Energy and Buildings 84 (2014) 169–181

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

External load-bearing walls configuration of residential buildings in Iraq and their thermal performance and dynamic thermal behaviour

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ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form 4 May 2014
Accepted 26 July 2014
Available online 4 August 2014

Keywords:
External wall
Walls thermal performance
Dynamic thermal properties
Walls thermal insulation

ABSTRACT

Improving thermal performance of external load-bearing walls in residential buildings could be the most effective way in reducing energy consumption for air-conditioning purpose in housing sector. The aim of this study is to characterize the already existing external load-bearing walls in the residential buildings, in Iraq, in terms of the thermo-physical properties of the used materials. In addition to that, the assemblies of these materials, i.e. wall configurations have been evaluated regarding the steady-state thermal performance and dynamic thermal admittance parameters. Different scenarios were suggested in order to improve the thermal performance of the existing walls. The effect of the binding material (cement mortar) on the global thermal performance of the wall fabrics has also been investigated by utilizing image analysis to calculate the percentage of this material from whole wall. The results showed that binding material has no significant effect on the thermal performance for the studied walls. Gypsum coating layer can be removed as it has marginal effect on the evaluated properties. It was found that involving two air-cavities (internally and externally) has much effect on the walls thermal performance than other approaches.

1. Introduction

Iraq is located in a hot and almost dry climate conditions region during summer, where the outer temperature, sometimes, exceeds 48 °C, while it drops below 10 °C only few days during winter [1]. Iraqi residential sector has about 5 million houses and this number is continuously increasing due to the fast population increase. These houses have mainly constructed using load-bearing walls technique with normally two floors. The external walls are mainly responsible for the transferred heat from/to the houses envelops as they represent more than 50% of the exposure surfaces (walls, roofs, and grounds). The housing sector globally consumes more than 40% of the total energy consumption [2], which contributes for about one-third of the total greenhouse gases emission. This sector, in Iraq, is estimated to consume more than 60% of the total consumed electricity mostly for air-conditioning purpose. The electricity demand has been continuously increasing (by about 5% annually) due to the improvement in living standards and population increase which obviously need more energy especially for air-conditioning during the summer season. This exacerbated by the large increase in temperature caused by global warming phenomenon coupled with using poorly insulated walling system as the single-skin system is still dominant.

The draft of Iraqi code of Buildings thermal insulation [3] has suggested different configurations for load-bearing walls to improve the thermal insulation; however, materials such as polystyrene and mineral wool suggested to be included as internal layers. These materials seem to be expensive and unaffordable for all the people in addition to the traditional mentality that does not accept change/modify the conventional design of the existent walling systems. Therefore, simple, applicable, and acceptable walling systems with better thermal performance/insulation should be designed and examined from both economic and environmental view, if the long-term benefit is taken into account. It was previously concluded that the thermal performance of a wall fabric mainly depends on the thermal properties of the used materials in constructing this wall [4] in addition to its thickness. It is

Abbreviations: System (a), wall configuration with stone as a load-bearing leaf; System (b), wall configuration with clay brick as a load-bearing leaf; System (c), wall configuration with concrete block as a load-bearing leaf; S_{x-1}, internal environmental temperature for system x where x is a, b, or c; S_{x-2}, internal surface heat flux for system x where x is a, b, or c; S_{x-3}, external surface heat flux for system x where x is a, b, or c; ρ, density (kg/m^3); λ, thermal conductivity (W/m^2 K); C_p, specific heat capacity; α, thermal effusivity (m^2/s); β, thermal diffusivity (j/s$^{0.5}$ m^2 K); *R-value*, thermal resistance (m^2/KW); *U-value*, thermal transmittance W/(m^2 K); *Y-value*, thermal admittance W/(m^2 K); Ø, thermal admittance time lag (hr); *f*, thermal decrement factor; *Ω*, thermal decrement factor time lag (hr); *F*, surface factor; *Ψ*, surface factor time lag.

