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CFD Simulation on Rural Residential Buildings for Sustainable Development: A Case Comparision

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Abstract: Now a days, engineers and architects are increasingly using engineering simulations to design buildings to attain energy efficiency, sustainable goals and utilize renewable resources. Fluid dynamics simulations have proven to be a powerful and effective tool providing flexible solutions. These simulations are extensively used as an optimization and validation tool at an early phase in the design process. Building as one of the largest industries has significant impacts on the environment and natural resources. Air velocity, temperature and humidity ratio are the most important parameters for the determination of building thermal comfort. Rural residences accommodate major population and were not much taken care of by the designers and builders. Selection of building materials and construction techniques found to play a major role in the sustainable development of rural building sector. Mud block construction and rat trap bonded brick wall construction were simulated and analysed for temperature and relative humidity distribution indoors at standard outdoor conditions. The analysis depicts the advantage of rat trap bonded wall construction for natural building cooling and thermal comfort.

Key words: Building simulation, CFD analysis, rat trap bond, relative humidity, thermal comfort

INTRODUCTION

With the ever increasing demands for sustainable buildings, engineers are developing more complex and diversified design to reduce loads, boost efficiency and utilize renewable resources. In today's world engineers and architects increasingly employ engineering simulations to enable the design of buildings to most energy efficient and sustainable goals within strict project timelines. Engineering simulation software is used to create a virtual prototype of a building or interior space on a computer and calculate the heating, cooling and ventilation performance. Fluid dynamics simulations have proven to be a powerful and effective tool, providing flexible solutions in increasingly complex and demanding projects. These simulations are extensively used as an optimization and validation tool at an early phase in the design process, since simulation supports implementation of innovative designs and energy saving measures geared towards decreasing the overall facility's energy costs while maintaining or improving occupant comfort (Haber and Nehme, 2011).

Currently, many buildings are constructed or remodeled without consideration of energy conserving strategies that could, in many cases, be incorporated in a cost effective manner. These buildings as well as most single and multi family residential buildings are generally designed and constructed by builders or building contractors, without the benefit of computerized building energy analyses and equipment sizing. Thermal and energy dynamic analysis of buildings is a well established procedure to evaluate the effective building energy performance, considering real climate. It is clear that all the decisions taken in the early stages of the architectural process affect both indoor thermal comfort and building energy efficiency that could not be independent also from the environmental stresses, typical of each macroclimate region (Pisello *et al*., 2011). Building, as one of the largest industries, has significant impacts on the environment and natural resources. The construction and operation of buildings generate tremendous pollution that directly and indirectly cause urban air quality problems and climate change. Poor design of buildings and systems not only wastes resources and energy and causes adverse impacts to the environment but also creates uncomfortable and

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unhealthy indoor environments. Reports of symptoms and other health complaints due to poor indoor environments have been increasing in the last decade (Zhai, 2006).

Normally in rural residential construction no importance is given for early design and analysis. But, some traditional construction techniques and usual material selection for rural house construction are naturally providing comfort and healthy environment to the occupants. Most commonly used rural house building materials, mud block and burnt brick with rat trap bonded wall construction were selected and Computational Fluid Dynamics (CFD) analysis was done. Some interesting observations were made and presented in this study.

Energy efficient buildings: Energy efficient buildings have been turned out to be promising for future building designs and are an effective way to reduce air conditioning energy consumption and to improve thermal performance of buildings. People spent most of their time in buildings, so a good indoor environment is important to occupants for their health and productivity. The indoor temperature, the indoor air quality and the indoor illumination are considered as the most important impacting factors of overall comfort in the building environment (Wang and Wang, 2013; Venancio and Pedrini, 2009). Green buildings refers to building life cycle to maximize conservation of resources like energy, land, water and materials, protecting the environment and reduce pollution provide people with health, suitable and efficient use of space and nature building harmony. Green building which marks the emergence of traditional architectural design to get rid of the only use of the building aesthetics, space, form of structure, colour structure, colour and other considerations, gradually go from an ecological point of view the building. The main parameters involved in the construction of indoor and outdoor air environment are temperature, relative humidity, CO_2 content and dust content (Yang, 2012).

MATERIALS AND METHODS

Building simulation and analysis: In the past few years, CFD has been playing an increasingly important role in building design, following its continuing development for over a quarter of a century. CFD by numerically solving the governing equations for fluid provides spatial and temporal distributed information of airflow, pressure, temperature, turbulence intensity, moisture content and contaminant concentration. These details can be used to evaluate the levels of thermal comfort, indoor air quality and building system energy efficiency which are interesting to architects, building designers, consultants and researchers (Zhai, 2006). The natural ventilation is an important strategy to improve thermal comfort in buildings that are located in hot and humid climates. The air velocity at certain limits can provide the sensation of cooling by decreasing the rate of evaporation from the skin surface. As seen, building simulation programs allow for many benefits such as the possibility of performing thermal and energy performance analysis for different alternatives.

