Evaluation of Thermal Performance of Modern Building Wall Constructions: Real Scale Experiment Under Arid Weather Condition

Zakariya Kaneesamkandi [1] * Abdulaziz Almujahid [2] *
1- Mechanical Engineering Department, King Saud University, Riyadh-11421, Saudi Arabia zkaneesamkandi@ksu.edu.sa
2- Mechanical Engineering Department, King Saud University, Riyadh-11421, Saudi Arabia zkaneesamkandi@ksu.edu.sa

Abstract
Thermal resistance of wall constructions plays a key role in determining the cooling load of buildings especially in regions with extreme ambient temperatures. With the construction industry having several options for wall material, selection of the best alternative is mainly based upon their thermal resistance. Experimental data presently available on wall resistances are based on steady state measurements which are not real indicators of their performance. Onsite real time thermal performance data under summer conditions of four commonly used wall constructions in Saudi Arabia have been collected using experimental study in a test room maintained under similar conditions for all the wall. The time lag, decrement factor and their relative thermal resistance values indicate that Insulated brick walls and Adobe walls are the most suited candidates in terms of thermal performance for decreasing the cooling load. This study will help construction engineers to select the appropriate building wall material and also to estimate the air conditioning system capacity.

Keywords:
Building walls, insulating bricks, wall thermal resistance, Energy efficient walls, decrement factor, Building envelope;

Article history: Received: May 18, 2020; Accepted: June 4, 2020

1. Introduction

Sizable part of building energy bill goes for air-conditioning interior spaces especially with the increasing average global temperatures due to global warming. Maintaining uniform and comfortable internal conditions in a building against the existing outside conditions depends on the ability of the building to regulate the heat transmission using its wall components. Hot deserts are among the most challenging regions in terms of energy consumption in buildings due to the intensive demand for cooling, as they experience extremely high air temperatures. One-third of the energy loss from a building occurs from the walls and another one-third is lost from the roof in the case of an un-insulated brick building, [1]. Hence performance study through experimental and simulation studies on walls were conducted by different researches. However, different types of building blocks having come into use with large variations in material properties which has made it difficult to maintain consistent parameters during performance simulation. Several experimental techniques have been developed to determine the thermal performance of the walls to help in proper choice of building wall components. Presently, building blocks with plain concrete as per ASTM C55 and C90 standards as well as blocks with insulation as per ASTM E2634 standards are in use. Also adobe blocks as per ASTM C62 standards are widely in use for single story buildings. Building walls under these categories are only tested in this study. This study does not include effect of plastering, wall paneling etc. Humidity pays an important role in thermal conditions of a building but it is not considered in this study.

Studies on wall thermal performance are classified under three categories, namely, numerical studies under steady state conditions, numerical studies under dynamic conditions and experimental studies on actual dynamic performance.

Theoretical studies on effect of building material on the energy balance of a building in an arid region is studied by [2] and the importance of construction according the local climatic conditions is stressed upon. [3] conducted a review of the experimental and numerical studies in energy conservation in buildings with the help of porous material. Computational fluid dynamics is used to study the steady state thermal performance of five different types of concrete blocks to study the effect of different configurations on the thermal transmittance by [4]. The effect of cavity filling and use of low emissivity coating on the thermal transmittance is studied with positive results. Similar studies are reported in several works by incorporating changes in the physical conditions of the wall. However, results of this method of wall performance analysis was grossly different when compared to real field performance. Conjugate heat transfer analysis using simulation of the heat transfer taking place between the solid concrete and fluid interfaces inside the air pockets within concrete blocks is done by [5]. Finite volume analysis with blocks of different configurations are done to study the effect of the air enclosure configurations and different void fractions by [6]. [7] made a steady state numerical model of clay bricks with cavities of different sizes and material and reported an increase in thermal resistance by about 20%. Similar numerical studies using finite element method is reported by [8].

[9] made a numerical simulation of a building wall to study the effect of thermal inertia on the wall temperature distribution. It is clear that thermal inertia of the wall played an important role in delaying the temperature changes occurring within the wall thereby increasing the comfort.

