A Comparison on Simulation and Validation of Rural Residential Buildings Using Low Cost Technologies

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Abstract  
Engineers and architects are 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 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. Thermal validation was done and the analysis depicts the advantage of rat trap bonded wall construction for natural building cooling and thermal comfort.

Keywords: CFD analysis, Rat trap bond, building materials, thermal imaging, thermal comfort

Introduction  
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 complex projects. These simulations are extensively used as an optimization and validation tool in the design process, since simulation supports implementation of innovative designs and energy saving measures focused towards decreasing the overall energy costs and in improving occupant comfort [1, 2]. Nowadays 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 without the benefit of computerized building energy analyses and equipment sizing [3]. Thermal and energy 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 [4]. Building, as one of the largest industries, has significant impacts on the environment and natural resources. Poor design of buildings and systems not only wastes resources and energy and causes adverse impacts to the environment, but also creates uncomfortable and unhealthy indoor environments. Reports of symptoms and other health complaints due to poor indoor environments have been increasing in the last decade [5]. 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. Thermal imaging of real buildings was used for validation. Some interesting observations were made and presented in this paper.

Energy Efficiency in Residential 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 [6, 7]. 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 healthy, suitable and efficient use of space and nature building harmony. The main parameters involved in the construction of indoor and outdoor air environment are temperature, relative humidity, CO₂ content and dust content [8].

Building Energy Simulation Using CFD
In the past few years, Computational Fluid Dynamics CFD has been playing an increasingly important role in building design, following its continuing development. CFD, by numerically solving the governing equations for fluid flow, 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 [5]. 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 methods and materials. [9]

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. Some designers used this technique to improve the efficiency of energy usage for the buildings which 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 different conditions [10].

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 [11, 12, 13].

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 [14].

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 [15]. 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 [16, 17]. 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 [18, 19]. 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 [20].

This paper presents outcomes of an analysis to investigate the thermal comfort level in naturally ventilated rural residential houses built with both mud blocks and burnt brick rat trap bonded walls using computational fluid dynamics method. Actual measurements of the temperature distribution and relative humidity were carried out. Thermal imaging of real model houses was also done. CFD simulations on the models of the houses allow us to visualize the temperature distribution and relative humidity pattern inside the houses.

Materials Selection for Residential Buildings
Heat flow through a material medium strongly depends on the thermal properties and the nature of the material. The heat experienced in the interior spaces of buildings in tropical regions is through various surfaces including the walls. 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 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 [21].

The present work was on mud block walled and rat trap bonded brick walled construction to find which can be a promising heat insulator for the purpose of constructing walls of houses in rural of a 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 the building self cooled.
Mud Block Walled Houses
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 block 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 Bond Walled 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 but 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.

Simulation Done On Naturally Ventilated Model Houses
We performed CFD simulation on two rural residential house models which are naturally ventilated, one constructed with mud block walls and another with rat trap bonded brick walls. 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.

Boundary Conditions Applied
The boundary conditions used for the CFD analysis on the model houses were as detailed 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 0.5m/s
  - Ceiling Temp of the houses is 40°C
  - Side wall temperature is 30°C on all sides
  - Floor of the houses are assumed to be adiabatic for analysis
  - Operating conditions assumed as standard temperature and pressure

All boundary conditions were same for both the model houses except the wall thickness and shape.

The material properties of the model houses taken for analysis were as presented in the table-1.

Table 1: Material properties for the model houses constructed and analyzed

<table>
<thead>
<tr>
<th>Material</th>
<th>Wall Thickness (mm)</th>
<th>Roof Thickness (mm)</th>
<th>Specific Heat Capacity (Cp) KJ/Kg. K</th>
<th>Thermal Conductivity(C) W/m.K</th>
<th>Density (p) Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat Trap Bonded wall</td>
<td>230</td>
<td>120</td>
<td>0.84</td>
<td>0.6</td>
<td>1820</td>
</tr>
<tr>
<td>Mud Block wall</td>
<td>250</td>
<td>120</td>
<td>0.92</td>
<td>2.5</td>
<td>2300</td>
</tr>
<tr>
<td>Cement Concrete Roof</td>
<td>-</td>
<td>120</td>
<td>0.90</td>
<td>1.13</td>
<td>2000</td>
</tr>
</tbody>
</table>

CFD Analysis on Model Residential Houses
This analysis 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 with the experimental data for validating the CFD simulation procedure. The values of all parameters were taken from the actual measurement from the model houses. Once all the boundary conditions were prescribed, the CFD model was submitted for the analysis. The results obtained by the CFD simulations were the air temperature distribution and the variation of relative humidity of the ambient air inside the model houses as in the figures 1a, 1b and 1c which are mud block walled and rat trap bonded walled.

Figure 1(a): Model house for CFD analysis- Mud block walled
Fig 1(b): Model house for CFD analysis – Rat trap bond walled

Fig 1(c): Model house for CFD analysis – Rat trap bond walled with meshing

Meshing Statistics Applied for Analysis
The following meshing statistics for both the model houses were applied for analysis
Mesh Type – Hexahedral & Tetrahedral
Mesh count – 3890245
Maximum Skewness – 0.9
Average Skewness – 0.15
Minimum Orthogonal Quality – 0.195
Average Orthogonal Quality – 0.90

5.0 Results and Discussions
Temperature and % Humidity contours of Mud block and Rat trap walled model houses were analysed and the case comparison was done.

5.1 Mud Block Walled House Contours
Figures 2 and 3 show the contour of temperature distribution and relative humidity inside the mud block walled model house. 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.
Rat Trap Walled House Contours
Figures 3 and 4 show the contour of temperature distribution and relative humidity on the rat trap bonded walls inside the model house. 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.

Comparison - Rat Trap Bonded Brick Walled and Mud Block Walled Construction
Figures 6, 7, 8 and 9 show the comparison on contour of temperature distribution and relative humidity on the mud block walls and rat trap bonded brick walls of the model houses along various planes. The maximum local air 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.

Figure 4: Contours across the flow at various XY Plane

Figure 5: Contour at various mid Planes

Figure 6: Temperature Contours across the flow at various XY Plane

Figure 7: Temperature Contours along the flow at YZ Plane

Figure 8: Temperature Contours at various XZ Plane
Validation
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. The thermal behaviour of building walls made of rat trap bond and conventional brick has been analysed using Thermal Imager.

Thermal Analysis of Rat Trap Bond Walled Model House
The rectangular area Ar1 selected on the wall of rat trap bond shows an average temperature of 27.4°C, maximum temperature of 27.8°C and a minimum temperature of 26.8°C. The thermal image of rat trap bonded walled house is shown in figure 10.

Measurements made were as presented below
- Maximum Temperature : 27.8°C
- Average Temperature : 27.4°C
- Minimum Temperature : 26.8°C
- Emissivity : 0.89
- Reflection Temperature : 20°C

Thermal Analysis of Mud Block Walled Model House
The rectangular area Ar1 selected on the mud block wall shows an average temperature of 27.2°C, Maximum temperature of 27.5°C and minimum temperature of 26.8°C. The thermal image of mud block is shown in figure 11.

Measurements made were as presented below
- Max. Temperature : 27.5°C
- Ave. Temparture : 27.2°C
- Min. Temperature : 26.8°C
- Emissivity : 0.90
- Reflection Temperature : 20°C

Observations
Observations based on the CFD analysis on the mud block walled and rat trap bonded brick walled constructed model houses were 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.
- 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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References


