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CFD Simulation and Validation on Rural Residential Buildings with Mud blocks for Sustainable Development

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Abstract - Energy performance of social housing plays an important role in sustainable development of the built environment. Nowadays building energy simulation, a calculation method of energy consumption for heating and cooling of buildings, is being adapted to the design of sustainable low energy buildings. Sustainable building design consists of methods to develop the built environment while meeting the purpose of sustainable development. Many sustainable building materials that are both environmental friendly and also elegant are available. Mud brick and poured earth construction techniques are few options. Earth has always been the most widely used material for building in India and is a part of its culture. We performed CFD simulation on a model house constructed with mud blocks, which was naturally ventilated. The thermal behaviour of building walls constructed with mud block has been analysed using Thermal Imager. It is suggested that the mud block is a sustainable building material and they prevent maximum heat transfer into the walls and keep the house self cooling.

Keywords -CFD analysis, Mud block, building energy, simulation, thermal comfort, thermal imaging, sustainable building materials.

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1. INTRODUCTION

Recent advances in the building industry have focused on energy conscious design. The main environmental factors which affect physical comfort are temperature, humidity and movement of air, the latter being the only one which can be controlled to a significant extent without substantial energy expenditure. Energy performance of social housing has an important role to play in sustainable development of the built environment. Building energy modelling can be applied early in the design phase, as a collaborative effort between the energy consultant and the architect. Building energy simulation, a calculation method of energy consumption for heating and cooling of buildings, has been adapted to the design of sustainable low energy building in recent years. The simulation is based on the assumption that room air is uniform hybrid. However, this approximation is not satisfactory in stratified indoor air environment. But the computational fluid dynamics simulation can provide more detailed information such as temperature, pressure, velocity distribution of airflow, heat transfer and contaminant transportation indoor and outdoor building environment. [1]

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Human thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment. It can be achieved by maintaining a thermal equilibrium between the human body and the environment. Sustainable building design is the application of sustainability to the built environment. Sustainable building design consists of methods to develop the built environment while meeting the intent of sustainable development. There are a range of sustainable building materials that are both environmental friendly and also elegant. Mud brick and poured earth construction techniques are few options available. Earth has always been the most widely used material for building in India and is a part of its culture. Approximately 55% of all Indian homes still use raw earth for walls. Mud block house preferable for rural Indian housing is considered for CFD analysis to predict the air flow, temperature and humidity variation for the given environment, the results are validated and presented in this paper.

1.1 CFD Analysis for Buildings Design

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. Computational fluid dynamics (CFD), as the most sophisticated air flow modelling method, can simultaneously predict air flow, heat transfer and contaminant transportation in and around buildings [1]. The use of computational fluid dynamics for modelling the built environment has gained interest from both the research and professional worlds in the past several years, due to an increase in knowledge in the field, vastly increased computational power, and more accessible software. It also allows for designers to develop low energy cooling and heating strategies such as natural ventilation systems and passive heating or cooling systems. [2]

CFD is mainly used to predict the air flow patterns using steady state schemes. Because the thermal mass of the enclosure is often not modelled and fixed thermal boundary conditions are assigned to the surfaces to reduce the computational effort, radiation modelling is often neglected [3]. Computational fluid dynamics (CFD) has immense effect in building system performance. It is found that the simulation outputs can give productive and convincing numerical details of the actual thermal comfort on the building occupants. Moreover, the simulation results appear to be adequate for the practical applications [4].

Air velocity, temperature and humidity ratio are the most important parameters for the determination of the predicted percentage dissatisfied (PPD) distribution in a building. PPD is a major index for building thermal comfort judgement. It can be calculated using relations from ASHRAE Handbook of fundamentals

$$PPD = 100-95 \text{ Exp } (-0.03353PMV^4 - 0.2179PMV^2) \ [\%] \quad - \quad (1)$$

The PMV (Predicted Mean Vote) in the equation is determined by

$$PMV = [0.303 \text{ Exp } (-0.036M) + 0.028] \ L \quad - \quad (2)$$

Where M is the body metabolism ($W.m^2$) and L is the thermal load on the body ($W.m^2$)

M and L are the functions of air velocity, temperature, humidity ratio and enclosure temperature.