[10] conducted experimental studies on a specially built room with different material and measured the effect of moisture

content and insulation thermal mass on the thermal performance of the building. Specific measurement of indoor and outdoor temperature, relative humidity, barometric pressure, wind speed, wind direction, sky radiation and solar radiation are done. Effective thermal conductivity of hollow bricks with the different cavity fillings is experimented with a setup involving a thermal insulation box and a set of temperature and heat flux probes at the different points is done by [11]. Experimental results helped to compare the thermal conductivities of different arrangements.

U-Value meters are used by [12] and a method for measuring the heat loss is presented. U-value meter measures the heat transfer in the unit W/m2K and is used in several projects to upgrade the energy performance in temperate regions. U-value meters are used to check whether heat transmission coefficients (U-values) meet the requirements as stipulated in the Building Regulations. Building wall heat conduction problems are multi-dimensional and transient that need numerical calculation or computer simulations. Experimental conditions also vary due to different external and internal factors making testing difficult under identical conditions. Hence a common construction incorporating the different wall structures becomes important. Thermal hot box method is one method of determining the heat transfer performance of building wall with different components. However, inconsistencies in the R-values of the different sub components of the wall structure leads to inaccuracies according to [13].

Experimental methods that are used to evaluate the building block thermal performance includes thermal hot box method, heat flow meter method and the Infra-red method according to [14]. Comparison of the results with that of numerical results indicate higher accuracy for experimental ones. This is because factors like wind speed and humidity were not considered in numerical studies. It can be inferred from the above studies than on site measurements will be the most accurate method of determining or comparing the thermal behavior of building blocks. This study will help construction engineers to select the appropriate building wall material and to estimate the air conditioning system capacity.

For the purpose of onsite experimental investigations of thermal performance of four exterior building system modules, the four types of walls constituting the north facing wall of an air- conditioned test room with dimensions 600x730 cm2 and 220 cm height was tested as part of thermal insulation test room by [15]. The room is constructed on the roof of the Mechanical Engineering Department, King Saud University, in Riyadh city which has latitude of 248°N and longitude of 46.460°E. Two 1.5 TR air conditioning systems were installed in the rooms to provide uniform indoor air temperature. The results of the experimental study which is conducted on a representative hot day were used to compare the thermal performance of the building walls.

2. Heat transfer across building walls

Although different methods have been adopted by researchers to determine the thermal resistance of building walls experimentally, numerically or analytically, on site comparison of the actually constructed wall structure gives the most accurate results. Heat transfer across building walls is determined by the thermal resistance of the wall structure and the heat transfer coefficients (Fig.1). This includes the convection and radiation heat transfer coefficients. The heat flux through the wall is determined by the inside wall heat transfer coefficients, the outside wall heat transfer coefficients and the thermal conductivity of the wall itself. Housing codes have standards for the minimum allowable R-Value, or the resistance to heat transfer, which is how well the insulation works. The general arrangement of the experimental stand is shown in Fig. 1. The experimental set up consists of the necessary instrumentation for measuring the surface temperatures. A set of thermocouples are placed on internal and external surfaces at specific points of each wall. The four types of wall modules are tested under the ambient conditions prevailing in the month of September. The specifications of the thermocouple shown in Fig.1 made by Omega Inc., USA are:

Type K (CHROME-ALUMEL),

Maximum Temperature 175°C (350°F) continuous

Minimum Temperature is -60°C (-75°F) continuous Dimensions is 25 L x 19 W x 0.3 mm

The calculated uncertainty of the thermocouple from bias and precision uncertainty tests with a level of confidence of 95% is ±0.0153 °C.

