SIMULATION OF NATURAL VENTILATION IN HOSPITALS OF SEMIARID CLIMATES FOR HARMATTAN DUST AND MOSQUITOES: A CONUNDRUM

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ABSTRACT

Computational Fluid Dynamics (CFD) is used to explore the performance of various natural ventilation strategies in hospital wards, as an alternative to costly mechanical ventilation strategies in Nigeria. The harsh climatic condition in the study area (semi-arid region) characterized by high levels of direct solar radiation, Harmattan dust blowing from the northeast Sahara desert, and mosquitoes, have made the strategies' to achieve acceptable indoor air quality difficult.

Results indicate that 8% opening area in relation to the space floor area is required to achieve the acceptable ventilation rate in hospital wards.

Keywords: Natural Ventilation, Simulation, Harmattan Dust, Mosquitoes, Buildings, indoor air quality

INTRODUCTION

Hospitals are places where people seek medical attention to recover from their illnesses. Multi-bed wards remain the most complicated of all spaces in hospitals because of the nature of patients it accommodates who are often immunosuppressed and immunocompromised. Vulnerable patients are prone to infection from indoor air acquired infections. Moreover, most indoor air associated infections in hospitals are believed to be a product of poor architectural design in terms of building material selection, ventilation system design and climatic situation of an area. According to Pepper, and Carrington (2009), indoor air pollution, is related to emission, accumulation, and assessment of pollutants commonly attributed to poor ventilation and air exchange in building. The health consequences of indoor air pollutants could be experienced shortly after exposure or, maybe, years later (EPA, 2010).

Sustainable and energy efficient ventilation systems are required for the removal of various indoor air pollutants in hospital wards. There are various sources of contaminants in hospitals, including building materials, utility chemicals, external sources and patients themselves. The external source of pollutants in semi-arid climates includes Harmattan dust and mosquito insects, which makes it difficult to achieve effective natural ventilations. Moreover, natural ventilation as a passive and non-energy consuming strategy is relevant to the prevalent energy shortage in Nigeria.

In Nigeria, the electricity demand exceeds the supply, and even the supply remains unreliable (Sambo, 2008). The total grid installed capacity produced by Nigerian power stations was 8,876 MW with only 3,653 MW available as at December 2009, meaning the available power supply is less than 41% of the total installed capacity (Emovon, et al. 2011). Moreover, According to the 2009 International Energy Agency (IEA) records, the electrification rate for the whole country was about 45% to 50%, thus, depriving approximately 76 million people access to electricity (EIA, 2012). According to a World Bank report, the yearly (2007–2008) average power outages experienced in Nigeria was 46 days, and an outage last for about 6 hours on average. In addition to problems such as insufficient maintenance, inadequate feedstock and insufficient transmission network, high population growth combined with underinvestment in the electricity sector have also resulted in increased power demand without any substantial growth in production (EIA, 2012).

CHARACTERISTICS OF SEMI-ARID CLIMATES

Due to the disparity in climatic and weather conditions, the environmental parameters for building design for tropical countries such as Nigeria are quite contrary with temperate regions. Climate references are required for the design of buildings in semi-arid climates to achieve acceptable indoor air quality and thermal comfort. Therefore, to accomplish indoor air quality and thermal comfort requirements with the presence of mosquitoes and Harmattan dust in hospital wards, the climatic parameters have to be considered right from the design stage. Three major parameters should be considered when designing for natural ventilation in semi-arid climates including Harmattan dust, Mosquitoes and high ambient temperatures.

Harmattan is a fugitive dust originating from the Faya Largeau area in the Chad basin and transported by dry North-East trade wind that usually blows across Nigeria between November and March annually and diminishing southwards. The consequences of this dust are higher in the Nigerian semi-arid climatic zone being situated in the Northern boarders of the country. The relationship between dust particles concentration and its effect on human health is established in literature, particularly linking cardiovascular and respiratory diseases to Dust outbreaks (Kwon et al. 2002, Chen et al. 2004, Meng and Lu, 2007). The dust particles size varies with location, depending on the proximity of the collection center from the dust origin in the Sahara desert. The amount collected also varies significantly from year to year with particle-size becoming finer towards the south with an increasing amount in organic matter. The dust median diameter was measured to be slightly above 15 µm close to the epicenter and 5 µm at the perimeter of the dust zone, with organic carbon content of 5% and 10-15% in the North and South of Nigeria respectively (Awadzi and Breuning-Madsen, 2007). Moreover, the mean sizes of dust samples collected in Nigeria for two Harmattan seasons are 2.7µm and 4.4 µm, respectively (Chineke and Chiemeka 2009). However, the elemental composition of Harmattan dust in Nigeria was measured using neutron activation analysis to determine the concentrations of 29 elements, with iron (Fe), aluminum (Al), and potassium (k) being among the highest at 61 mg g^{-1}, 431 mg g^{-1}, and 15 mg g^{-1}, respectively (Adepetu et al. 1988).