In addition, CFD results can be used to calculate the distribution of percentage dissatisfied (PD) people due to draft, another major thermal comfort index, through the equation,

$$PD = (34 - T) (U - 0.05)^{0.62} (3.14 + 0.37 \ U \ T_U) \ [\%] \quad - \quad (3)$$

Where T is the local air temperature (^0C), U is the local air speed ($m.s^{-1}$), and T_U is the turbulence intensity (%).

New areas and directions for using CFD for building study have been promoted, with the goal of providing a more accurate and rapid prediction of building performance. Recent trends in the application of CFD for building design are Integration of CFD with other Building Modelling Programs, Simplification and Intelligence of CFD Tools, Improvement of CFD Computing Cost and Development of Critical Modelling Methods [5]. While modelling and simulating a building to evaluate its energy related performance, reproducing the behaviour of the contained air volumes is very important. For that purpose, fully mixed models easily prove inadequate, while computational fluid dynamics do not provide sufficient simulation speed, and are difficult to formulate and manage in a modular manner [6].

High quality commercial CFD is an effective engineering tool for the building services engineering industry. It can determine detailed flow distributions, temperatures and pollutant concentrations to better than 5% accuracy, without excessive effort by the software user, permitting engineering decisions to be made with considerable precision [7]. The one main attractive feature of computational fluid dynamic is its potential to assist investigation of large scale structures of 3D flows, allowing incorporation of realistic boundary condition and obstructions. CFD allows the explicit calculation of average air velocity, also the details of the ventilation mechanism and its consequences on the microclimate [8].

1.2 Building Energy Simulation

Building energy simulation, a calculation method of energy consumption for heating and cooling of buildings has been adapted to the design of sustainable low energy building in recent years. The BES is based on the assumption that room air is uniform hybrid. However, this approximation is not satisfactory in stratified indoor air environment.[1] Building energy modelling can be applied early in the design phase, as a collaborative effort between the energy consultant and the architect. Initial energy modelling uses forward simulation models such as, the degree-day method, bin method, or hourly computer simulation tools to predict annual energy consumption and energy costs. [2]

Simulation tools are developed and designed to answer specific questions, such as lighting, thermal or structural problems. Each of these specialized simulation tools has problems that must be modelled and simulated differently. The limitation of thermal simulation using empirical coefficients for outdoor conditions can be solved by performing CFD simulation to find more reasonable outdoor boundary information.[9] Building simulation programs are now relatively mature in their modelling of deterministic features influencing building energy balances, with the most fully developed integrated solvers supporting simultaneous solutions of building thermal, plant, fluid, electrical power and computational fluid dynamics equation sets.[10].

Recent advances in the building industry have focused on energy conscious design. The resulting simulation tools have had limited impact on building design in practice because they lack the ability to represent simulation results adequately. The lack of design oriented building performance simulation tools is not entirely due to lack of visualization means but also due to lack of an efficient methodology for generating performance data. Such methodologies would support design decision making and create opportunities for optimization as part of the design process [11]. In many situations, it is useful to model dynamic behaviour of buildings whilst simultaneously predicting the spatial variations in temperature and air flow [3].