Two thermocouples are used for each measurement and their average values are taken. Outdoor air, indoor air, inside wall and outside wall temperatures were measured. Thermocouples were used to measure outdoor air, indoor air, inside and outside wall surface temperatures by using two thermocouples each at two different levels and the average of their temperatures were taken. Two heat flux sensors were used on each wall to obtain the heat flux through the walls. data acquisition system OMB-DAQ-PDQ is capable of receiving 30 differential inputs or thermocouples. The data acquisition system is connected to a USB hub by data cable which in turn is connected to the computer for recording the measurements. Measurements were taken in September which represents hot climatic conditions. The average of the temperatures measured by the top and bottom thermocouples was taken.

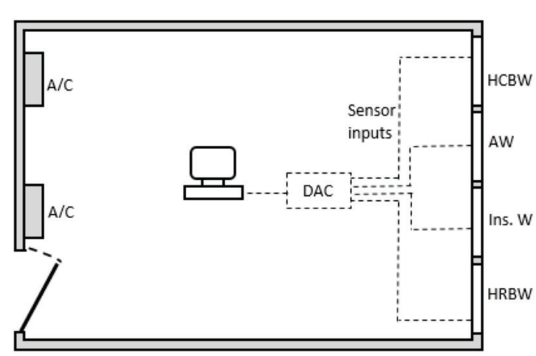

Fig.1 Scheme of the experiment

3. Structure and physical properties of the experimental walls

Four types of wall systems or modules are constructed as part of the north wall of the test room. The four modules are maintained under same indoor and outdoor conditions. Each building wall module has a surface area of 120x120 cm2. The structure of each module was different in material and design. Each module is isolated from effects of lateral heat flow using siporex blocks with a thickness of 20 cm on all sides. Thus heat flow is allowed only normal to the wall surface area. The four building system modules are shown in Fig. 2. The thermal performance of the four walls is analyzed under real indoor and outdoor climatic conditions. The time lag and decrement factor of the four wall types are determined and compared.

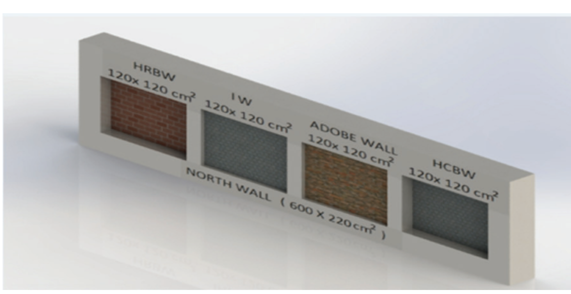

Fig.2 The four building wall systems separated by siporex layer

The structural, physical and thermal properties of the four walls; namely, Hollow Concrete Block Wall (HCBW), Adobe wall (AW), Insulated Wall (Ins.Wall), and Hollow Red Block Wall (HRBW) which are the subject of the present work are described in Fig.3 and Table 1.

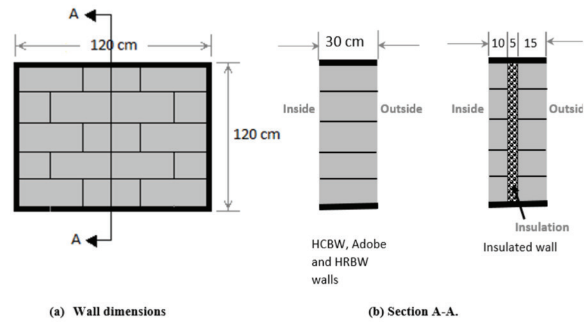

Fig.3: Schematic of the wall type constructions

The section of the Hollow Concrete Block Wall (HCBW) consists of single layer made from heavy weight concrete blocks with 30 cm thickness. The section of the Adobe wall consists of one layer made from solid adobe (clay) bricks with 30 cm thickness. The section of the Insulated Wall (Ins.Wall) is shown in Fig.3b, which consists of three layers. The inside layer is a 10 cm thickness hollow concrete blocks and the outside layer is 15 cm thick hollow concrete block with an insulation layer in between.

The section of the Hollow Red Block Wall (HCBW) consists of one layer made from Hollow Red Block with thickness 20 cm.