In hot and humid climates thermal comfort can become a problem to the occupants of many residential buildings especially when they are not equipped with air conditioning system. Standards that may be used to evaluate thermal comfort are widely available and numerical methods such as computational fluid dynamics may be utilized to assist in the analysis. CFD software such as fluent is a useful tool that can be used to create a virtual model of the building interior and simulate air flow, temperature profile and humidity which are directly related to thermal comfort before the actual construction can be done. Modifications to an existing building can also be simulated using the CFD method prior to any physical renovations. Many researchers have used CFD to analyze thermal comfort in building spaces and investigating the effects of natural and stratified ventilations on the thermal comfort. Some used this technique to improve the efficiency of energy usage for the building. These are very difficult to be carried out by using other methods. It is possible to predict the temperature distribution and velocity profile of the ambient air inside the house for many conditions (Masine *et al*., 2011).

This study presents outcomes of an ongoing research work to investigate thermal comfort level in naturally ventilated rural residential houses using computational fluid dynamics method. Actual measurements of the temperature distribution and relative humidity were carried out. CFD simulations on the models of the houses allow us to visualize the temperature distribution and relative humidity pattern inside the houses.

CFD as an effective tool in building simulation: Computational fluid dynamics is the term used to describe a family of numerical methods used to calculate the temperature, velocity and various other fluid properties throughout a region of space. CFD when applied to buildings can provide the designer with information on probable air velocities, pressures and temperatures that will occur at any point throughout a predefined air volume in and around building spaces with specified boundary conditions which may include the effects of climate, internal heat gains and heating ventilation and air conditioning systems. Building performance simulation involves the use of computational models of buildings and components thereof for prediction of future behaviour in terms of physical performance indicators. Computational fluid dynamics makes it possible to simulate airflow patterns, thermal comfort and concentration distributions of pollutants in a space at much less cost. This technique, allows the simulation and the visualization of environmental problems (Blocken *et al*., 2011; Yang *et al*., 2014).

In order to predict air flow in and around a building, CFD analyzes the air velocity, temperature, contaminant concentrations and amount of turbulence around that building by solving a set of mathematical equations. These equations derive from three basic principles namely conservation of mass, conservation of momentum and conservation of energy within that fluid. It is therefore necessary to conduct mathematical modeling at the outset to establish the necessary computational inputs. Unlike other building simulations such as energy simulations, CFD requires users to have some knowledge of mathematical modeling and experience with numerical methods. In addition, the CFD modeling approach relies on physical models such as turbulence. It is difficult for non experts or architects to conduct CFD simulations (Kim, 2014; Gaspar *et al*., 2003; Zhai and Chen, 2005; Yao *et al*., 1972).

Applications for the building simulation are often used within the planning process to improve the energy efficiency of the building. For the realization of such simulation calculations, the used building simulation tools have to be configured and parameterized for each building in an individual way. It is necessary to provide instructive materials on how to verify, validate and report indoor environmental CFD analyses. It can determine detailed flow distributions, temperatures and pollutant concentrations to better than 5% accuracy, without excessive effort by the software user (Geusen *et al*., 2003; Chen and Srebric, 2002; Fletcher *et al*., 2001; Haupt *et al*., 2010; Pollock *et al*., 2009). The energy consumption of buildings is affected by many factors such as building size, thermal performance of building envelope, performance and operation mode of building services systems, temperature and so on. Therefore, dynamic simulation methods have to be used in order to make the energy efficient design of buildings more reliable (Ma and Zhao, 2008).

The aim of the CFD simulations in the early planning and design stage is to generate visualized flow phenomenon of a particular flow problem and through which to understand the wind environment and create innovative solutions to the particular problems (Lau and Tsou, 2009). Experimental studies in building energy usage and environmental analysis are very time consuming and expensive and require sophisticated sensors and instrumentation techniques. So, there has been great interest in developing CFD computer codes to improve building design and heating ventilation and air conditioning systems.

The majority of these CFD programs are based on the solution of Navier-Stokes equations, the energy equation, the mass and concentration equations as well as the transport equations for turbulent velocity and its scale (Gaspar *et al*., 2003).

For the study of natural ventilation and wind microclimate, CFD is most widely used and perceived as an appropriate tool with reasonable accuracy. It can be applicable to architectural or engineering fluid dynamics and transport phenomena including airflow inside and outside a building (Niu, 2004). The simulation of thermal and energy performance of buildings allows the evaluation of design process and architectural alternatives through technical decisions such as site orientation, building components, materials, thermal inertia, lighting systems and air conditioning. These elements have significant impacts on indoor environment and energy consumption for building operation (Mohamed *et al*., 2010). The advantage of CFD modeling is that instead of examining the average temperature in a room, a CFD investigation can identify parts of a room or building that are not cooled or heated sufficiently (Stoakes, 2009).

Building materials selection: Heat flow through a material medium is strongly dependent on the thermal properties and the nature of the material. The heat experienced in the interior spaces of buildings in tropical The walls release the absorbed heat from the environment into the interiors of buildings by the process of conduction and radiation which causes discomfort to the inhabitants. It is, therefore essential to consider how to regions is through various surfaces including the walls.

Table 1: Material properties for the model houses analyzed

Materials	Wall thickness (mm)	Roof thickness (mm)	Specific heat capacity (CP) KJ/kg/m	Thermal conductivity (C) W/m/K	Density (ρ) kg m^{-3}
Rat trap bonded wall	230	120	0.84	0.60	1820
Mud block wall	250	120	0.92	2.50	2300
Cement concrete (roof)	-	120	0.90	1.13	2000

reduce or eliminate if possible the heat in the interior spaces when constructing the walls of living houses in such regions. The interior spaces must be made conducive and comfortable for the general well being of the occupants (Alausa *et al*., 2013).

