figure 6.
Computational domain for analysis.

3.2.4 The physical model

This is the geometry of the area for the simulation. It constitutes the site plan and the room. The cross-ventilated building model used in this model is showed in **Figure 6**. The computational model was sized 17.4 m × 9 m × 3 m (length × width × height). The building height served as the reference length scale H. Two openings with dimension 2.4 m × 1.5 m (width × height) were installed at the rear end of both the windward walls.

The temperature range of the location is between 22 and 35°C, the outdoor relative humidity is between 35 and 90% and the wind speed is between 2.0–6.0 m/s. The lower value of the wind speed was used as the maximum for the computational analysis being the worst case scenario.

3.2.5 Grid generation of physical model (meshing)

In the CFD set up, the field is subdivided into several grids and the partial differential equations governing a flow field (e.g. velocities, temperature pressure, etc.) are solved at all points of the field [33, 35] as shown in **Table 3**.

In order to analyse fluid flow, flow domains are split into smaller sub domains. The process of obtaining an appropriate mesh is called grid generation (**Figure** 7).

3.2.6 Discretise the governing equations

After meshing, the governing equations are then discretised and solved in each of these sub domains. ANSYS Fluent uses the finite volume method for equation discretisation, which was used to perform the simulations in this study.

Number of nodes	Number of elements	Smoothing	Mesh type
2478	7337	Medium	Mixed • Triangular/Tetrahedron • Quadrilateral/Hexaheron

Table 3.
Grid analysis.

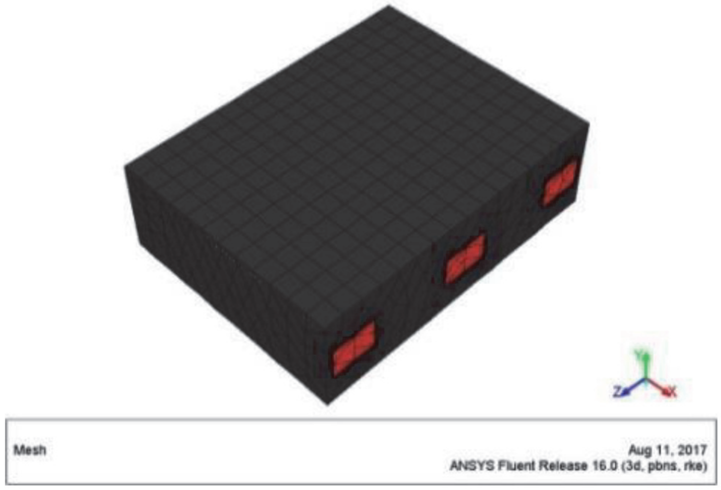

Figure 7.
Grid (mesh) generation for computational domain.

3.2.7 Initial and boundary conditions

The boundary conditions (**Table 4**) and the initial conditions are then set. The reasonable set up of physical quantities at the boundaries of the flow domain affect the overall accuracy of the CFD model. Initial conditions are essential for all CFD model. **Figure 8** indicates the point where solar radiation effect is introduced into the model, **Figure 9** shows the points initially set as flow outlets into the lecture hall, while **Figure 10** shows the wind inlet into the model. It is noted that an open corridor exists under the hanging roof and aid inflow to the lecture hall as shown in **Figures 8–10**.

3.2.8 Solution method

The solution method used is the SIMPLE Algorithm method. SIMPLE is an acronym for Semi-Implicit Method for Pressure Linked Equations. It is used to couple the pressure and velocity equations.

Wind velocity (m/s)	Solar radiation (W/m^2)	Pressure outlet (atm)	Turbulence model
0.05–2.0	200–1000	1	K - ε (Realisable)

Table 4.
Boundary conditions.

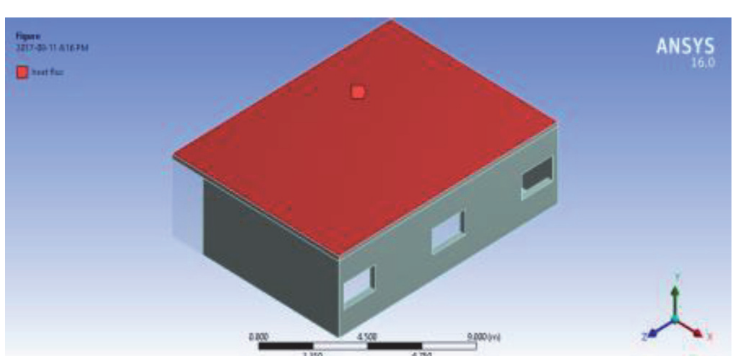

Figure 8.
Solar radiation input.