Type of wall		Width, Cm	Density, kg/m^3	Specific heat, $J/kg.k$	Thermal conductivity, $W/m.K$
HCBW [9]		30	1105	840	1.05
AW [10]		30	1400	1000	0.58
IW [11][12]	Inner Concrete layer	10	1618	480	0.81
	Insulation	5	26	1215	0.032
	Outer Concrete layer	15	1618	480	0.81
HRBW [13]		30	1450	837	0.55

Table 1. Thermal properties of the wall components

4. Time lag and decrement factor

Time lag and decrement factors are very important thermal performance indicators that reflect the heat conducting and storage capacities of building wall material.

Higher storage capacities will increase the time lag as per the studies by [16]. The thicker and more resistive the material, the longer it will take for heat waves to pass through. Time lag (Φ) is the difference in time corresponding to maximum temperature points at the outside ($t_{To\ max}$) and inside ($t_{Ti\ max}$) when subjected to periodic conditions of heat flow (IS 3792-1978) as given in Eq.1. Decrement factor (f) is defined as the ratio of the maximum inside and outside surface temperature amplitudes as given in Eq.2. Lower decrement factor means the heat transfer across the material is lesser. For example, a material with a decrement value of 0.5 which experiences a 200 diurnal variation in external surface temperature would experience only a 100 variation in internal surface temperature.

$$\Phi = t_{T_o^{max}} - t_{T_i^{max}} \quad (1)$$

The first term in the above equation represents the time of maximum value of the outside temperature and the second term represents the time of maximum value of the inside temperature.

$$f = \frac{T_i^{max} - T_i^{min}}{T_o^{max} - T_o^{min}} \quad (2)$$

The numerator in the above expression represents the difference between the maximum (T_i^{max}) and minimum temperatures (T_i^{min}) of the inside wall and the denominator represents the difference between the maximum (T_o^{max}) and minimum (T_o^{min}) temperatures of the outside wall.

Results and discussion

The plotted data is from measurement of the following items:

- Inside surface temperatures of the four types of walls (2 set of readings)
- Outside surface temperatures of four types of walls (2 set of readings)
- Ambient temperature (1 set of reading)
- Room temperature (1 set of reading)

The difference in readings in the first and second case was less than 1%. The plot is made by fitting the data to a 6th degree polynomial with a regression coefficient R2>0.992 for all the cases.

The curve showing the instantaneous indoor and outdoor air temperatures and surface temperatures are given in Fig.4a to Fig.4d for the four types of walls. The indoor air temperature ranges between 23 and 26°C. The outdoor air temperature ranges between 19 and 48°C. The indoor air temperature must ideally be maintained at 24 degrees but the delay in response of the air conditioner thermocouple produced a temperature range of 3 degrees. The outdoor air temperature followed the typical pattern and disturbances were minimal in this measurement.

The curve showing the instantaneous indoor and outdoor air temperatures and surface temperatures are given in Fig.4a to Fig.4d for the four types of walls. The indoor air temperature ranges between 23 and 26°C. The outdoor air temperature ranges between 19 and 48°C. The indoor

air temperature must ideally be maintained at 24 degrees but the delay in response of the air conditioner thermocouple produced a temperature range of 3 degrees. The outdoor air temperature followed the typical pattern and disturbances were minimal in this measurement.

Table 2 gives the results for the four types of walls considered in this study. It can be seen that as the thermal transmittance is reduced the decrement factor is also reduced. Maximum heat flux ix obtained from the data recorded by the heat flux sensors. Since time lag is calculated based on the room temperature and ambient temperature, it has a value of 2 hours and 12 minutes. The decrement factor values also agree with the difference in temperature between the wall outside and inside temperatures. Lower decrement factor means that the rise in the inside surface temperature is less while the simultaneous outside surface temperature rise is higher. These mainly depend on the specific heat capacity and thermal diffusivity of the building materials and not on the surface heat transfer coefficient.