The present study was aimed at among mud block and rat trap bonded brick wall construction and find which would be more suitable as a heat insulator for the purpose of constructing walls of houses in tropical region. The observation from this study recommended rat trap bonded construction technique for walls to minimize heat conductivity from the environment to the interior and make self cooling buildings.

Mud block wall construction: There are a range of sustainable building materials that are both eco friendly and elegant at the same time. Earth is the oldest material used by man and has always been the most widely used material for building in India. Mud brick and poured earth construction techniques are just a few of the options available for earth friendly construction. Mud brick has several advantages over conventional fired clay or concrete masonry like low embodied energy, high thermal mass, good insulation properties and its ability to breath. The compressed mud block can be used for construction of houses. Greater design care and stabilization enable the construction of more ambitious structures that need less maintenance and are longer lasting.

Rat trap bonded wall construction: The rat trap bond is a masonry technique where the bricks are used in a way which creates a cavity within the wall while maintaining the same wall thickness as for a conventional brick masonry wall. While in a conventional English bond or flemish bond, bricks are laid flat, in a rat trap bond, they are placed on edge forming the inner and outer face of the wall with cross bricks bridging the two faces. The main advantage of rat trap bond is reduction in the number of bricks and sand mortar required because of the cavity formed in the wall. The air cavity also makes the wall more thermally efficient. This also reduces the embodied energy of brick masonry. It is suitable for use, wherever one brick thick wall is required.

CFD simulation on naturally ventilated rural residential house: We performed CFD simulation on two rural residential house models which are naturally ventilated, one constructed with mud block wall and another with rat trap bonded brick wall. After meshing the model, we imposed the boundary conditions on the models that represent the natural ventilation conditions, namely with the front door and two side windows opened as in typical rural residential building.

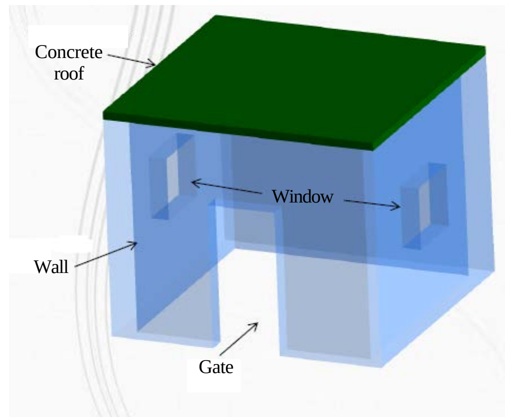

Fig. 1: Model house, CAD Model

Boundary conditions: The boundary conditions used for the CFD analysis on the model houses were as shown below:

- Inlet temperature of the incoming air is 30°C
- Incoming volume fraction of water vapor is 2.5% and remaining is air
- Velocity of the incoming air flow is 0.5 m sec^{-1}
- Ceiling Temp of the houses is 40°C
- Side wall temperature is 30°C on all sides
- Floor of the houses are adiabatic
- Operating conditions assumed as standard temperature and pressure

All boundary conditions were same for both the models except the wall thickness and shape. The material properties of the model houses taken for analysis are as presented in Table 1. Material properties for the model houses analyzed.

CFD analysis of the model residential houses: This research was to investigate the air temperature distribution, the variation of relative humidity of the ambient air inside the rural residential houses. We compared the results of the CFD simulations on mud block walled and rat trap bonded brick walled model houses as shown in Fig. 1 (10×10×10 feet). The values of all parameters were taken from the actual measurement from the model houses available in the Gandhigram Rural Institute Deemed University campus. Standard climatic conditions prevailing in this region were prescribed as boundary condition and the CFD Model was submitted for the analysis. The results produced by the CFD simulations are the air temperature distribution and the variation of relative humidity of the ambient air inside the model houses.

RESULTS AND DISCUSSION

Temperature and percentage humidity contours along various planes of mud block and rat trap walled houses were analysed and the case comparison was presented in this study.

Mud block wall contours: Figure 2 and 3 show the contour of temperature distribution and relative humidity