1.3 Thermal Comfort in Residential buildings

Human thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment that is by a combination of physical and psychological factors. It can be achieved by maintaining a thermal equilibrium between the human body and the environment. Comfort conditions may vary by individual and by factors including physical activity, clothing and environmental variables such as air speed, temperature, humidity and mean radiant temperature. Proper ventilation will provide thermal comfort for the occupants. Ventilation uses either natural or mechanical methods to replace stale room air with fresh air from the outdoors [12]. Incorporating climatic considerations into the preservation process require sensitivity. When a building exhibits thermal comfort, it is desirable to preserve and restore its inherent energy savings features.[13]

1.4 Sustainable Building Design

Sustainable building design consists of methods to develop the built environment while meeting the purpose of sustainable development. Sustainable building design considers the economic, social and ecological impact of buildings on their surroundings [2]. Energy performance of social housing has an important role to play in sustainable development of the built environment. Reducing energy consumption in existing social housing provides environmental benefits both locally, by reduced pollution, and globally, by reducing emissions into the atmosphere of CO_2 and other greenhouse gases. The main socio-economic benefit is affordable warmth [14]. In predicting and designing sustainable and human friendly buildings, a number of representative requirements, like energy saving, thermal comfort, and indoor air quality, involves trade off interactions and optimization issues. CFD simulations can provide more detailed information. [15]

According to the Rio de Janeiro agreement (United Nations, 1992), sustainable buildings should take account of environmental, economical and social stakes. This includes, among other things, good energy performance, good indoor environment quality (IEQ) and health of the occupants. If planning, construction and management are performed by persons aware of the stakes of sustainable architecture, the result will be low energy use with a good IEQ [6]. Natural ventilation is a sustainable building technology that can provide a good indoor environment and save energy. It is preferred over mechanical ventilation for sustainable building design. However, the design of natural ventilation is more difficult than that for mechanical ventilation because the driving force of natural ventilation is complicated and its performance is highly dependent on various factors, such as outdoor microclimate, building shape and orientation, window location and orientation, and internal heat sources. These factors should be thoroughly considered at the early stage of building design in order to achieve good natural ventilation [17]. There are a range of sustainable building materials that are both environmental friendly and also elegant. Mud brick and poured earth construction techniques are few options available. For energy efficient building construction, some preferable sustainable building materials are mud brick, cast earth and stabilised compressed earth block.

2 RURAL RESIDENTIAL BUILDING MATERIALS IN INDIA

Earth is the oldest building material used by man. As new technologies became popular the earth construction skills were lost slowly. But earth has always been the most widely used material for building in India and is a part of its culture. Approximately 55% of all Indian homes still use raw earth for walls. Traditionally, mud construction varies enormously with topography, climatic condition and needs of different regions. The common methods used for earth construction are cob, wattle and daub, rammed earth, and adobe.

2.1 Earth Building – Mud Blocks

Earth as building material has certain disadvantages such as high maintenance and low durability. Other major limitations are water penetration, erosion of walls at level by splashing of water from ground surfaces, attack by termites and pests. The compressed earth block overcomes these limitations by an increase in block density through compaction using a mechanical press. The water content in soil is low for compaction as compared to the puddle clay required for mud bricks and ensures much greater dimensional stability. A compressed earth block has high density which varies between 1.8 and 2.1 gm/c.c., this gives more load bearing capacity and improved water resistance.

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Some advantages are low cost, easy to manufacture locally by small group of people, low in energy consumption because no fuel is burnt for block making or transportation, we can use soil available at site and has smooth surfaces. Because of these advantages a compressed earth block can be used for construction of houses. Mud bricks are becoming increasingly commercially available in a range of stabilised and non stabilised bricks .Mud brick has several advantages over conventional fire clay or concrete masonry. The advantages include low embodied energy, utilisation of natural resources and minimal use of manufactured products, good sound absorption characteristics, high thermal mass, ability to breathe, suitable to a wide range of soils, easy to manufacture, flexibility in design, colour, surface finishes and the similar insulation properties to those of concrete or brickwork.

Mud bricks are typically 250 mm wide x 125 mm high x 375 mm long and normally made from earth with a clay content of 50 to 80% with the remainder comprising a grading of sand, silt or gravel. Stabilising the mud brick with straw or other fibres is sometimes employed where the soil mix displays excessive shrinkage behaviour. Cement and bitumen stabilising is also used with the latter particularly effective in waterproofing. Mud bricks have compressive strength of around 1 to 2 MPa and need to possess a demonstrated resistance to erosion and cracking before being accepted for construction.