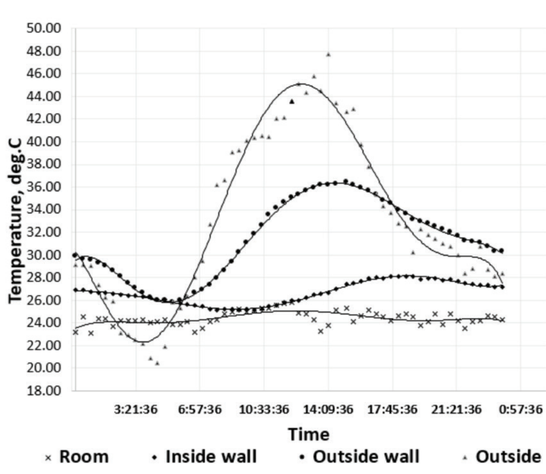

Fig.4a Temperatures distribution for HCBW for 24 hours

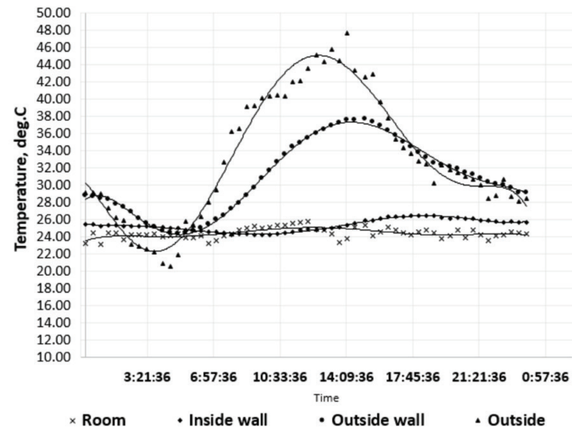

Fig.4b Temperatures distribution for ADOBE wall for 24 hours

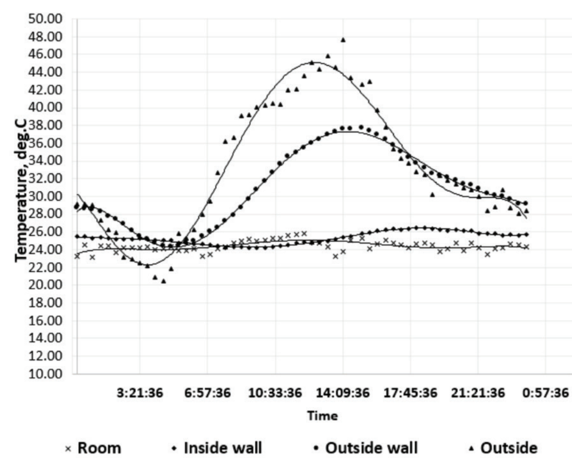

Fig.4cTemperatures distribution for HRBW wall for 24 hours

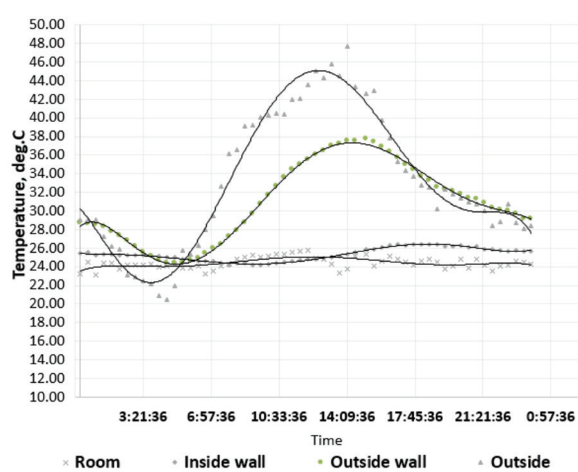

Fig.4d Temperatures distribution for INSULATED wall for 24 hours

Mean inside air temperature was about 24 o C whereas the mean outside surface temperature was about 38 o C in the hot day. Fig.5 shows the temperature difference between the outside and inside surface of each type of wall.