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http://dx.doi.org/10.1016/j.enbuild.2014.07.064
0378-7788/

Fig. 1. External wall fabric using natural stone, clay brick, and solid concrete block.

known that air thermal conductivity is much lower than that for the construction materials such as concrete, stone, gypsum, and clay brick; therefore, the dominant walling systems could be improved by involving air-cavity somewhere into the constructed external walling systems.

A few researchers [4–6] have studied the thermal performance of different fabric walls (multi-layered structural element); however, they mostly studied the steady-state-transmittance, i.e. *U-value*. Based on the best knowledge of the author, just one study [5] assessed the stabilized earth walls using the cyclic-response admittance method, which is not widely applied. It was stated that the calculated *R-value* does not precisely reflect the wall thermal resistance as it does not reflect the change in behaviour of the entire system where it does not take into account the benefit of the thermal mass of the wall layers on the wall's behaviour [7]. Regardless the assessing parameters/approaches, envelop building walls are usually evaluated/modified to reduce heating/cooling energy consumption [8]. However, as the temperature is almost continuously changing over the day/night time (at least in Iraq), studying the dynamic thermal properties of admittance is important to be carried out. This could perhaps simulate the real situation better than steady-state thermal transmittance. The aim of this investigation is to characterize the existing load-bearing external walls fabric, for residential buildings in Iraq, in terms of their thermo-physical properties and dynamic thermal behaviour. Also, different simple and applicable scenarios were suggested and evaluated to improve the residential building envelops thermal performance.

2. Characterization of existing and modified external load-bearing walls

There are mainly three external walls configurations (load - bearing walls) in Iraqi residential buildings that depend on the availability of the main construction materials. These walls configurations can be briefly described as follow:

- System (a): It is built using uncut natural stone (limestone) or random rubble that having different shapes and sizes that bound together using mainly cement mortar (1:3 or 1:4 cement:sand) and to less extent gypsum mortar as seen in Fig. 1(1-A). The thickness of this wall fabric is usually 40 cm and to less extent is 30 cm. There are many finishing types for walls outer face including natural stone, ceramic, and marble, but, for normal residential buildings, using about 1 cm thickness of cement mortar in addition to a thin layer of either white or coloured cement is dominant. Regarding the internal face, the wall is coated with a layer of 2–3 cm of normal gypsum (rendering coat) class B based on BS EN 13279-2:2004 [9], which aims to level the wall's face before coating it with a layer of 2 mm of Paris gypsum as a finishing coating layer [10], (see Fig. 2). This system is used in the west of Iraq and needs skilled workers.
- System (b): It is built using clay brick with standard dimensions of 240 × 115 × 75 mm, as shown in Fig. 1(2-A). The thickness of this wall is usually 240 mm and rarely 120 or 360 mm are used. As in system (a), the binding material is mainly cement mortar (1:3 or 1:4 cement:sand) and rarely gypsum mortar is used. The finishing materials are almost same as that used in system (a), as seen in Fig. 2. This system is used in the middle and south of Iraq which is described as expensive and more popular over the other walling systems.
- System (c): It is built using solid concrete blocks with dimensions of 400 × 200 × 200 mm and cement mortar is normally used as a binding material and the width is 200 mm, as shown in Fig. 1(3-A). As same as for system (a), cement mortar and gypsum were used in same manner (see Fig. 2). This system is mainly used in the north and middle of Iraq, which is regarded the fastest and cheapest one over the other systems.

In order to calculate the percentage of binding materials (cement mortar) from the whole wall area, which is important in determining the thermal properties of the wall, image analysis technique has been utilized. ImageJ software tool vl.44p was