Mosquitoes are cold-blooded insects that have the same body temperature as the surrounding environment. There are only three species out of more than 3,000 species of mosquitoes that are largely responsible for the spread of human infections including; Anopheles, Culex and Aedes. The Anopheles mosquitoes are found in the study area (Maiduguri, Nigeria), and are the only species known for transmitting the malaria parasite (National Geographic, 2013). The average lifespan of a Mosquito is from 2 weeks to 6 months and its average size is 0.3 to 2 cm, with average weight of 2.5 mg) (National Geographic, 2013). Habitually, Mosquitoes cannot survive outside the rainy season, which is between June and September, but due to the lack of proper sewage and drainage systems in the study area, mosquitoes could be found throughout the year. In tropical countries where the cases of infections from mosquitoes and other insect bites are prevalent, wire gauze insect netting systems are employed. However, the installation of such netting materials will result in resistance to the direct airflow in and out of the indoor spaces through the affected openings thereby, resulting in insufficient ventilation rates.

The consideration of high outdoor air temperatures that exceed human comfort thresholds creates a challenge in designing natural ventilation strategies for acceptable thermal comfort in semi-arid climates. In the dry season the temperature in Maiduguri (Study area) peaks with wide diurnal and annual ranges of dry bulb temperatures, with the hottest months of April, May and June. Dry bulb temperatures can exceed 43°C but falls to a mean of 24°C or 29°C with the start of the rainfall (Maxlock Group Nigeria, 1976).

Since, the thermal comfort and human preferences are related to acclimatisation to local conditions the neutrality temperature of the study area (Maiduguri) has been estimated using the outdoor average ambience temperature using the formula $T_n = 17.8 + 0.31T_{oav}$ (Szokolay, 2008). The thermal neutrality temperature of Maiduguri is found to be 26.7°C, and considering a temperature band of ±2.5 as recommended in Szokolay, S. V. (2008), the thermal comfort zone will fall between 24.2°C and 29.2°C. Figure 1 illustrates the annual ambient temperature in the study area in relation to the neutrality temperature range. The ambient average temperatures that are within the comfort zone includes February, August and November, while the remaining nine months are out of the comfort temperature zone.

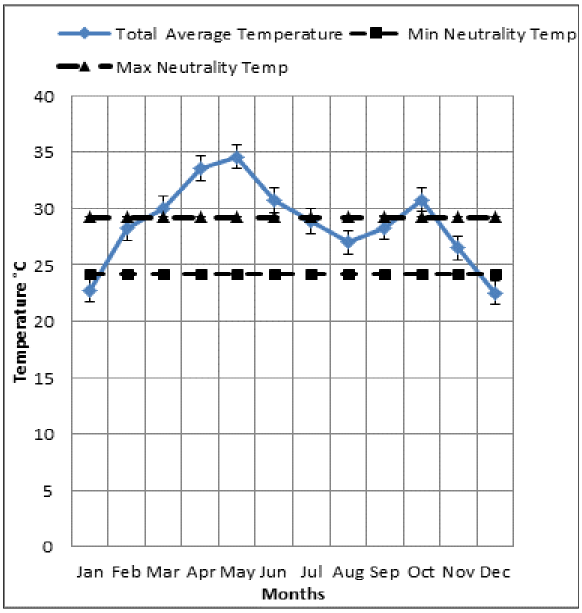


Figure 1: Total Average Ambience Temperature of the Study Area in Relation to Neutrality Temperature Zone

INDOOR AIR QUALITY AND NATURAL VENTILATION IN HOSPITAL WARDS

The quality of indoor air dictates the health status of a space and its occupants, as fresh air quality is critical for healthy indoor environment. Poor indoor environmental qualities are responsible for many health problems due to contaminants concentration including allergies, eye irritations, and respiratory problems (Yau, et al, 2011). These contaminants are very difficult to predict as they generate from both indoor and outdoor sources, and contain different types of substances (Hobday, R. 2011).