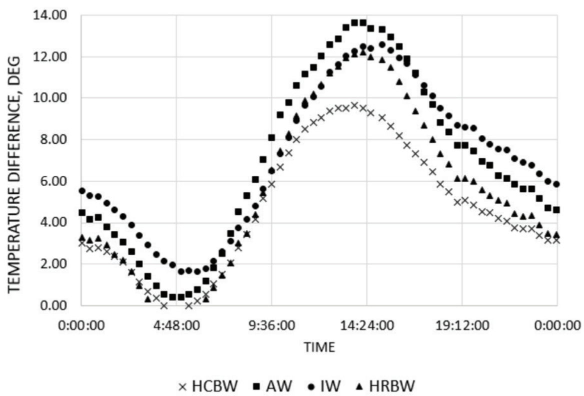

Fig.5 Difference between the outside and inside surface temperatures

Wall Type	$\overline{T}_{si}$, °C	A_{is}, °C	Max $(T_{so} - T_{si})$, °C	Max q_{max} W/m^2	Max $(T_{si} - T_i)$ °C	Decrement factor
HCBW	26.6	1.8	9.5	49.9	4.1	0.0847
HRBW	24.37	1.15	12	34.3	2.5	0.0309
Adobe Wall	25.5	0.45	13.5	26.1	2	0.0257
Insulated Wall	24.5	0.4	12.5	6.6	1	0.0631

Table 2. Results of the temperature measurements

The most important indicators of the thermal performance of exterior building walls are:Wall inside surface temperature; this has to be very close to the inside air temperature for better thermal comfort.

• Amplitude of inside surface temperature; the lower its value is an indication of lower fluctuation of inside surface temperature.

• The heat flux through the wall; of course the lower its value the better is the thermal performance of the wall. This means lower electric bill.

Results presented in Fig. 4a to Fig.4d and Fig.5 and Table 2 reveals interesting points. Table 2 summarizes the following parameters: Average inside surface temperature,T_{si} . This is calculated by taking the average of all the temperature readings over the complete working cycle. Amplitude of inside surface temperature, A_{is}, Maximum heat transfer flux, q_{max}, and maximum (T_{so}-T_{si}). The most important two parameters of the thermal performance of exterior walls are the inside surface temperature and the heat flux through the wall. Results presented in Table 2 shows clearly the superior performance of the insulated wall as compared to the rest of the walls. It's inside surface temperature is very close to that of indoor temperature and its amplitude is only about 0.4 o C. Most interesting is its maximum heat flux which is only about 13% of that for the concrete wall, 19% of that for red block, and 25% of that for the adobe wall. Comparing the other three walls, the Adobe wall has a better performance with regard to time lag and decrement factor.

6. Conclusions

The experimental comparative study of thermal performance of four types of wall construction material used locally in Saudi Arabia was evaluated experimentally by building a test room of real size under real working conditions. Temperature measurements were recorded for a representative hot weather day. Interpretation of the results indicated that the insulated wall shows superior thermal performance, with regard to thermal comfort and heat flux through the wall. Insulated walls demonstrated better performance in terms of wall inside surface temperature, Amplitude of inside surface temperature and heat flux. Comparing the other three walls, the Adobe wall has a better performance with regard to time lag and decrement factor. The adobe wall gives a maximum value of time lag followed by the insulated wall. The remaining two walls showed poor performance, where both have higher inside surface temperature and amplitude together with high heat flux. The results obtained are useful for designing appropriate building envelope configurations for buildings under similar conditions. It is also useful for air condition engineers to determine the het lod in buildings with above types of walls.

Acknowledgement

The authors would like to acknowledge with thanks the support and encouragement given by the Deanship of Research, King Saud University for successfully completing this experimental study.

Nomenclature

IW	Insulated wall
AW	Adobe wall
Φ	Time lag
$t_{T_o^{max}}$	Time taken to reach maximum temperature of outside air, hrs
$t_{T_i^{max}}$	Time taken to reach maximum temperature of inside air, hrs
f	Decrement factor
T_i^{min}	Minimum inside temperature, ^oC
T_i^{max}	Maximum inside temperature, ^oC
T_o^{max}	Maximum outside temperature, ^oC
T_o^{min}	Minimum outside temperature, ^oC
$\bar{T}_{si}$	Average inside surface temperature, ^oC
A_{is}	Amplitude of inside surface temperature, ^oC
T_{so}	Outside surface temperature, ^oC
T_{si}	Inside surface temperature, ^oC
q_{max}	Maximum heat flux, W/m^2
T_i	Inside temperature, ^oC

References

[1] Wheeler, A., 2012. Energy and Architecture Australia. http://www.dab.uts.edu.au/ebrf/research/comparative analysis of thermal performance.