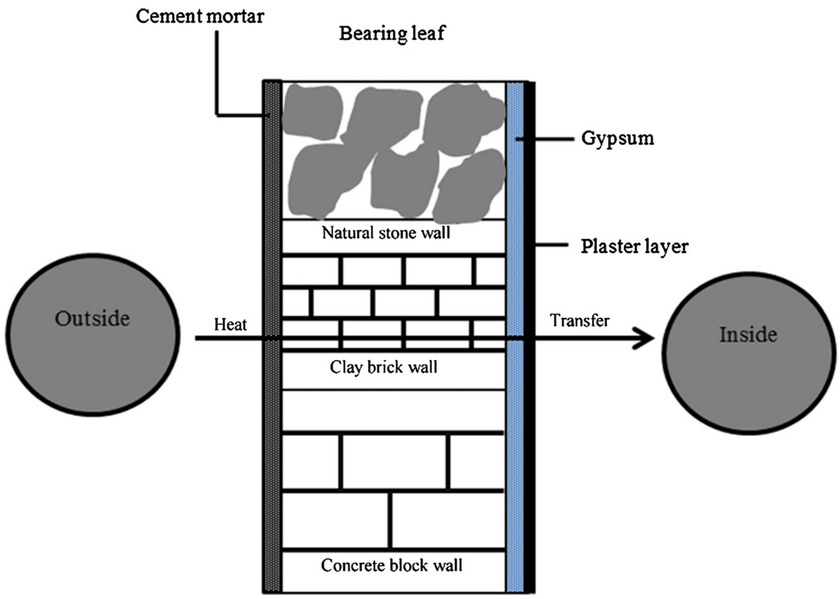

Fig. 2. External walling configurations in Iraq.

Table 1
Mortar bonding material for each configuration.

Configuration	Width (cm)	Mortar type	Mortar percentage from the whole wall (%)
System (a)	40	Cement	15.7
System (b)	24	Cement	18.5
System (c)	20	Cement	3.5

used to analyse the captured images (using 14.1 mega pixels camera) for the three walling systems as shown in Fig. 1. In order to eliminate any potential edge effects, the captured images were cropped into a 4000 × 3000 pixel rectangular and then 'clear outside' edit feature was applied. The brightness/contrast was manually adjusted to bracket the upper/lower limits of the greyscale histogram before applying a 1-px median filter followed by one pass of the despeckle noise filter. Thereafter, the brightness/contrast was again re-adjusted to bracket the upper/lower limits of the new histogram followed by applying the 'default' thresholding algorithm as seen in Fig. 1(1-3B). The analysed particles feature then was used and the area of cement mortar binder (2D) was found as a percentage of the whole wall area, as presented in Table 1.

In order to enhance the external walls thermal performance without affecting the bearing-leafs (structural part), simple, applicable, socially acceptable, and costly effective scenarios (configurations) have been suggested. Indeed there may be more efficient configurations could be suggested in this regards, but the social attitude and familiarity with the traditional configuration could be the reasons to think about using almost same configuration in terms of appearance with simple changes. The suggested scenarios are explained below.

2.1. Internally changed scenarios

2.1.1. Changing the plaster layer by sheathing timber sheets with air-cavity

This configuration consists of same fabrics as in the existing systems; the only difference is that the internal face (leaf) consists of gypsum+ air-cavity of 50 mm thickness and a timber sheathing of 5 mm in addition to a layers of paint (as schematically presented in Fig. 3(A)). The paint layer is assumed to have negligible effect in this study. This configuration was suggested because of sheathing timber has low thermal conductivity as shown in Table 1 and easy to be installed. The effect of the fixing frame has been neglected for all systems to simplify the calculations as previously mentioned.

2.1.2. Same previous system without gypsum

Same configuration has been examined but without gypsum and plastering. In order to find out the effect of gypsum layer on the studied properties, it was removed and the internal face was covered by only a sheathing timber sheet of 5 mm and air-cavity layer of 5 cm was left between them as seen in Fig. 3(B).

2.2. Externally changed scenarios

These configurations differ than the existing configurations by removing the external cement mortar layer and instead of that a layer of ferrocement was used (see Fig. 4). An air-cavity of 5 cm space between the load-bearing leaf and the fixed ferrocement layer was involved. Ferrocement is described as cement-based material that composed using cement mortar reinforced by malty layers wire meshes (chicken wires). This configuration was suggested to simulate the traditional cement coating as it is popular and common finishing. It can be used for external finishing works with painting it using different types of paints that are assumed to have negligible effects. This external-modification was applied on the already-existing systems in addition to different internally changed configurations as explained below.