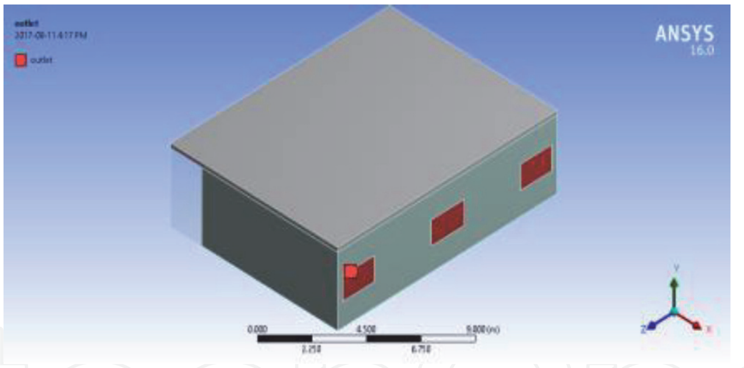

Figure 9.
Pressure outlet (mass flow) input.

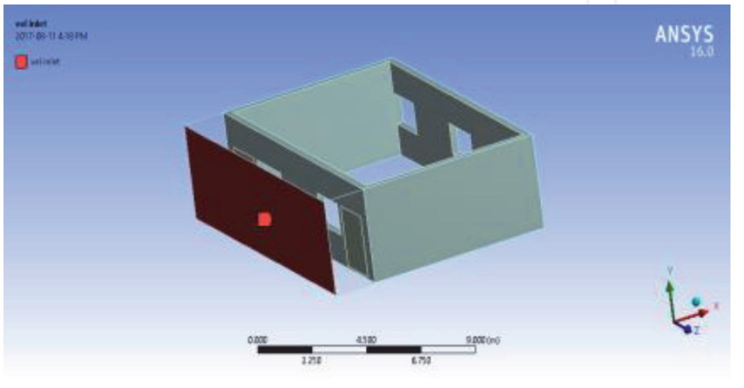

Figure 10.
Selection of the point for wind flow input to the model.

3.2.9 Visualisation

Results are the objectives of CFD simulation. They reveal the performance of the design. They reveal if the design satisfies or meet its objectives. Results are essential for making informed design decisions as revealed in **Figures 8–10**.

3.3 Performance analysis

Thermal comfort is determined by various factors. These factors include temperature, humidity and evaporative cooling. Using the values for the mass flow rate, the values for the air change per hour of the room can be deduced. Thermal comfort is very important to humans; therefore, using computational fluid dynamics analysis, ventilation performance of a room is determined with or without passive ventilation systems. The main driving force for the ventilation performance is the air change in the room depicted by the air change per hour, ACH.

The model for the performance analysis is written as:

$$ACH = \frac{3600m}{\rho fsV} \tag{9}$$

where,
m = Mass flow rate of air (kg/s).
V = Volume of the room (m^3).

3.3.1 Solar chimney model

Using data from various researchers, values which include room size, solar chimney size, etc. have been used to investigate the use of passive ventilation

Room size (m^3)	Solar chimney size (m^3)	Ratio = SCS/RS	ACH (1/h)	Author
64	2.25	0.035	1.5	Bansal et al. [36]
50	2.5	0.05	3.46	Maerefat and Haghighi [37]
27	1.64	0.0607	5.6	Mathur et al. [38]
25	6	0.24	8	Khedari et al. [39]
15	2.5	0.167	7	Yan et al. [40]

Table 5.
Parameters of previous researches by various authors.

system (solar chimney) for improving the natural ventilation of a room. These data helped in developing a mathematical model that was used to predict the rate of ventilation (the air change per hour) of a room or space given by Eq. (10):

$$Y = mX + c \tag{10}$$

where,

$$X = \frac{Solar\ Chimney\ Size}{Room\ Size} \tag{10a}$$

and,

$$Y = ACH\ (Air\ change\ per\ hour) \tag{10b}$$

Since the various solar chimney models used had different sizes and different room sizes, a means to normalise the data was found by diving the solar chimney volume by the room size. All these data were presented in **Table 5**. This ratio of the solar chimney size to room size was then used to develop a mathematical model (Eq. (11)) to predict the ventilation rate of the system (**Figure 11**).