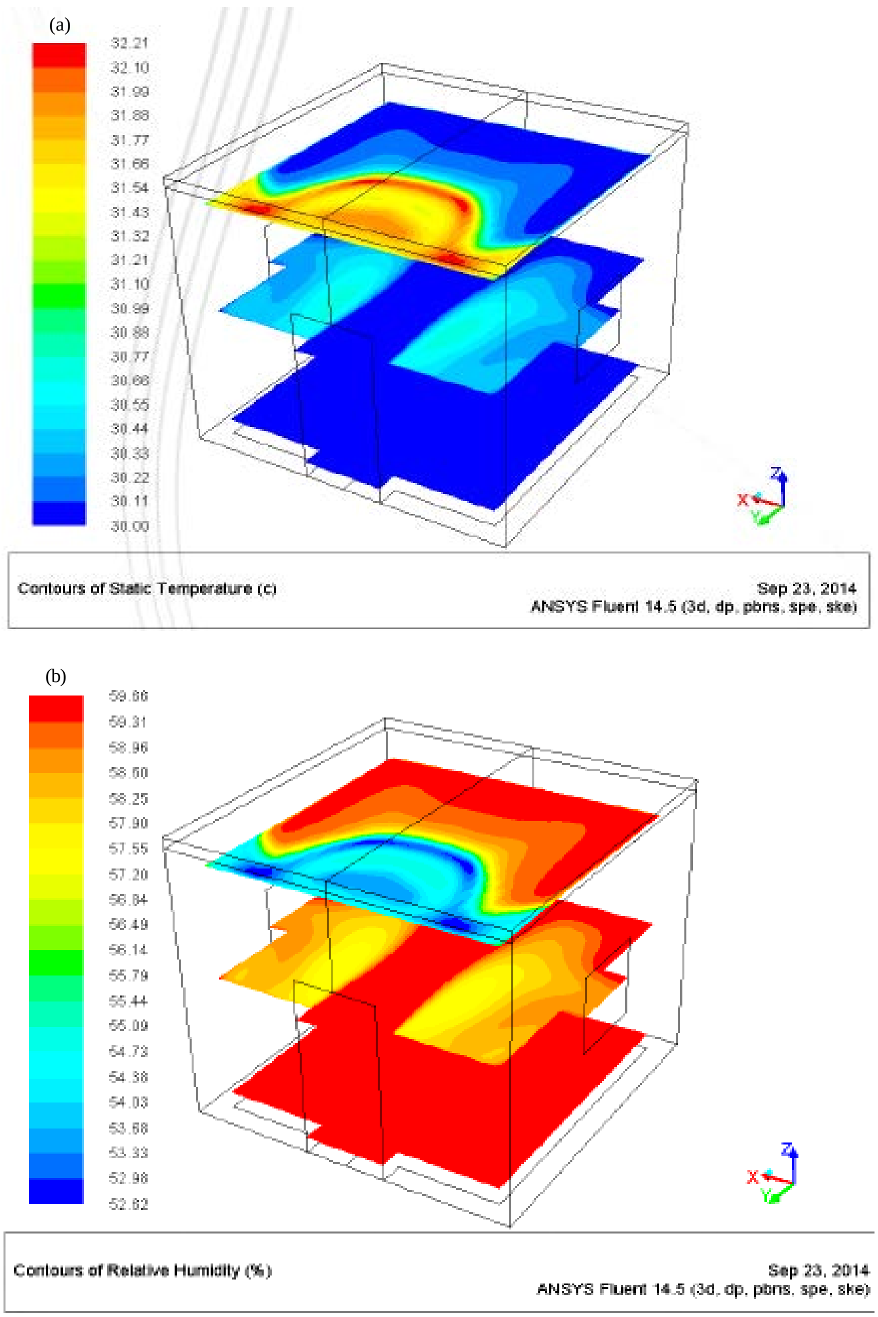

Fig. 2: Contours across the flow at various XY plane

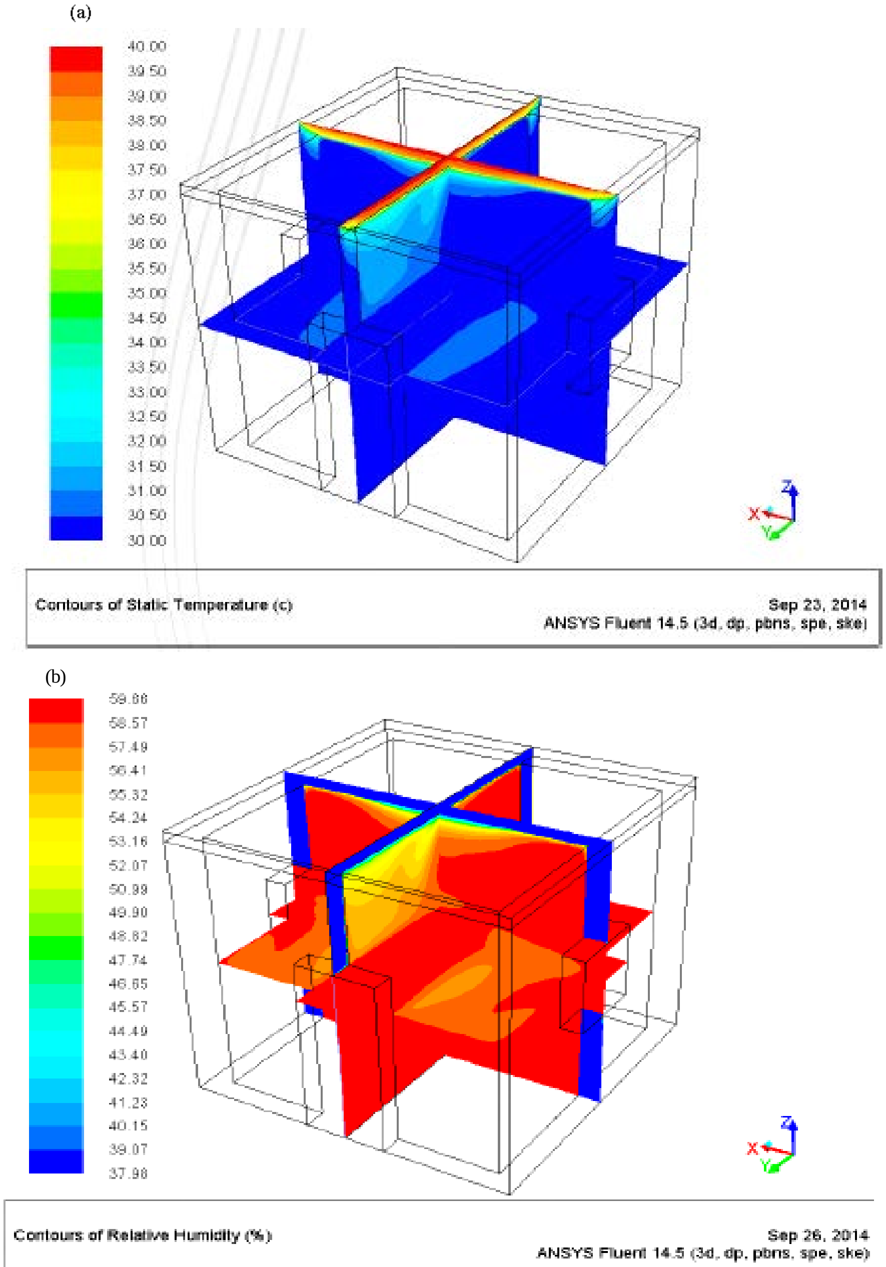

Fig. 3: Contours at various mid planes

on the mud block walls inside the model house along X-Y and various mid planes. The air temperature is slightly higher close to the front wall.

Rat trap wall contours: Figure 4 and 5 show the contour of temperature distribution and relative humidity on the rat trap bonded walls inside the model house along X-Y and various mid planes. The air temperature is slightly higher close to the front wall. There is a significant temperature variation on the front wall surface with the highest temperature. This is due to a high heat gain through this wall. The front wall and back wall of the house are at a fairly uniform temperature.