2.2.1. Existing configuration with air-cavity and Ferrocement for external cladding

In this configuration, the internal face was kept as same as in the existing wall systems where the difference was just in the external finishing as shown in Fig. 4.

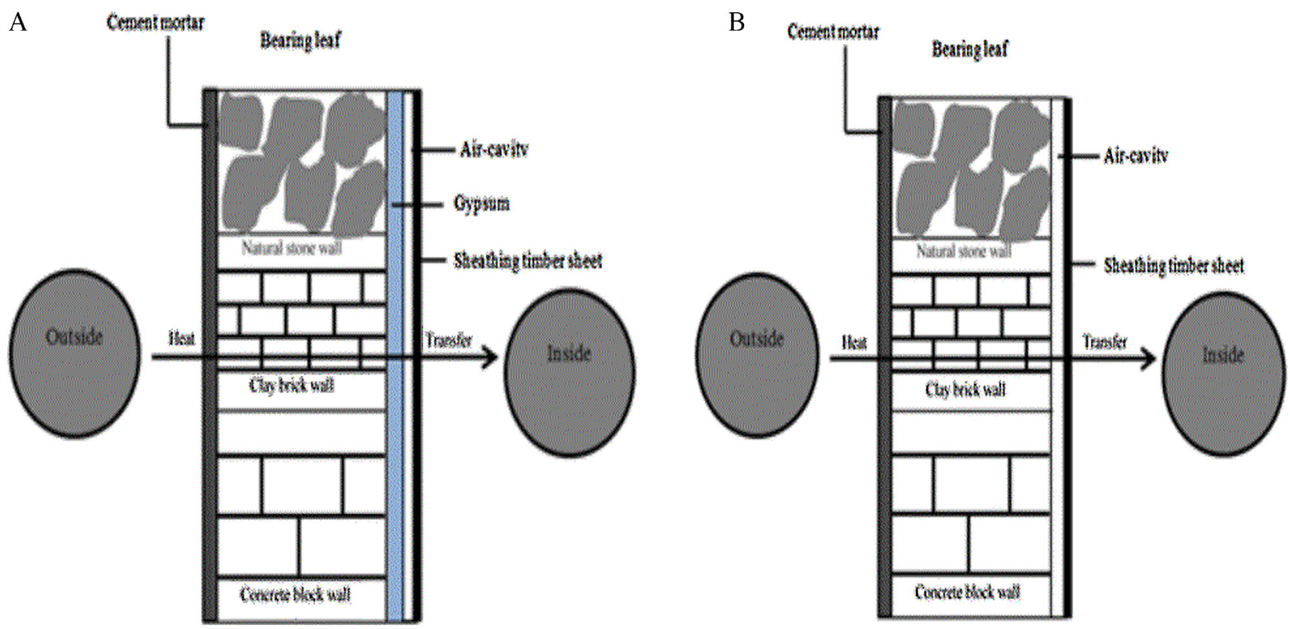

Fig. 3. Scenarios 5.1.1 and 5.1.2.

2.3. Alternative wall configurations regarding internally and externally scenarios

2.3.1. Ferrocement with air-cavity externally with timber sheet internally

The external face consists of ferrocement and air-cavity (as in Section 2.1.1) whereas the plastering layer at the internal face has been replaced by a sheathing timber sheet with an air-cavity space of 5 cm between the timber sheet and gypsum layer as illustrated in Fig. 5.

2.3.2. Ferrocement with air-cavity externally without gypsum and plaster internally

In this configuration, the gypsum layer was removed and the other fabric layers were kept as same as the previous configuration. The external face is similar to that explained in Section 2.2, as illustrated in Fig. 6.