3 CFD ANALYSIS WITHIN A MUD BLOCK MODEL HOUSE

We performed CFD simulation on a model house constructed with mud blocks, which was naturally ventilated. After meshing the CAD model as shown in figures 1a and 1b, we imposed the boundary conditions on the model house that represent the natural ventilation conditions, namely with the front door and two side windows opened, as in typical rural residential building. This analysis was to investigate the air temperature distribution, the variation of relative humidity of the ambient air inside the rural residential house. We compared the results of the CFD simulations with the experimental data noted in the model house for validating. The boundary conditions were prescribed as per standards and the CFD meshed model was submitted for the analysis. Tools used for analysis were, for pre processing ANSYS Design Modeller and ANSYS Meshing and the CFD Solver ANSYS FLUENT 14.5 and 15.0. The Meshing statistics applied were 1) mesh type –hexahedral, 2) mesh count-190608, 3) maximum skewness- 0.9, 4) minimum orthogonal quality-1.0. 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 shown in the in the figures.

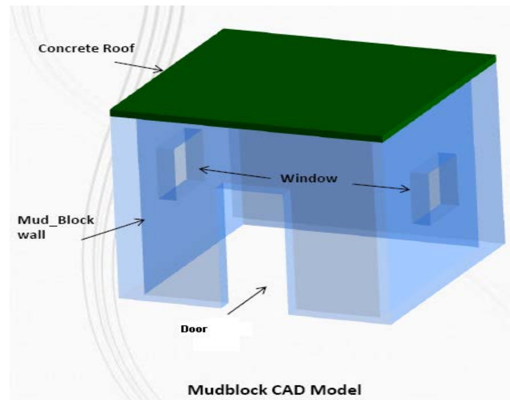

Figure 1a. CAD model of the Mud block house

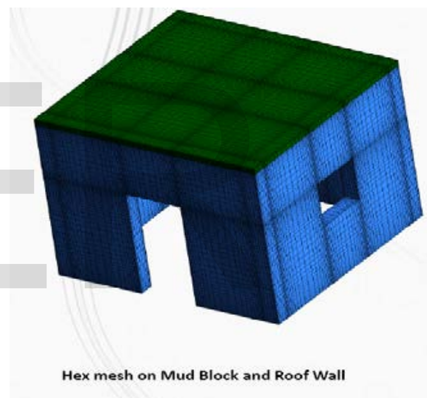

Figure1b. Meshed model for CFD analysis

3.1 Assumptions for CFD Analysis

- The flow is assumed to be steady.
- There is no external source to add and remove humidity within the room.
- Density changes due to compressibility are neglected and as per ideal gas law density changes with respect to temperature is accounted.
- The thermo physical properties except density of the fluid are assumed constant.
- Solar radiation is included by assuming fixed 40°C temperature at the ceiling.

3.2 Boundary Conditions Applied

Boundary conditions used for the CFD analysis on the model house were as follows,

- Inlet temperature of the incoming air is 30°C
- Incoming volume fraction of water vapour is 2.5 % and remaining is air.
- Velocity of the incoming flow is 0.5m/s
- Ceiling Temp is 40°C
- Side wall temp is 30°C
- Floor wall is adiabatic
- Operating conditions taken for analysis are Standard Temperature and Pressure

4 RESULTS AND DISCUSSIONS

Air flow and temperature distribution, temperature and % humidity contours of Mud block walled model house were obtained by CFD analysis and presented.

4.1 Velocity Vectors

One of the usual methods to access thermal comfort is by measuring air velocity due to radiation inside the building. Air movements can be analysed using methods such as measurement, wind tunnel experiment and numerical simulation using computational fluid dynamics. Figures 2, 3, 4,5,6,7 represent the air flow velocity vectors inside the mud block walled house.