Natural ventilation is usually driven by natural forces such as wind, thermal buoyancy force owing to variations in indoor and outdoor air density, which force in fresh air from outside through custom-made building envelope openings (Atkinson, 2009). It relies on the pressure differences caused by either wind or the buoyancy effect created by temperature or humidity difference to move fresh air through buildings. The use of natural ventilation in buildings becomes an increasingly attractive means of cutting energy cost and achieving acceptable quality of indoor environment, due to the improvement on the cost and environmental consequences of energy utilization (Walker, 2010). However, the performance and condition of ventilation in hospitals have great impact on the perceived indoor air quality (Hellagren, U. et al, 2011).

The achievement of acceptable indoor air quality and thermal comfort passively, while excluding unwanted parameters such as mosquitoes and Harmattan dust in the semi-arid climates is a difficult task that requires a holistic approach. The exclusion of these unwanted parameters are easy to realize when using mechanical means for ventilation, as the need for opening large ventilators to the outside is not required. Regrettably, there is insufficient energy in the study area to cater for such demands. Therefore, there is a salient need to explore the possibility of using natural means for achieving acceptable indoor air quality and thermal comfort.

CASE STUDY

Description of the Studied Hospital Wards

A multi-bed hospital ward at the Umaru Shehu Ultra-Modern Hospital Maiduguri (USUHM) was chosen for the purpose of this study. It is a single storey building surrounded by other buildings and vegetation. The rectangular shape ward with North-south orientation has floor area of 142.5 m^2 and floor to ceiling height of 3.2 m. It has capability of accommodating 24 beds. The ward has eight insect screen installed sliding windows of 1.2 m x 1.2 m size as shown in Figure 2.

The Full Scale Measurement Description

A detailed full-scale measurement of an existing hospital multi-bed ward was conducted in the semi-arid climate of Nigeria (Maiduguri). The measurement was carried out using tracer decay techniques with CO_2 as the tracer gas. The results obtained from these measurements were used to estimate the air change rates of the hospitals wards using the mathematical expression in equation 1.

$$N = \frac{\ln C(0) - \ln C(\tau 1)}{\tau 1} \qquad (1)$$

Where
N = Air Change Rate
C = Tracer Gas Concentration in Rooms
τ = Time (h)

The results from the full-scale measurement were compared with simulation and the error was found to be about 15%. These errors are due to many factors including climatic considerations such as wind direction, temperature, relative humidity and building orientation. Moreover, the existing of cracks and gaps in the building also affects airflow rates.