[2] Soufiane Merabti1, Karima Grioui1, Younes Menni, Ali J. Chamkha, Enzo Lorenzini, Nasreddine Sakhri, Houari Ameur, 2019. Study of Some Parameters Influence on a Saharian Building Balance Sheet, Revue des Composites et des Materiaux Avances, Vol 28, No 2, pp-83-88.

[3] Saman Rashidi, Javad Abolfazli Esfahani, Nader Karimi, 2018. Porous materials in building energy technologies—A review of the applications, modelling and experiments, Renewable and Sustainable Energy Reviews, Vol 81, pp 229-247.

[4] Marcelo Adriano Fogiatto, 2019. Gerson Henrique dos Santos and João Victor Reia Catelan. Two-Dimensional Steady-State Evaluation of the Thermal Transmittance Reduction in Hollow Blocks, Energies, Vol.12, p.449.

[5] Antar, M.A. and Baig, H., 2009. Conjugate conduction-natural convection heat transfer in a hollow building block. Appl. Thermal Engineering, Vo.29, pp, 3716-3720.

[6] Sun, J.P., Fang, L., 2009. Numerical simulation of concrete hollow bricks by the finite volume method. Int. Journal of Heat Mass Transfer, Vol.52, pp. 5598-5607.

[7] Ammar Bouchair, 2008. Steady state theoretical model of fired clay hollow bricks for enhanced external wall thermal insulation, Building Environment., Vol.43, pp. 1603-1618.

[8] Li, L.P., Wu, Z.G., Li, Z.Y., He, Y.L. and W.Q., 2008. Numerical thermal optimization of the configuration of multi-holed clay bricks used for constructing building walls by the finite volume method. Int. J. Heat Mass Transfer, Vol.51, pp. 3669-3682.

[9] Lahcene Bellahcene, Ali Cheknane, Bekkouche, SMA. and Djemal Sahel, 2017. The effect of the thermal inertia on the thermal transfer in building wall. E3S Web of Conferences 22, 00013 (2017) DOI: 10.1051/e3sconf/20172200013.

[10] Coureville, G.E., Childs, K.W., Walukas, D.J. and P.W.Childs, 2010. Thermal performance measurement of insulated roof systems, Building systems division, U.S. Department of Energy.

[11] Zbyšek Pavlík, Miloš Jerman and Anton Trník, 2014. Journal of building physics Vol.37, No.4, pp. 436-448.

[12] Lars Schiøtt Sørensen, 2013. Heat Transmission Coefficient Measurements in Buildings Utilizing a Heat Loss Measuring Device, Sustainability, Vol. 5, pp. 3601-3614.

[13] Asdrubali, F. and Baldinelli, G., 2011. Thermal transmittance measurements with the hot box method: Calibration experimental procedures, and uncertainty analyses of three different approaches, Energy and Buildings, Vol.43, pp.1618-1626.

[14] Caruana, C., Yousif, C., Bacher, Peder, Buhagiar, S. and Grima, C, 2017. Determination of thermal characteristics of standard and improved hollow concrete blocks using different measurement techniques, Journal of building engineering, Vol.13, pp.336-346.

[15] Almujahid, A. and Kaneesamkandi, Z., 2013. Construction of a test room for evaluating thermal performance of building wall systems under real conditions, International Journal of Innovative Research in Science, Engineering and Technology, Vol.2, pp.2000-2007.

[16] Asan, H., 1998. Effects of wall's insulation thickness and position on time lag and decrement factor, Energy and Buildings, Vol.28, pp.299-305.