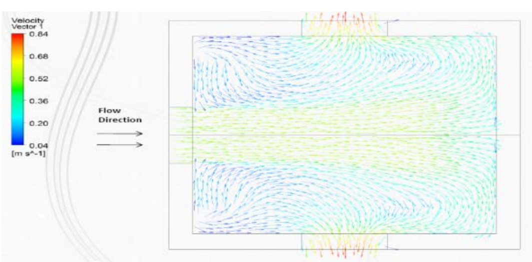

Figure 2. Top view of Velocity Vectors along flow at mid XY plane

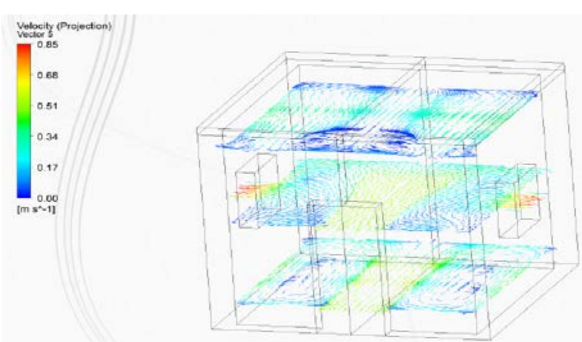

Figure 3. Velocity Vectors along flow at various position

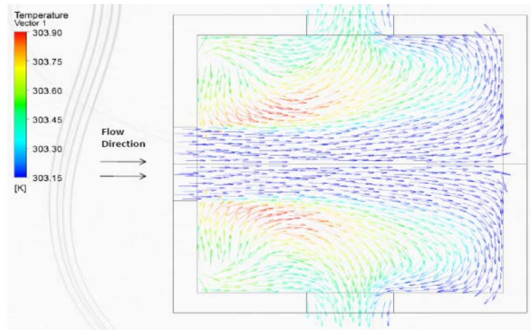

Figure 4. Top view of Velocity Vectors coloured with temperature along flow at mid XY plane

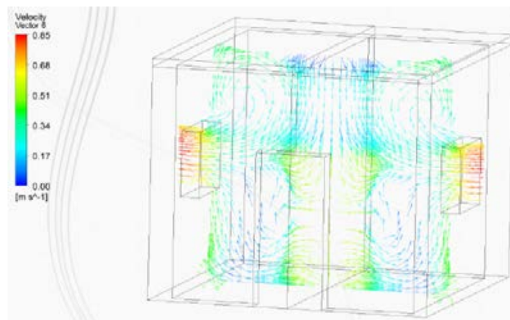

Figure 5. Velocity Vectors across flow direction at mid XZ plane

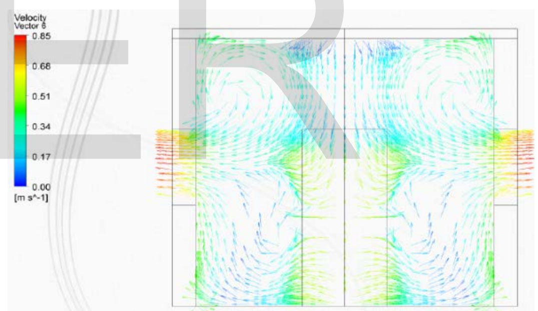

Figure 6. Front view of Velocity Vectors across flow direction at mid XZ plane

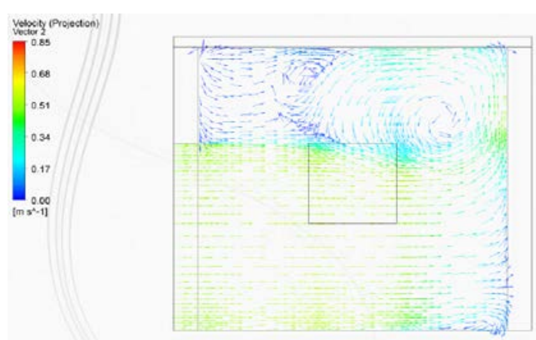

Figure 7. Side view of velocity vectors across flow direction at mid YZ plane

It is observed that the velocity just above the floor that is near to the inlet is high and it decreases when we

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move away the inlet. Therefore, the buoyancy force effect appears only near to the inlet and this effect can be neglected far from the inlet, and this effect appears also on temperature contours and in the relative humidity contours.