Figure 11 shows the trend-line graph of the solar chimney in which a model equation is obtained from a quadratic fit and given by;

$$y = -190.9x^2 + 77.753x + 0.0625 \tag{11}$$

$$R^2 = 0.8559.$$

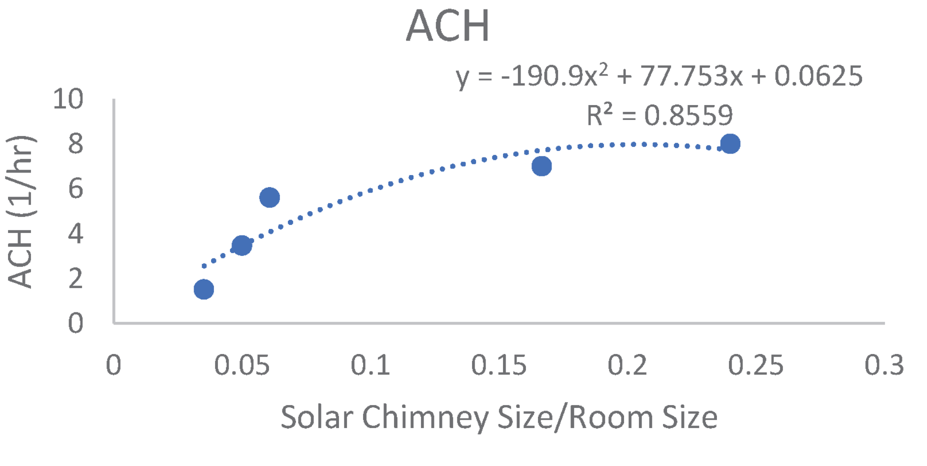

Figure 11.
Thread-line graph of solar chimney model.

Country [standard]	Outdoor air [m^3/h]	CO_2 concentration [ppm]	ACH [h^{-1}]
Portugal [RECS (2013)]	600	1250	4.0
UK [Building Bulletin 101 (2006)]	450	1500	3.0
Germany [DIN 1946–2 (2005)]	500	1500	3.3
USA [ASHRAE 62.1 (2013)]	558	1080	3.7
Europe [EN 15251 (2007)]	756	550	5.0

Table 6.
IAQ requirements in classrooms [41].

3.4 Energy saving model

This model was developed to reveal the energy saving potential of the passive ventilation system (the solar chimney). Energy saving is described as the level of energy saved and the reduction in cost derived from such saving. The model equations are as follows:

The cost of using mechanical ventilation system is given by,

$$\text{Total Cost} = \text{Installation Cost} + \text{Operation Cost} + \text{Maintenance Cost} \tag{12}$$

Also, the cost of using a passive ventilation system (solar chimney) is given by,

$$\text{Total Cost} = \text{Design Cost} + \text{Installation Cost} + \text{Maintenance Cost} \tag{13}$$

The percentage increase (energy saved) of both ventilation systems is given by,

$$\%Increase = \frac{C_{Mech} - C_{sc}}{C_{Mech}} * 100\% \tag{14}$$

where
C_{Mech} = mechanical ventilation cost.
C_{sc} = solar chimney cost.

3.5 Comparison against standards

Indoor air quality (IAQ) requirement is determined by various factors. **Table 6** shows some the acceptable IAQ international standards for classrooms. Therefore, the results obtained were compared with standard to validate the result.

4. Results and discussion

4.1 Air quality analysis

4.1.1 Lecture hall

Using CFD methods, the computational study was successfully performed to obtain the air properties for the lecture room. At the initial condition, where the wind velocity was 0.05 m/s, the air change per hour was found to be 3.1 and this value increases as the wind velocity increases.