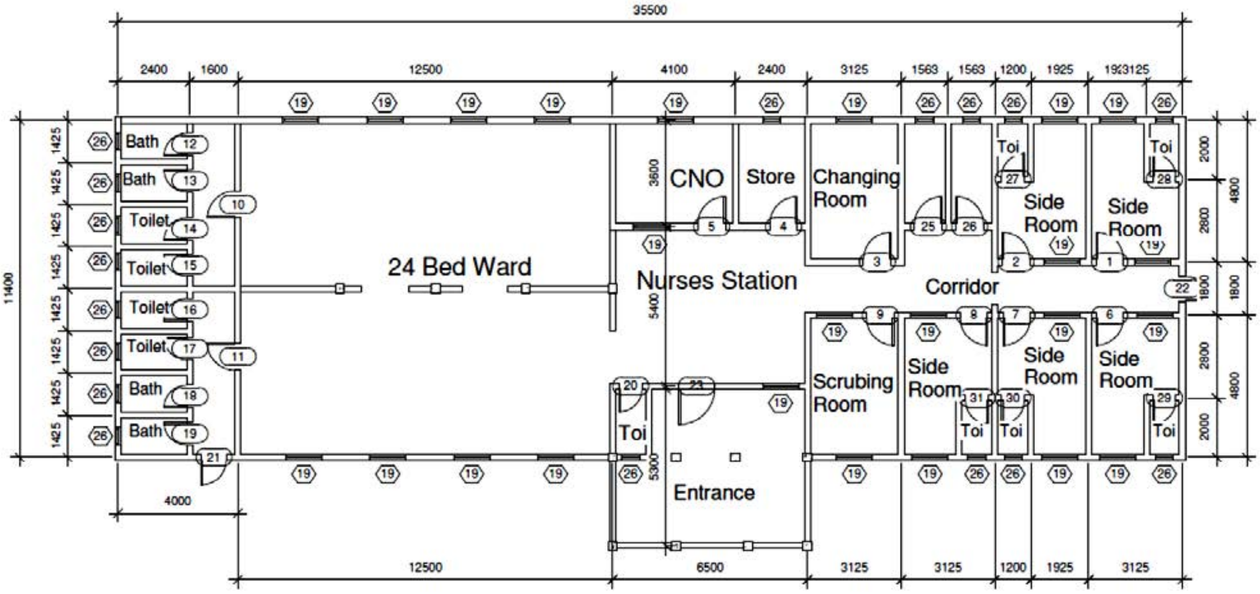


Figure 2: The Plan of the Studied Multi-bed Ward

The Multi-bed Ward Simulation

The simulation was carried out using a state-of-the-art CFD software Fluent. The 3D steady RANS equations were solved together with stress transport realizable *k-ε* turbulence model, and SIMPLE algorithm were applied for pressure velocity coupling. Second order were used for both pressure interpolation and discretisation schemes. A computational domain of dimension 49.4 m x 81.4 m x 19.3 m (l x w x h) was used according to the guideline suggested by Franke et al. (2007) and Tominaga et al. (2008), in which minimum distance of 5 times the building height are specified to avoid domain size interference on the numerical simulation results. Simulation convergence were achieved when the scaled residuals reached the limits of 10^{-6} for x, y, and z momentums, 10^{-5} for *k-ε* and continuity. The scaled residual for the simulation is illustrated in Figure 4.

In order to evaluate the characteristics of the window screen material to determine their permeability K, and inertial factor Y, the correlation derived by Miguel et al. (1997) relating the screen permeability and inertial factor to the porosity has been adopted as shown in equations 2 and 3 respectively.

$$K = 3.44 \times 10^{-9}\alpha^{1.6} \qquad (2)$$

$$Y = 4.3 \times 10^{-2}\alpha^{-2.1} \qquad (3)$$

Where α is the screen porosity

A typical insect screen of porosity 0.66 and thickness 0.36mm was used for the calculation of the screen permeability and inertial loss factor. The insect screen was simulated as a porous jump boundary condition. The air change rates (ACR) was estimated for two scenarios, first with insect screen installed to imitate the original building and the second, without the insect screen. The model with the insect screen is the replication of the existing wards simulated for the purpose of validation, the result shows that, the difference in ACR between the full-scale measurements (3.0 ACH), and the simulation (3.5 ACH) is 0.5 ACH, which is about 15%. These errors are possibly acquired from the full-scale measurement, as researchers have agreed with the possibilities of experiencing errors in this type of measurements. The Errors obtainable from full-scale measurements could be larger than well controlled wind tunnel test (Easom, 2000). According to Yang (2004), the error range obtainable with full-scale measurement could reach 10 – 15%, while Willemsen and Wisse (2002) affirm that, errors implanted in full-scale measurements can extent up to 20%. Therefore, the 15% error experienced between the full-scale measurement and the simulations results in this study is within the acceptable error limit and could possibly be from the full-scale measurement.

Moreover, the mean ACR in the ward without the insect screen has been simulated and found to be 10.8 ACH, which is far above the ASHRAE's total ACR specification of 6 ACH in hospital wards. The result comparing the full-scale measurement and the simulations with and without screens is shown in Figure 3.