4.2 Temperature and Humidity Contour

Figures 8, 9, 10 and 11 shows 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.

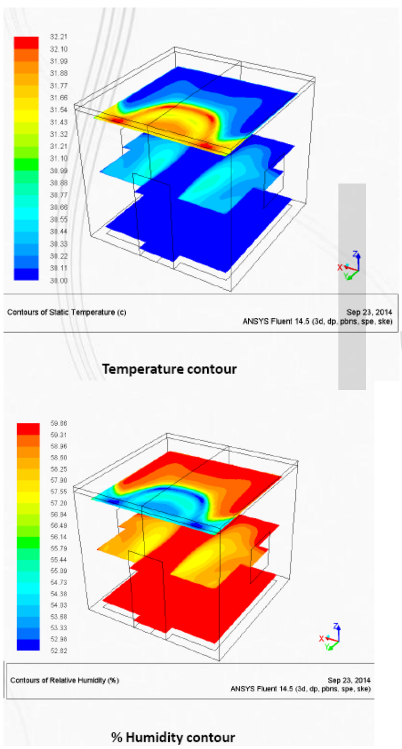

Figure 8. Temperature and %Humidity Contours across the flow at various XY Plane

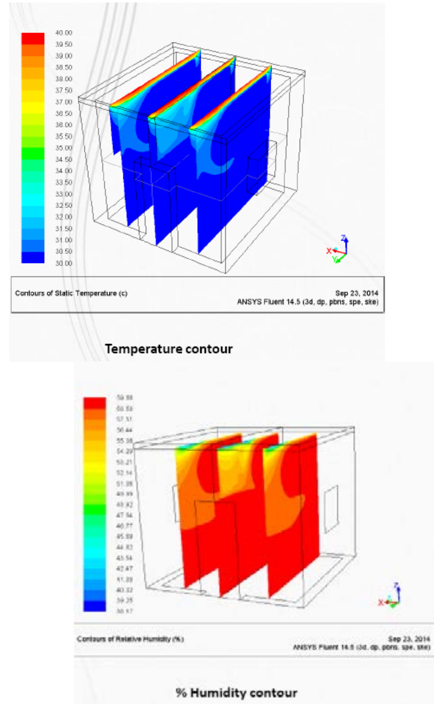

Figure 9. Temperature and %Humidity Contours along the flow at YZ Plane

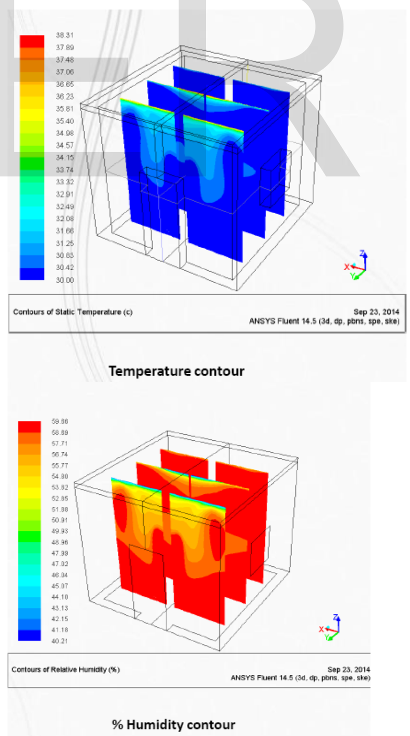

Figure 10. Temperature and %Humidity Contours within air domain at various XZ Plane