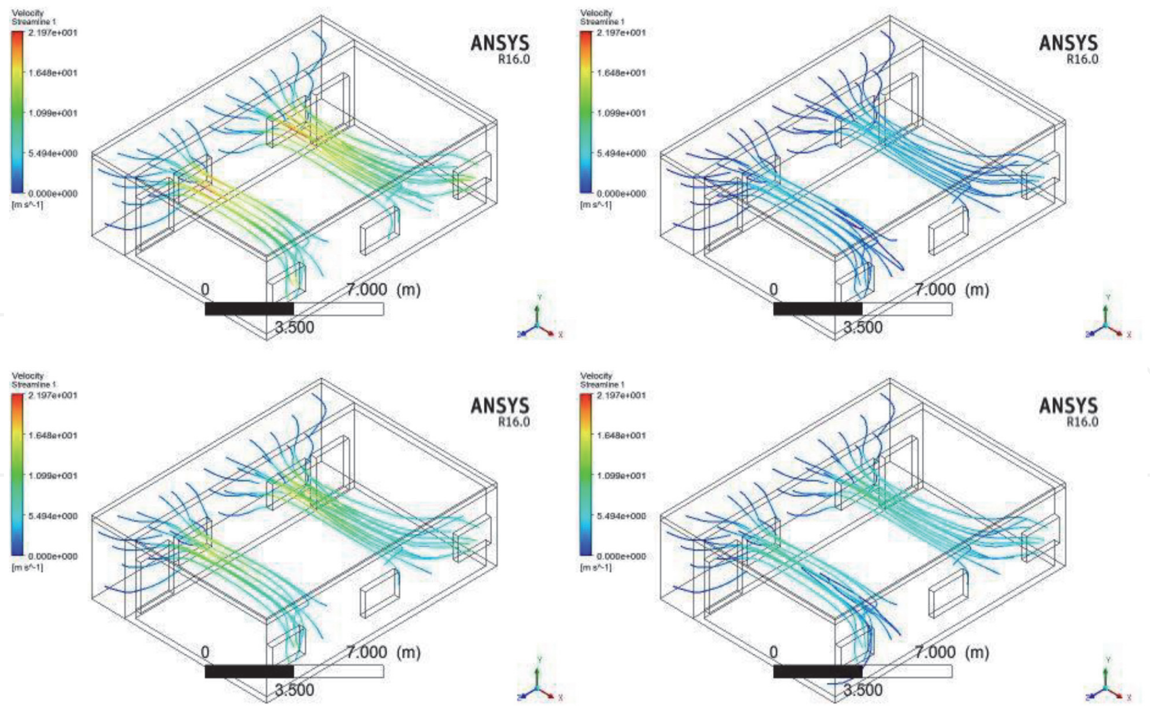

Figure 12.
Velocity streamlines of wind in the mechanical lecture room at different inlet velocities (0.05 TRH, 0.5 BRH, 1.0 BLH and 2.0 TRH m/s).

From the initial data, the results obtained fall short of the ASHRAE standard [42, 43], which proposed an average air change per hour of between 4 and 6 in a lecture room with an average wind velocity ranging from 0.12–0.5 m/s.

Figures 12–14 show the velocity streamlines, temperature contour, and velocity vector streamlines of the model.

4.1.2 Flow and thermal conditions of the lecture hall

Figures 12 and **13** reveal that the air velocities at the window sections are higher than in other places within the lecture hall. This is expected, as the airflow past the windows and enters the room, the flow velocity decreases as a result of the sudden expansion of the space in the room and increase in pressure according to Bernoulli's principle. It can also be observed that there are no obvious air movements at the centre and edges of the room. This is due to the initial condition that the inflow is from the side with two windows. This condition would not be pleasant for the occupants at these sections of the room. However, when the inflow comes from the sides with the three windows more sections of the room would have air considerable movement.

Figure 14 reveals that the air temperature distribution in the whole room is stratified. The lowest temperature appears to be at the side with three windows and highest at the areas with two windows. This is due to the higher convective heat transfer at the side with the three windows coupled with the increase in velocities at this section due to the venture effect. This indicates that areas closest to the three windows are more ventilated as compared to areas closest to that of two windows and this is a result of different in the number of windows.

Table 7 shows that the thermal comfort/air quality changes with air mass flow rate. As the mass flow rate increases air quality is also increased which shows that air quality is directly proportional to mass flow rate. At the initial state when the mass flow rate is 2.8 kg/s the air change per hour is 3.10. According to ASHRAE, in public places like the classroom, it must be ventilated in such a way that it has