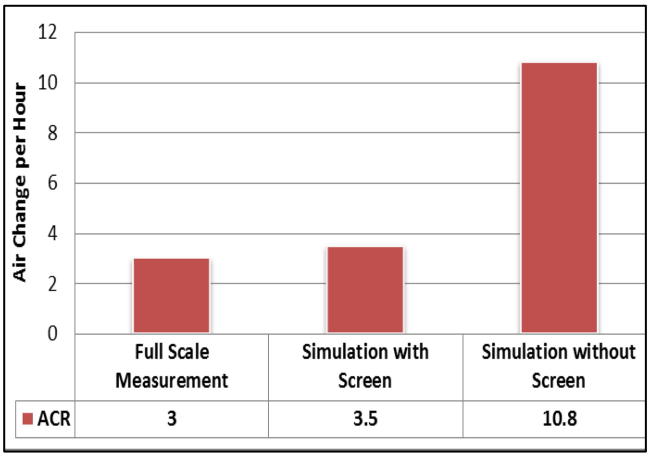


Figure 3: Air Change Rates obtained for Full Scale Measurement and Simulation

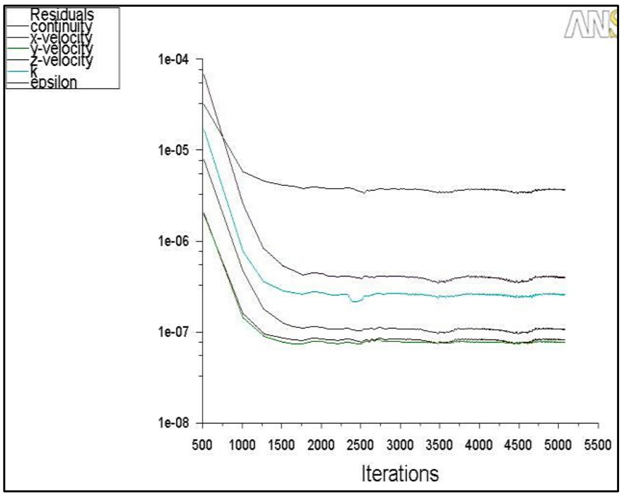


Figure 4: Scaled Residuals showing convergence history

Wind induced cross ventilation strategies with different opening areas were tested using reference wind speed of 3.1 m/s at 10 m above ground level. The wind speed data was collected from the nearest meteorological station. The percentage of opening in relation to the ward floor area required to provide acceptable ventilation rate to achieve the ASHREA standard of 6 ACH (Ninomura and Bartley, 2001) has been simulated and identified as 8% as illustrated in Figure 5. The variation in average air velocity with opening area within the simulated space is shown in Figure 6. It has been observed that, the air velocity increases with increase in opening size.