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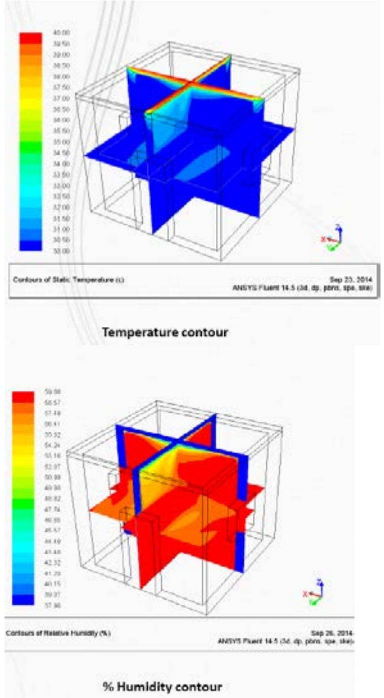

Figure 11. Temperature and %Humidity Contours within air domain at various mid Planes

5 VALIDATION

To assess the level of thermal comfort in the mud block model house as shown in figure 12, 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 constructed with mud block also been analysed using Thermal Imager.

Figure 12. Mud Block Walled Model House

5.1 Thermal Analysis of Mud Block Walled Model House

The thermal image of Mud block wall is shown in figure 13. 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.

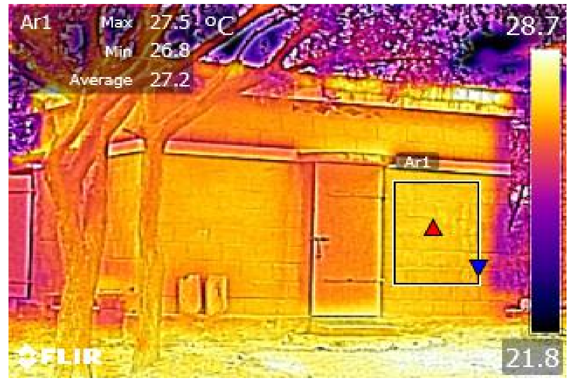

Figure 13. Thermal image of Mud block walled model house

Maximum Temparature	: 27.5°C
Average Temparture	: 27.2°C
Minimum Temparature	: 26.8°C
Emissivity	: 0.90
Reflection Temperature	: 20°C

For mud block wall, two types of temperature measurements were taken, Elliptically (El2) and Linearly (Li2). The elliptical selection shows a temperature of maximum 27.7°C, minimum of 27.2°C and an average temperature of 27.5°C. The linear selection shows a temperature of maximum 27.5°C, minimum of 27°C and an average temperature of 27.2°C.

6 CONCLUSIONS

Analysis on the Mud block walled house for sustainable building design suggestion to the rural residential and sustainable development using CFD helped in arriving at the following observations and suggestions.

- The percentage of relative humidity is decreasing near the upper half of the mud block room as air is absorbing some heat from the ceiling.
- Effect of heated roof wall is negligible inside the lower half of the room because air is being introduced forcefully from the gate which cools down the air.
- Volume-weighted average temperature of air is increasing by 0.3°C

- Velocity of the air near the window is increasing to accommodate the incoming flow rate

It is suggested that the mud blocks are preferable building material, as they prevent maximum heat transfer into the walls and help to keep the house self cooling. As locally available materials are used for construction sustainable development can be achieved in the rural building sector.

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REFERENCES

[1]. Yunqinn FAN, T.Hayashi, K.Ito, "Coupled simulation of BES-CFD and performance assessment of energy recovery ventilation system for office model," *J.Cent.South Univ.(2012)19: 633-638*, DOI: 10.1007/s11771-012-1049-7

[2]. Zhiqiang (John) Zhai, James S.McNeill, "Roles of building simulation tools in sustainable building design", *Build Simul (2014) 7: 107-109*, DOI 10.1007/s12273-013-0169-9

[3]. M.J.Cook, t.Zitzmann, P.Pfrommer, "Dynamic thermal building analysis with CFD modelling radiation", *Journal of Building Performance Simulation (2008)* 1:2, 117-131, DOI:10.1080/19401490802250421