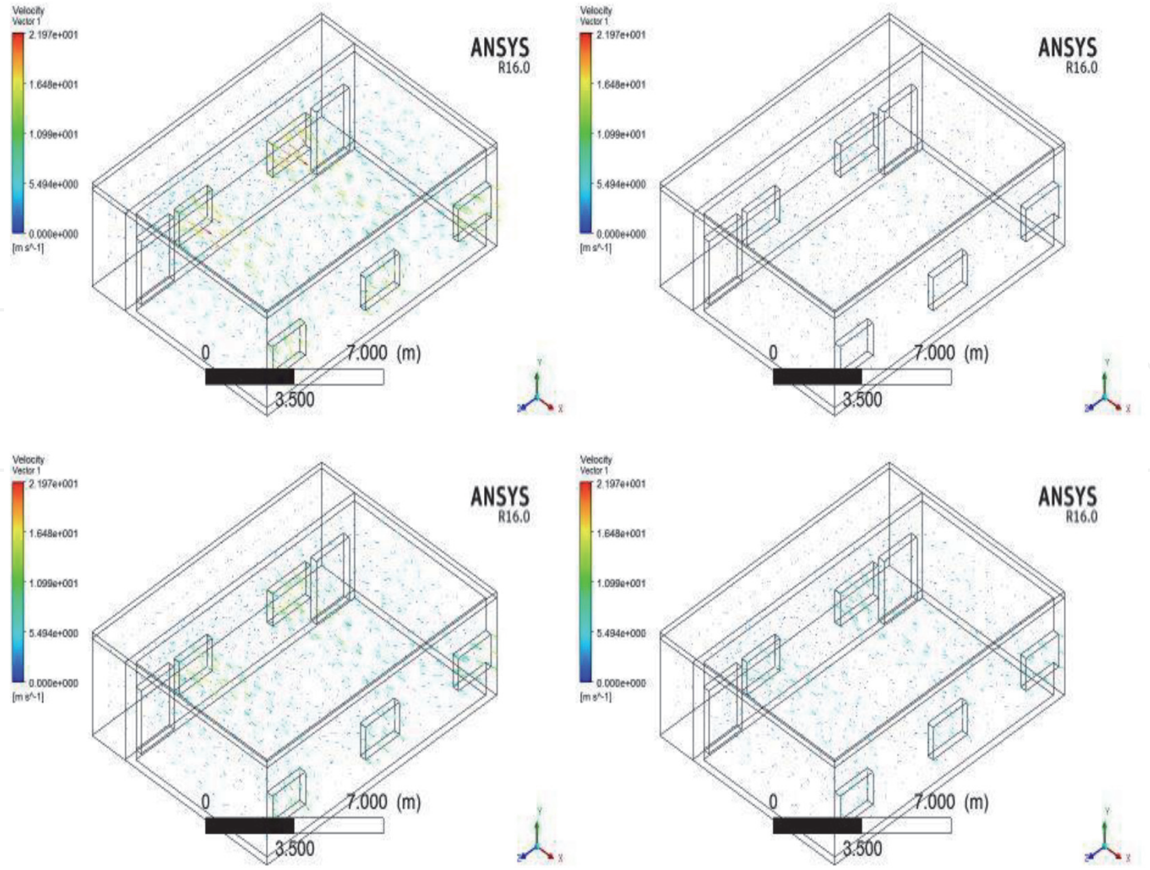

Figure 13.
Velocity vector of air in the mechanical lecture room at different inlet velocities (0.05 TRH, 0.5 BRH, 1.0 BLH and 2.0 TRH m/s).