Case comparison-rat trap bonded brick wall and mud block wall construction: Figure 6-9 shows the case comparison on contour of temperature distribution and relative humidity on the rat trap bonded brick walls and mud block walls of the model houses along XY, YZ, XZ and various mid planes. The maximum local air

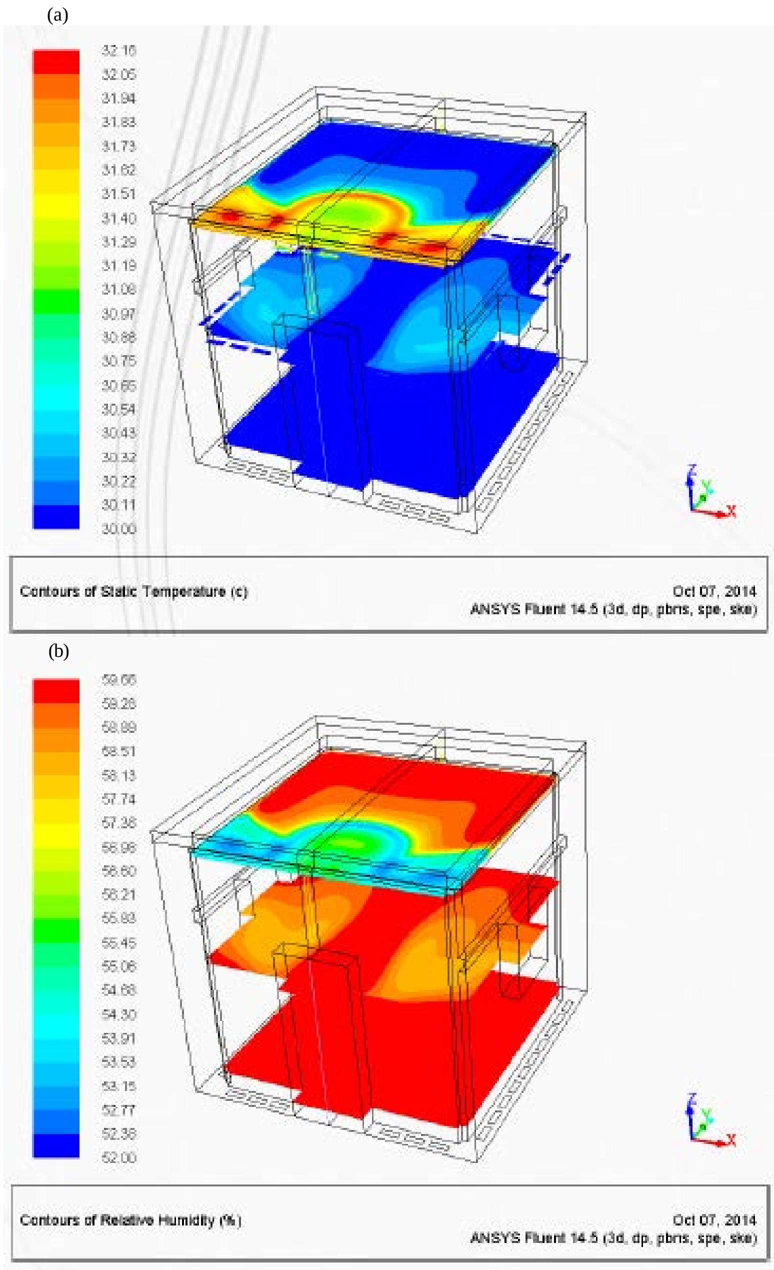

Fig. 4: Contours across the flow at various XY plane

temperature difference near the roof is 6°C; however the average temperature difference is 0.5°C. The average wall temperature difference between mud block wall and rat trap bonded brick wall is 0.3°C.