3. Materials' thermo-physical properties

In order to simplify the calculation and also to simulate the actual situation in Iraq (mostly hot and dry weather), all the properties were tested/calculated in the dry state; therefore, the effect of moisture on these properties was not taken into account. The density of the tested materials was measured based on BS 1881-114 [11]. Thermal conductivity λ was experimentally measured using a downward vertical heat flow computer-based P.A. Hilton B480 uni-axial heat flow meter, which compiles with ISO 8301:2010 [12]. The tested specimens for concrete were 300 ×300 ×50 mm slab whereas specimens of 240 × 115 × 70 mm were used for natural stone and clay brick λ calculation. The average of λ-*value* of

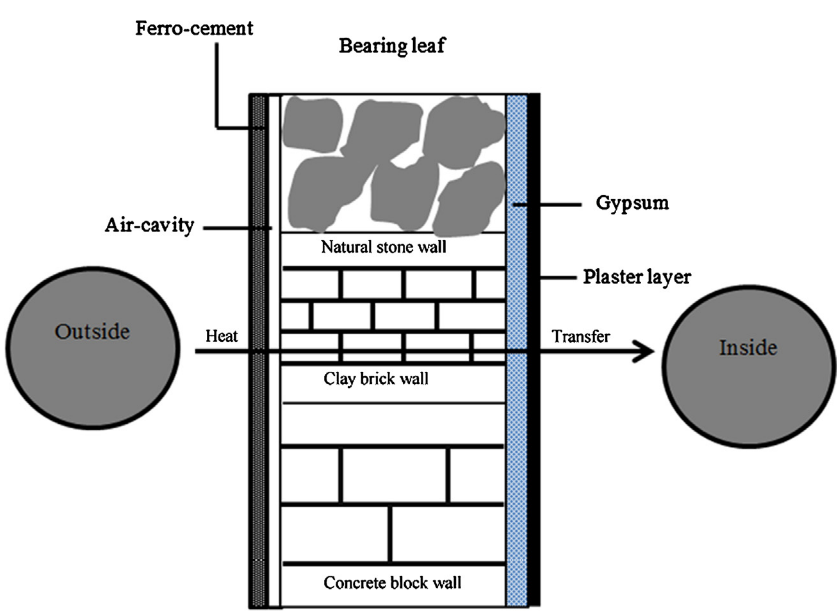

Fig. 4. Scenario 5.2.1.

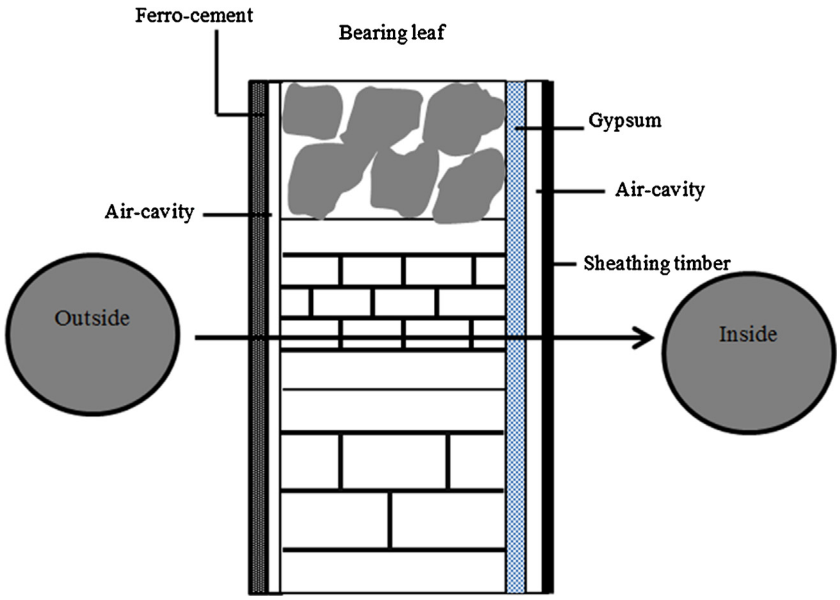

Fig. 5. Scenario 5.3.1.

two specimens was recorded. All the tested samples were oven-dried at 50 ± 5 °C for 3 days before cooling to ambient laboratory temperature in a desiccator prior to the test. The calculation of the λ-*value* was computerized using Eq. 1, which is explained in depth elsewhere [13]:

$$\lambda = \frac{(d * \left[\left(k1 + (k2 * \bar{T}) + ((k3 + (k4 * \bar{T}))) * \mathrm{HFM}\right) + ((k5 + (k6 * \bar{T})) * \mathrm{HFM})\right]}{dt}$$

where λ is the thermal conductivity (W/m K), d the thickness of specimen (m), dT the temperature difference between the cold and hot plate (°C), $\bar{T}$ the average of hot and cold plate temperature (°C), HFM the heat flow meter reading (mV), and $k(n)$ the calibration constant with silicone rubber mate.