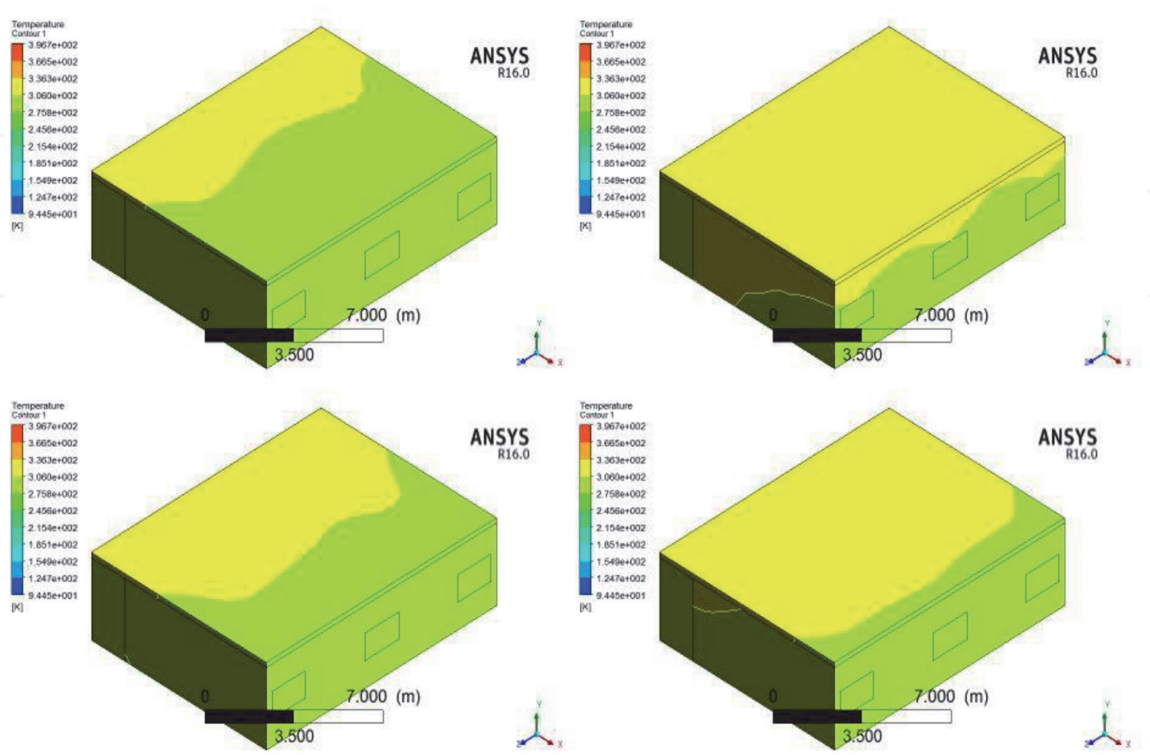

Figure 14.
Temperature contour of air in the mechanical lecture room.

Wind Velocity (m/s)	Mass Flow (kg/s)	ACH (1/h)
0.05	2.8	3.10
0.5	28.68	31.79
1.0	57.36	63.58
1.5	86.04	95.36
2.0	114.72	127.15

Table 7.
Mass flow rate and corresponding indoor air quality (ACH).

Airflow rate of 7.5 cfm/person. If the class will accommodate 100 students comfortably, the ventilated facilities must give 750 cfm air quality.

4.1.3 Room ventilation improvement methods

There are various means of improving the ventilation of the lecture room, they are:

4.1.3.1 Cross ventilation

It has been revealed by CFD simulations above that indeed the lecture room was inadequately ventilated at low wind speeds. The number/size of openings and introduction of another passive or mechanical system is required to improve the ventilation of the lecture hall. Positioning the ventilation openings such that a pair face each other to induce crossflows, and also positioning openings at the top allowing hot stale air to easily exit the building would create and optimise airflow and circulation pattern of the lecture hall. Windows or vents placed on opposite sides of the building induces natural flow pathway through the structure. Therefore, to improve the indoor air quality of this model, a cross ventilation of the lecture room and addition of topside opening would improve the thermal comfort and IAQ of the lecture hall.

4.1.3.2 Passive ventilation system (solar chimney) attachment

From the Eq. (11), a solar chimney model for the lecture room was developed and the graph shown in **Figure 11** was obtained. **Figure 15** reveals that using passive ventilation system such as a solar chimney with the right size, the indoor air quality of the lecture room can be improved. The graph is parabolic, which implies that some sizes of the solar chimney would work negatively when applied to the lecture hall. After the peak value (100 m^3), air change per hour begins to decrease with increasing chimney size.

4.2 Energy cost analysis

4.2.1 Energy saving potential

The energy saving potential of using a passive ventilation system was carried out in comparison to using mechanical ventilation system, which is given as follows:

4.2.2 Mechanical ventilation system's cost analysis

Installation Cost: The installation cost consists of the purchase cost and the fixing cost of the system i.e. fans. The average cost of purchase was found to be ₦5000 per fans and fixing cost was ₦200 per fans. For nine fans present in the room, we have:

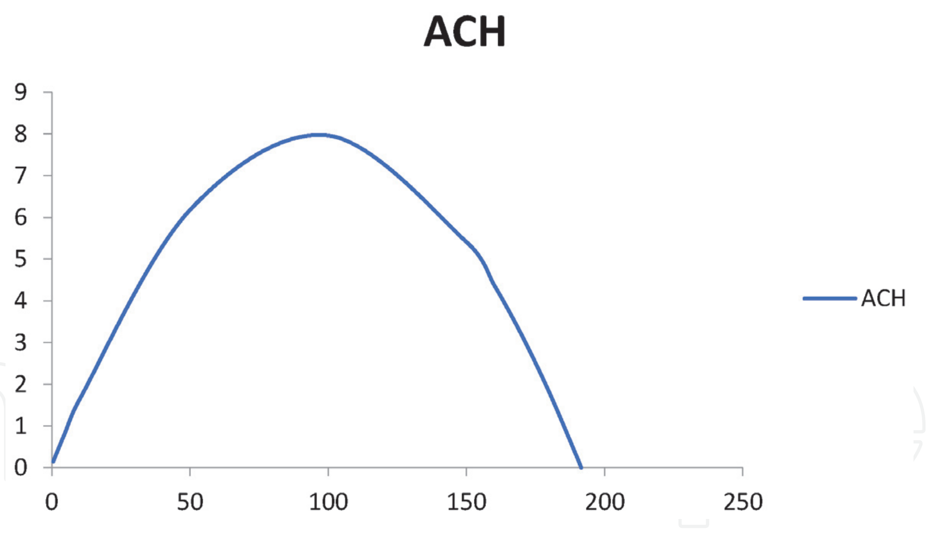

Figure 15.
Effect of solar chimney size on the air change per hour of the lecture room.

System	Unit Watt (W)	Number of fans	Energy demand (9 fans) (kW)	Hours/day (8 h)	kWh/day	kWh/year
Fan	25	9	0.225	8	1.8	657

Table 8.
Energy demand information of a unit of the ventilation device.

System	Cost (₦) per kWh	Cost/day (₦)	Cost/month (₦)	Cost/year (₦)
1 fan	25	5	150	1825
9 fans	225	45	1350	16,425

Table 9.
Annual energy cost for the mechanical ventilation system.

Installation Cost = (₦5000 * 9) + (₦200 * 9) = ₦ (45,000 + 1800) = ₦46,800.

Operation Cost: This is the average cost for the day to day running of the system. **Tables 8** and **9** shows the operational cost of running the fans.

Maintenance Cost: This is the cost of maintaining the system. It includes repair and basic cleaning. The average charge for maintenance was found to be at ₦500 per year.

Maintenance Cost = ₦500 * 9 = ₦4,500.

4.2.3 Passive ventilation system's (solar chimney) cost analysis

Design Cost: This entails the cost of materials used for the design e.g. wood, glass, pvc piping, washers, eye hook, grease, nozzle etc. and overall fabrication of the chimney. Using an exchange rate of ₦250 = $1.

Design Cost = ₦25,000.

Installation Cost: This includes cost of installing the design to the lecture room. Installation cost was found to be between ₦5000 and ₦15000. The average from this was obtained as ₦10,000.

Installation Cost = ₦10,000.

Maintenance Cost: It is referred to as the expense of using the solar chimney daily. The average maintenance cost was found to be ₦5000 yearly.

	DC (₦)	IC (₦)	OC (₦)	MC (₦)	TT (₦)
Mechanical System (Fans)		46,000	16,420	4500	66,920
Passive System (Solar Chimney)	25,000	10,000		5000	40,000

Table 10.
Total cost of ventilation systems.

Years	MVS (₦)	PVS (₦)	Increase (₦)	% Increase
1	66,920	40,000	26,920	40.23
2	87,840	45,000	42,840	48.77
3	108,760	50,000	58,760	54.03
4	129,680	55,000	74,680	57.59
5	150,600	60,000	90,600	60.16
6	171,520	65,000	106,520	62.10
7	192,440	70,000	122,440	63.63
8	213,360	75,000	138,360	64.85
9	234,280	80,000	154,280	65.85
10	255,200	85,000	170,200	66.69

Table 11.
Cumulative cost and percentage increase.

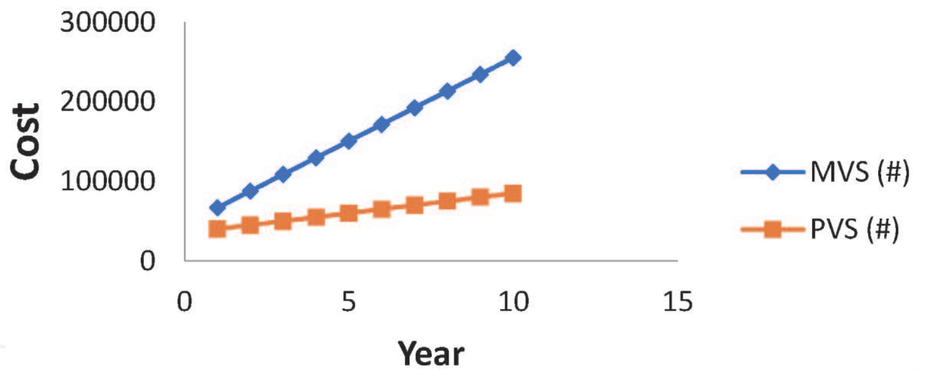

Figure 16.
Graph of the cost of solar chimney and fans against number of years.