To assess the level of thermal comfort in the model houses, we carried out measurements to acquire the average temperature, the relative humidity and the average velocity of the ambient air inside the houses.

Observations: Observations based on the CFD analysis on the mud block walled and rat trap bonded brick walled constructed model houses are presented as follows:

- Pattern of temperature in both the cases of mud block walled house and rat trap bonded brick walled house are same
- Air temperature inside the house in case of mud block walled is more than rat trap bonded brick walled house

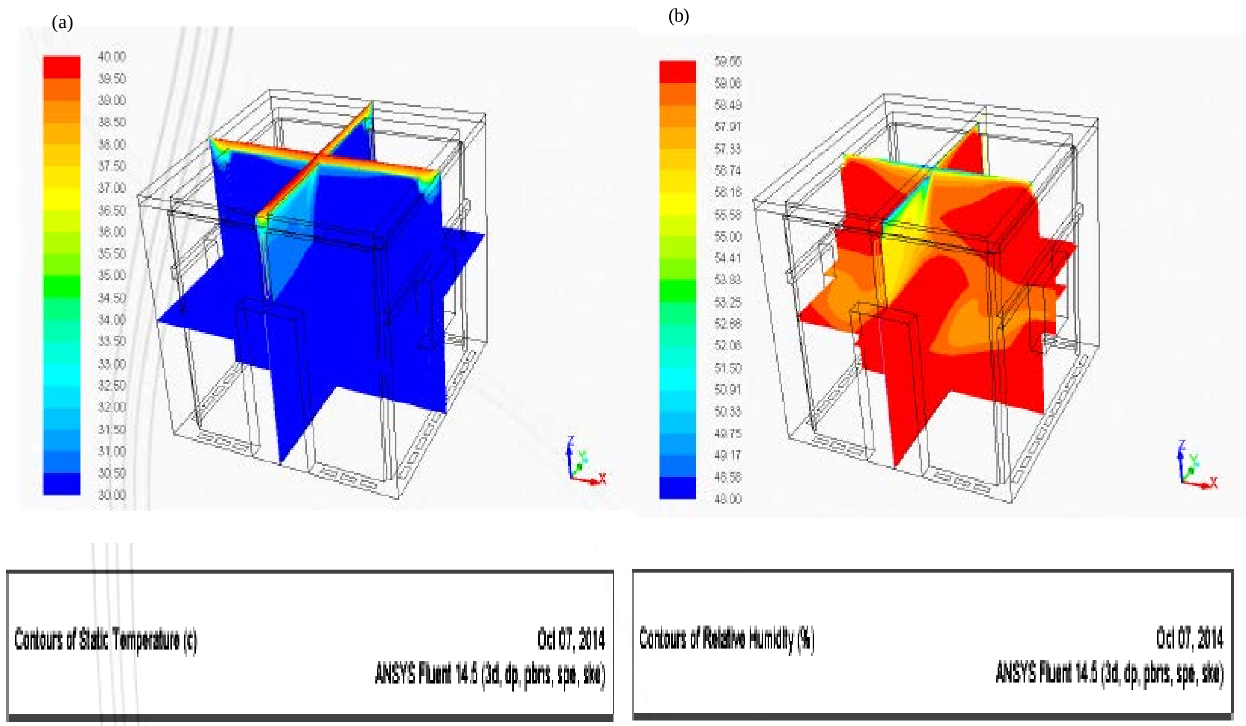

Fig. 5: Contour at various mid planes

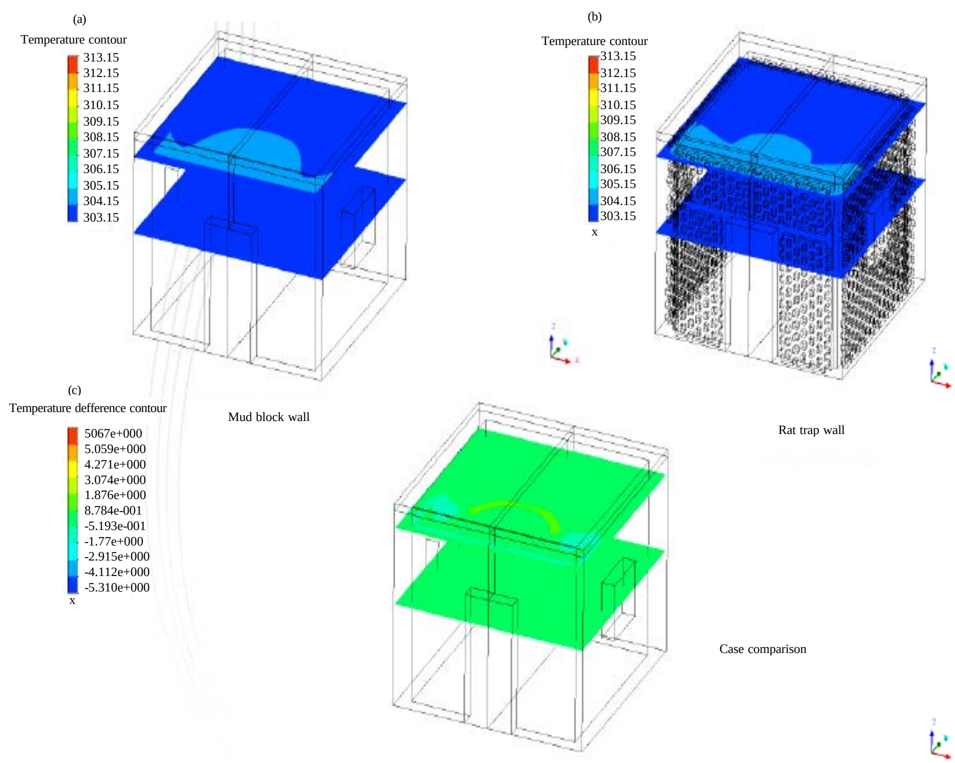

Fig. 6: Temperature contours across the flow at various XY plane

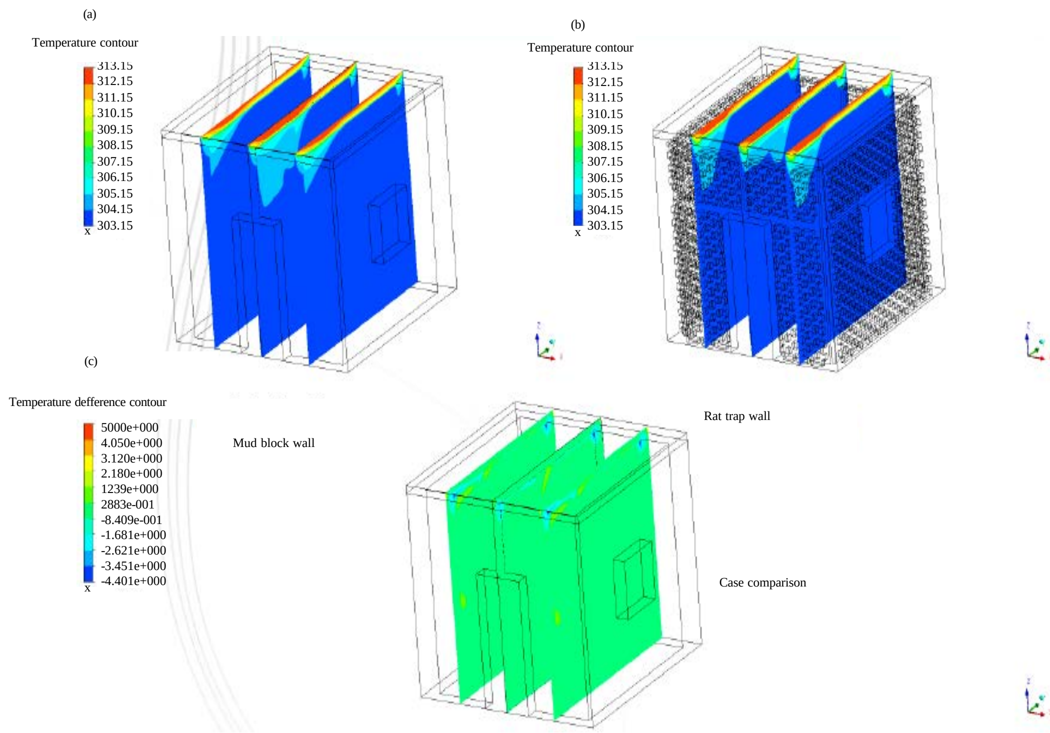

Fig. 7: Temperature Contours along the flow at YZ Plane

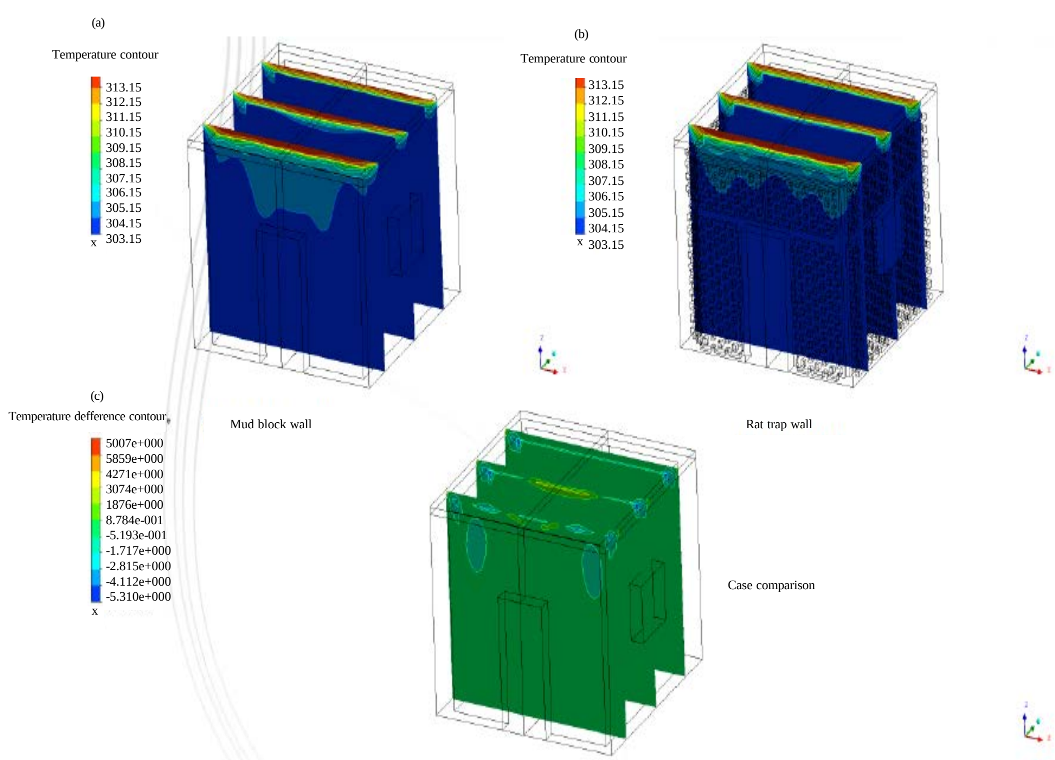

Fig. 8: Temperature contours at various XZ plane