The specific heat capacity C_p was determined for each ingredient/material using a Differential Scanning Calorimeter and the ramp rate method, where the mean of five readings across the range between −15 °C and 60 °C was taken. For the inhomogeneous materials, i.e. brick, concrete, cement mortar, and gypsum, it was proportionally calculated as the summation of the heat capacities of all ingredients [14]. The air content, within the construction materials, was assumed to have negligible effect on the specific heat capacity as it has ∼1.205 kg/m^3 density at ambient temperature and it assumed to have zero mass for gravimetrical material bulk density calculation purposes [15]. The specific heat capacity C_p was calculated based on Eq. 2 [16].

$$C_p = \frac{1}{W_{\text{total}}}\left[W_{\text{HCP}}C_{\text{HCP}} + W_{\text{CA}}C_{\text{CA}} + W_{\text{FA}}C_{\text{FA}} + W_{\text{ADD}}C_{\text{ADD}}\right] \quad (2)$$

where W is the mass of each ingredient in kg and C_p is the specific heat capacity of each ingredient in J/kg K, whereas thermal diffusivity (α) and effusivity (β) were calculated using Eqs. 3 and

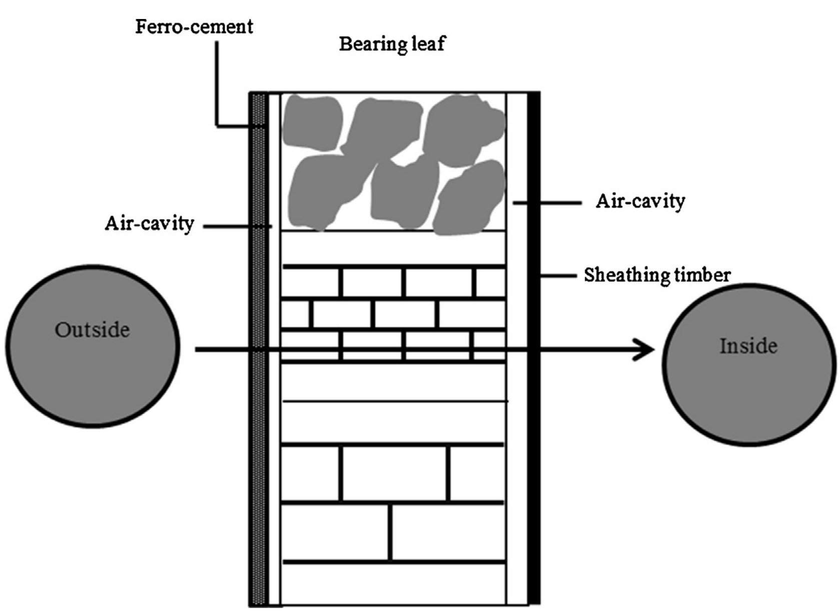

Fig. 6. Scenario 5.3.2.

Table 2
Thermo-physical properties of used materials.

Material	ρ (kg/m^3)	λ (W/m^2 K)	C_p (J/kg K)	$\alpha \times 10^{-7}$ (m^2/s)	β (J/s$^{0.5}$ m^2 K)	Thickness (cm)
Natural stone (limestone)	2019	1.12	906	6.12	1431.3	40
Clay brick	1570	0.81	930	5.55	1087.5	24
Solid concrete block	2084	1.24	840	7.08	1473.3	20
Cement mortar	2105	1.45	850	8.10	1610.7	1
Gypsum	1416	0.57	1006	4.00	901.1	3
Plaster	1068	0.32	1115	2.69	617.3	0.2
Air	1.205	0.025	1005	0.016	5.50	5
White sheathing timber	500	0.13	1600	1.62	322.5	0.5
Ferrocement layer	2500	1.53	720	7.94	1604.4	2