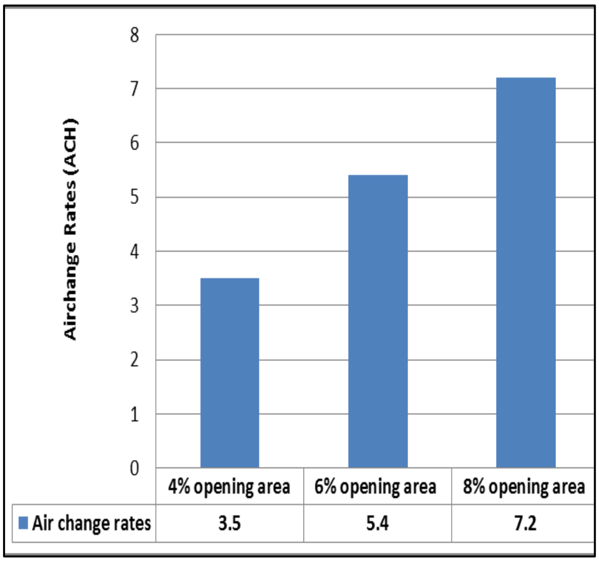


Figure 5: Air change Rates of different cases Simulated

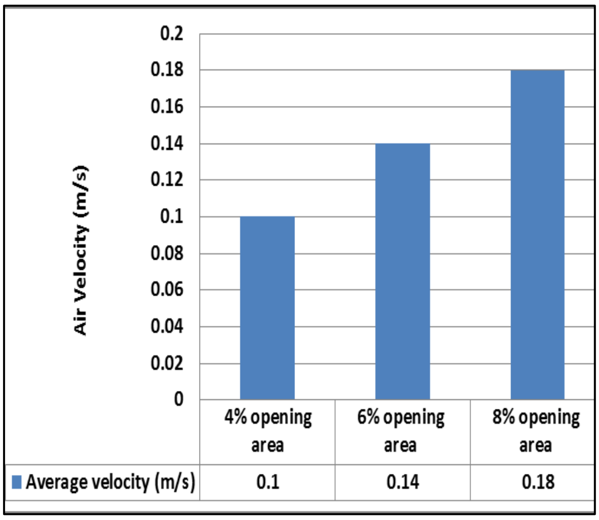
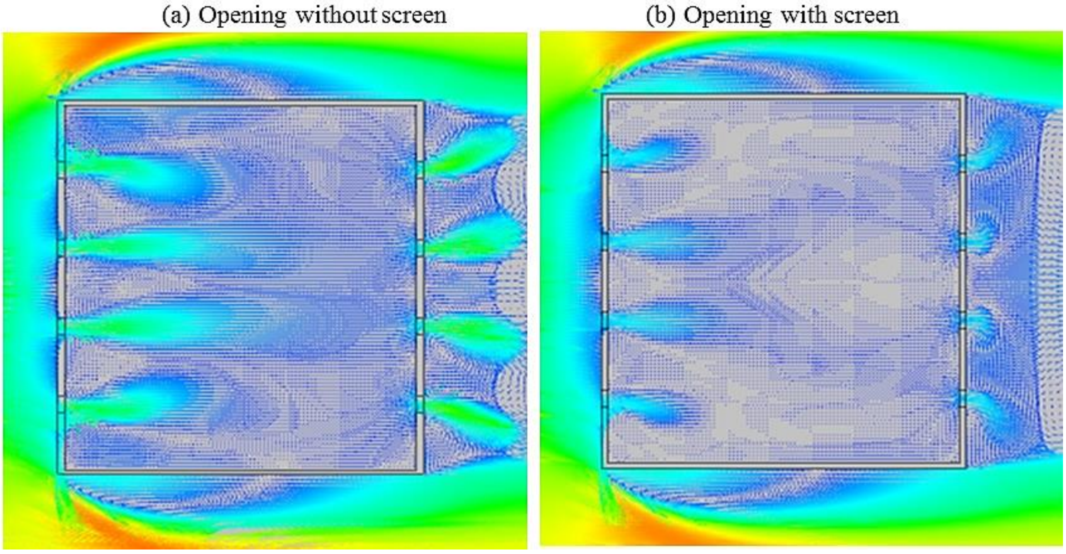


Figure 6: Air velocity inside the wards of different cases Simulated

The installation of insect screens on the openings of the multi-bed ward to prevent mosquitoes is responsible for about 70% reduction in air change rate. Since the air-change rate measured in the wards for cases with insect screens and without screen is 3.5 ACH and 10.8 ACH respectively. Hence, if another strategy for excluding dust is added the air change rate will decrease further, leading to discomfort within the indoor environment. The airflow pattern for the ward simulated with and without insect screen is shown in Figure 7. The horizontal plane cutting across the ward at about 1.5 m above ground level illustrates airflow pattern within the ward especially at the inlets and outlets. The presence of insect screen in the openings in Figure 7b resulted in lower airflow at both inlets and outlets compared to Figure 7a, where no screen is used. The difference is clear from the jets length and size at the inlets and outlets.

Figure 8 illustrates and compares airflow pattern in terms of jet characteristics between 4%, 6% and 8% window openings in relation to the ward floor area. The difference between the three strategies in terms of jet size and length is more prominent in the outlets compared to the inlets. Moreover, the airflow characteristics across the inlets and outlets openings in the ward for three different opening sizes of 0.6 x 1.2 m, 0.9 x 1.2m, and 1.2 x 1.2 m (w x h) has been illustrated in Figure 9. The jet at the openings in all the three cases moves downward direction and the difference in the size and length of the jet is more noticeable in the outlets compared to the inlets.