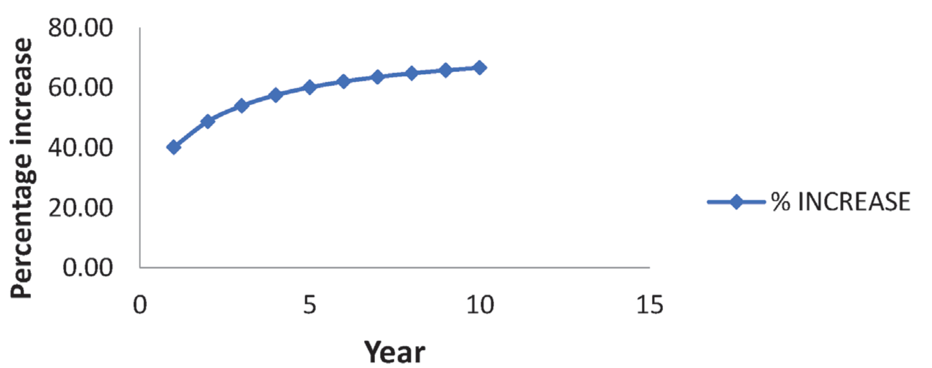

Figure 17.
Graph of percentage increase against number of years.

The total cost implications are presented in **Table 10**. The cumulative costs and respective percentage increases are presented in **Table 11**.

Figure 16 depicts the relationship between the cost of solar chimney and fans against number of years. It can be observed that the cumulative cost of running the mechanical ventilation system (fans) kept increasing continuously by over 30% each year and that of passive ventilation was lesser with about 12.5%. This indeed tells that the use of the solar chimney for ventilation is less costly, and invariably, energy efficient.

Figure 17 shows a relative increase in cost over number of years with the use of fans. It can be deduced that there was a 66.69% increase in cost due to the use of fans compared to the use of solar chimney in the lecture room for over 10 years. Therefore, with this percentage increase it can be understood that there is more energy and cost saving potential for the use of passive ventilated systems than mechanical ventilated systems.

5. Conclusion

Passive ventilation systems are a natural ventilation technique that has the potential of saving energy as well as maintaining good air quality in a building as compared to mechanical ventilated systems. This research was carried out with the aim of improving the ventilation performance (thermal comfort and indoor air quality) of a lecture hall. In this project, a detailed and systematic assessment of a lecture hall using CFD simulations was performed for determining the air flow caused by wind velocity stratification (0.05–2.0 m/s), solar radiation (200–1000 W/m^2) and pressure outlet of 1 atm within a space with seven ventilation openings. The air change per hour was deduced using different boundary conditions in the lecture room. The research revealed the airflow and temperature pattern within the room. It was obtained that a solar chimney of size between 1 and 100 m^3, improved the natural ventilation in the room. Also, from an energy and cost analysis carried out, cost-saving potential of the passive system (solar chimney) was established and found to be both energy and cost-effective in comparison to mechanical systems for better indoor air quality and thermal comfort. There was a 66.69% increase after 10 years in the saving of energy and cost using Solar Chimney (SC) as compared to fans. It is therefore acceptable to state that objectives were achieved and in turn a contribution to knowledge.

The knowledge of temperature stratification and mass flow rate is essential so as to aid the thermal comfort of occupants in indoor environments, especially in public buildings like lecture rooms, conference halls, etc.

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Conflict of interest

The authors declare no conflict of interest.

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Nomenclature

ACH	air change per hour
ASHRAE	American society of heating, refrigerating, and air-conditioning engineers
BC	before Christ
Btu	British thermal unit
CFD	computational fluid dynamics
cfm	cubic feet per minute
C_{mech}	mechanical ventilation cost
C_{sc}	solar chimney cost
CIBSE	chartered institute of building services engineers
CO_2	carbon dioxide
HVAC	heating, ventilation and air conditioning
HSE	health and safety executive
IAQ	indoor air quality
kg/m^3	kilogram per cubic metre
kg/s	kilogram per second
mm	millimetre
m^3	cubic metre
NASA	national aeronautics and space administration
RANS	Reynolds average Navier stokes
SC	solar chimney
TC	thermal comfort
UNCHS	United Nations centre for human settlements
^oC	degree celsius
ZE	zero energy

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