[4]. Ashfaque Ahmed Chowdhury, M.G.Rasul, M.K.Khan, "Analysis of Building systems performance through integrated computation fluid dynamics technique", *Proceedings of the 13th Asian Congress of Fluid Mechanics*, 17-21 December 2010, Dhaka, Bangladesh, 625

[5]. Zhiqiang Zhai, "Application of Computational Fluid Dynamics in building design: Aspects and Trends", *Indoor and built environment*, (2006) 15; 4:305-313, DOI:10.1177/1420326X06067336

[6]. Marco Bonvini, Alberto Leva, "Object- oriented sub-zonal modelling for efficient energy-related building simulation," *Mathematical and Computer modelling of Dynamical Systems: Methods, Tools and Applications in Engineering and Related Sciences*, 17:6, 543-559, DOI: 10.1080/13873954.2011.592143

[7]. C.A.J.Fletcher, I.F.Mayer, A.Eghlimi, K.H.A.Wee, "CFD as a building services engineering tool", *International Journal on Architectural Science*, Volume 2, Number 3, p.67-82, 2001

[8]. Ali A.F.Al-Hamadani, S.K.Shukla, alok K.Dwivedi, "CFD application in passive building designs", *Proceedings of the National Conference on Trends and Advances in Mechanical Engineering*, YMCA University of Science and Technology, Faridabad, Haryana, October 19-20, 2012, 114

[9]. Yun Kyu Yi, Ali M.Malkawi, "Integrating neural network models with computational fluid dynamics (CFD) for site-specific wind condition", *Build Simul (2011)*4: 245-254, DOI 10.1007/s12273-011-0042-7

[10]. Marcel Schweiker, Frederic Haldi, Masanori Shukuya, Darren Robinson, "Verification of stochastic models of window opening behaviour for residential buildings", *Journal of building performance simulation (2012),*5:1, 55-74, DOI: 10.1080/19401493.2011.567422

[11]. Eleni Primikiri, Michael kokkolaras, Panos Y.Papalambros, "Interpolation of energy performance data for building design decisions", *International Journal of Sustainable Energy (2006)* 25:2, 79-88, DOI:10.1080/14786450600631400

[12]. Paramasivam Ravikumar, D.Prakash, "Analysis of thermal comfort in an office room by varying the dimensions of the windows on adjacent walls using CFD: A case study based on numerical simulation", *Build Simul(2009)*2:187-196, DOI 10.1007/s12273-009-9317-7

[13]. Anat Geva, "Energy Simulation of Historic Buildings: St.Louis Catholic Church, Castroville, Texas", *APT Bulletin*, Vol.29, No.1 (1998), pp.36-41, URL:http://www.jstor.org/stable/1504546

[14]. Kirk B.P.Shanks, Steve N.G.Lo, Brain Norton, "Appropriate energy efficient building envelope technologies for social housing in the Irish climate", *J. Housing Built Environ* (2006) 21: 191-202, DOI 10.1007/s10901-006-9042-9

[15]. Yunqing Fan, Kazuhide Ito, "Optimization of Indoor environmental quality and ventilation load in office space by multilevel coupling of building energy simulation and computational fluid dynamics", *Build Simul* (2014) 7: 649-659, DOI 10.1007/s12273-014-0178-3

[16]. Claude-Alain Roulet, Flourentzos Flourentzou, Flavio Foradini, Philomena Bluyssen, Chrit Cox, Claire Aizlewood, "Multicriteria analysis of health, comfort and energy efficiency in buildings," *Building Research and Information* (2006) 34:5, 475-482, DOI: 10.1080/09613200600822402

[17]. Mingang Jin, Wangda Zuo, Qingyan Chen, "Simulating Natural Ventilation in and around buildings by Fast Fluid Dynamics, Numerical Heat Transfer, Part A: Applications," *An International Journal of Computation and Methodology* (2013) 64:4, 273-289, DOI: 10.1080/10407782.2013.784131