(a) Opening without screen

(b) Opening with screen

Figure 7: Airflow characteristics of opening with and without screen

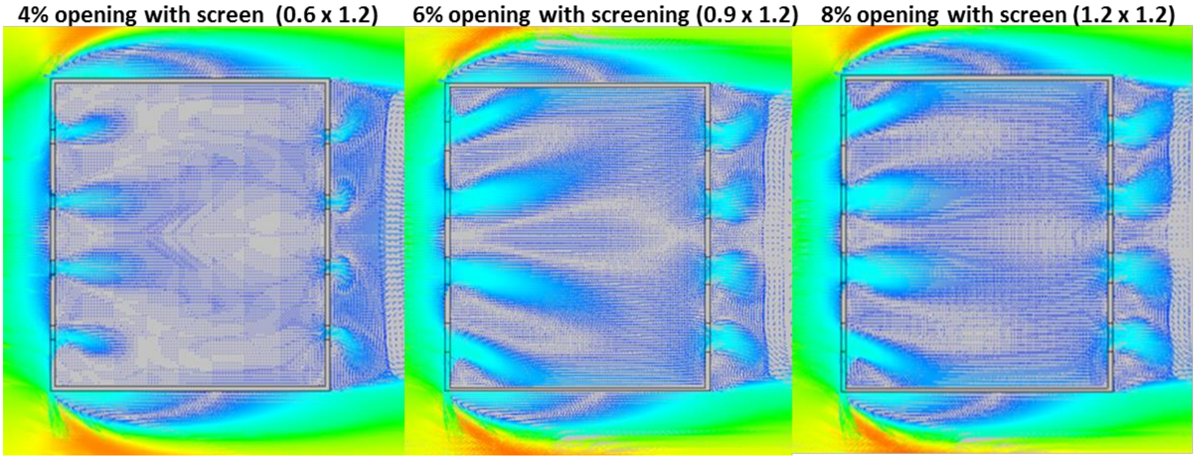


Figure 8: Airflow pattern in relation to different opening sizes on horizontal plane

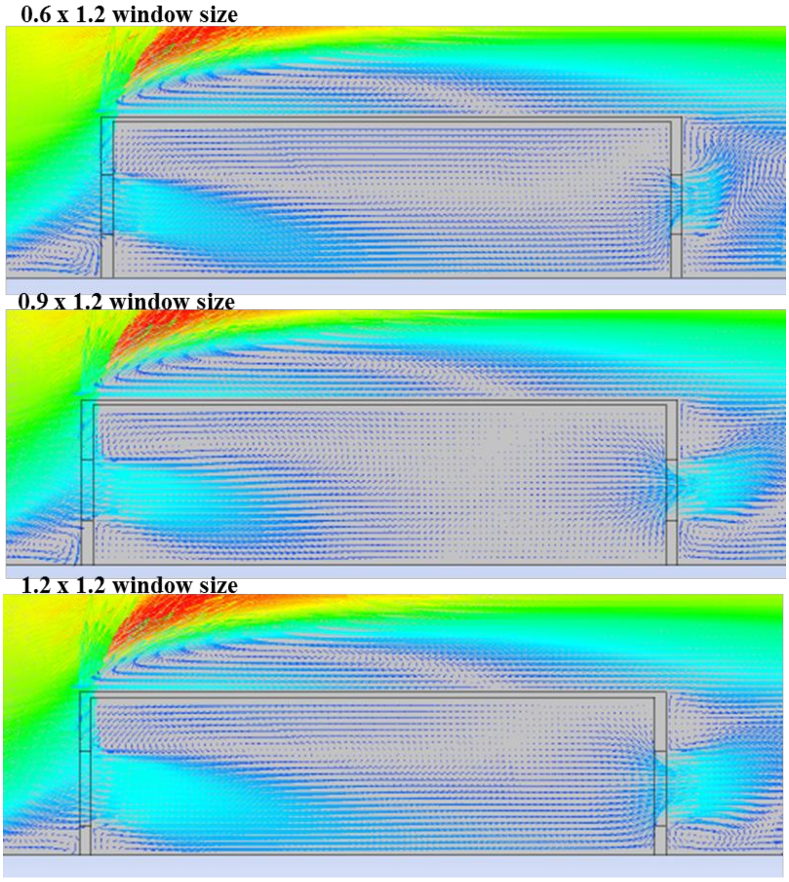


Figure 9: Airflow pattern and jet direction in relation to different opening sizes on vertical plane

METHODOLOGY FOR SIMULATING NATURAL VENTILATION IN HOSPITAL WARDS

The methodology employed to achieve acceptable indoor air quality in hospitals of semi-arid climates indicate the difficulty of achieving efficient natural ventilation. When factors like mosquitoes and Harmattan dust are prevented through insect filters and dust separation techniques, the consequences will lead to the reduction in ventilation and air change rates. Then, the question remains, what opening space is required to make up for the pressure drops due to insect nets and dust filters? This opening area is established to be 8% of the building floor area (see Figure 5). However, this area might change when simulated with higher or lower wind speed than the one used in this study. The methodological framework to achieve acceptable indoor air quality and thermal comfort through Natural ventilation in hospital wards of semi-arid climates is illustrated in Figure 10.

In order to achieve acceptable indoor air quality and thermal comfort in the hospital wards, simulation has to be carried out comparing different natural ventilation strategies, taking into consideration the three major militating factors of dust, mosquito and high outdoor temperatures. The possible solutions for these three hurdles are provision of insect nettings, dust separation techniques, and efficient ventilation rate. However, the major consequence of the two techniques including insect nettings and dust separation is pressure drop and subsequent reduction in ventilation, which requires increasing the opening sizes to achieve required ventilation rates. Moreover, due to the energy shortage in the study area, these three solutions should be achieved with less or zero energy techniques.