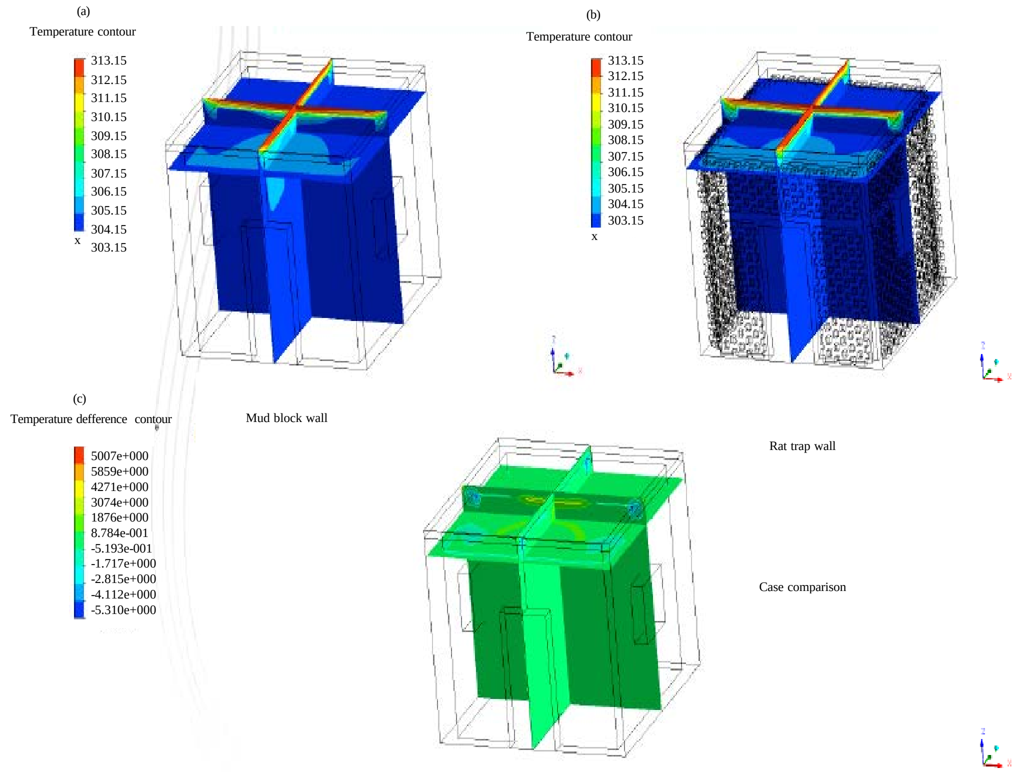

Fig. 9: Temperature and humidity contour at various planes

- The temperate of Rat trap bonded brick wall is more than Mud block wall
- The maximum local air temperature difference near the roof is 6°C; however the average temperature difference is 0.5°C in both cases
- The average wall temperature difference between mud block wall and rat trap bonded brick wall is 0.3°C

CONCLUSION

CFD analysis on the rural residential model houses, one with mud block walls and another with rat trap bonded burnt brick walls helped in arriving at the following conclusions:

- Pattern of air temperature within the houses in two cases mud block walled and rat trap bonded brick walled are almost same
- Air temperature is lesser inside the house in case of rat trap bonded brick wall and it is higher in case of mud block walled house
- The average air temperature difference between two cases, mud block walled and rat trap bonded brick walled is around 0.7°C whereas the maximum local temperature difference for the same is around 6°C
- The wall temperature is maximum in case of rat trap bonded brick walls and minimum in case of mud block walls
- The average wall temperature difference between two cases, mud block walled and rat trap bonded brick walled is around 0.3°C

It is concluded from this study that rat trap bonded construction technique for walls will minimize heat conductivity from the environment in to the interior of houses and make buildings self cooling. Using the locally available building materials like burnt bricks and the construction techniques like rat trap bonded wall construction will help to achieve some level of thermal comfort in rural residences with no extra cost. Some other combinations can also be identified with CFD analysis for achieving sustainable development in rural building sector.

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