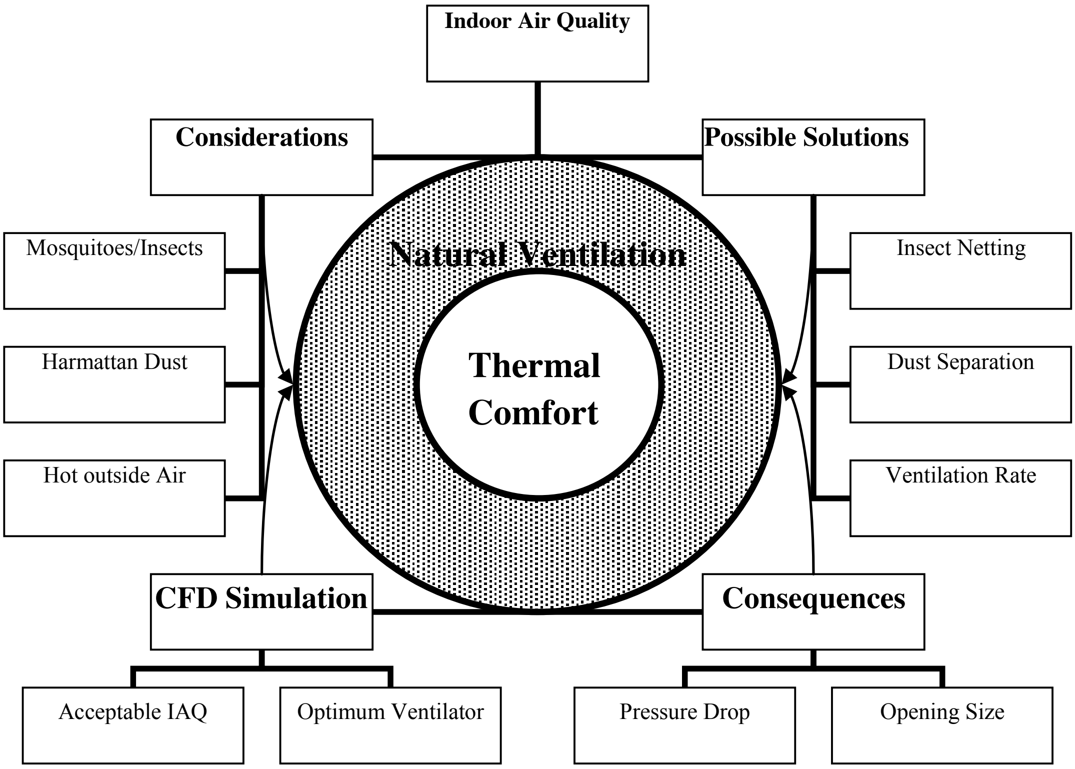


Figure 10: Methodological Framework for Natural Ventilation simulation in Multi-Bed Wards of Semi-Arid Climates

CONCLUSION

The study analyses and subsequently explores the possibility of using natural ventilation strategy for achieving acceptable indoor air quality and thermal comfort and to ascertain the major influential factors affecting these strategies. It has been established that, mosquito insects, Harmattan dust, and high outdoor air temperatures are the three major factors challenging the design of natural ventilation in semi-arid climates. The study shows that, the average total ambient temperatures in the study area are higher than the comfort neutrality temperature throughout the year except for February, August and November, in which temperatures falls within the comfort limits. Moreover, the ventilation rates in the existing hospital ward measured is below the standard minimum limits of 6ACH. Fluent Computational Fluid Dynamic (CFD) Software has been used in modelling the natural ventilation strategies. The result shows that, the installation of insect screen will result in 70% reduction in air change rate and 8% opening area in relation to building floor area is required to achieve acceptable ventilation rate. Other natural ventilation configurations apart from the cross ventilation will be investigated, with the aim of increasing the air exhaust from the ward and strategies for low energy dust removal. The study mainly focuses on mosquito prevention strategies, while the research on Harmattan dusts part of the problem is in progress. Therefore, a methodology has been developed to simulate Natural ventilation strategies for acceptable indoor air quality and thermal comfort, excluding mosquitoes and Harmattan dust and without compromising occupants comfort.

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