4 [14], respectively [16]. Materials thermo-physical properties are presented in Table 2.

$$\alpha = \frac{\lambda}{\rho_d C_p} \tag{3}$$

$$\beta = \sqrt{\lambda\, \rho_d c_p} \tag{4}$$

4. Walls thermal performance calculations

4.1. Thermal resistance and transmittance

It was previously highlighted that wall thermal performance depends on the used building materials properties, ambient weather conditions, and wall thickness [4]. Although the consumed energy by the households affects the walls thermal performance, it is out of the aim of this study as it focuses on the external-walls thermal performance brought about by building materials properties and walls configuration.

The thermal resistance (*R-value*) is commonly used in evaluating the thermal performance of buildings, materials, or assembly of materials like wall fabric [17], which is basically the opposite of heat transfer [18]. It was reported that three types of thermal resistance need to be determined in order to determine the *R-value* of a wall fabric that are materials, surface, and airspace (if there is any) resistance [18]. *R-value* was calculated as shown in Eq. 5 [19,20]:

$$R = \frac{d}{\lambda} \tag{5}$$

where R is the thermal resistance and it is measured by (m^2 K)/W, d is the material thickness (m) and λ is thermal conductivity. It was well-agreed that *R-value* of a wall fabric is equal to the summation of the *R-values* of each layer, i.e. for the studied existing configuration [19]:

$$R_{\text{total}} = R_{\text{si}} + R_{\text{cement mortar}} + R_{\text{bearing wall (brick, stone, block)}} + R_{\text{gypsum}} + R_{\text{plaster}} + R_{\text{so}} \tag{6}$$

It was highlighted that surface thermal resistance, whether it is indoor (R_{si}) or outdoor (R_{so}), depends on the conduction, convection, and radiation at the specified surface. CIBSE Guide A [21] provides tabulated standard values for the conventional materials that are typically 0.13 m^2 K/W for R_{si} and 0.04 m^2 K/W for R_{so}.

Thermal transmittance *U-value* is defined as a steady-state measure of the overall rate of heat transfer by all mechanisms through a building element [20]. The measured *U-value* should be different than other quoted *U-value* as it does not consider the thermal bridging effect in addition to its sensitivity to the values of used surface thermal resistance. As the wall fabrics are not homogeneous, it consists of brick, stone, or concrete block in addition to cement mortar as a binding, the effect of the later on the walls fabric thermal resistance has been proportionally calculated based on its percentage of the wall total area, as demonstrated in Table 1. The bridging effects such as that come from used frames in fixing the exterior (ferrocement) and interior (timber sheets) cladding were neglected. *U-value* is calculated as the inverse of the total thermal resistance as in Eq. 7 [18]:

$$U = \frac{1}{R_{\text{total}}} \tag{7}$$

4.2. Dynamic thermal admittance properties and its related parameters

It was highlighted that ‘dynamic’ analysis should be applied when the climate temperature is considerably varied, i.e. daytime and seasonal temperature variations are significant [22], which the case in Iraq is. In order to consider the heat transfer through studied wall fabrics configurations under dynamic conditions (thermal dynamic storage), non-steady state factors are determined, i.e. thermal admittance, Y, and related parameters as specified in EN ISO 13786:2007 [23]. These have been calculated using ‘Dynamic Thermal Properties Calculator’ software tool [24], which was previously used by other researchers [14] in studying reamed earth walls and later was used by the author and others in studying 100 mm walls made from different rubberized concretes [15]. The calculations assumed a vertical wall with one-dimension horizontal heat flow and conventional surface boundary layer heat transfer coefficients of (i) inside surface coefficient R_{si} = 0.13 m^2 K/W and (ii) outside surface coefficient R_{so} = 0.04 m^2 K/W, both are taken from ISO 6946: 2007 [25], as previously mentioned. For direct comparison among different materials/wall configuration, the sol-air mean temperature variation was set at ±1 K. The thermal admittance parameters are deeply explained elsewhere [18,19,24].

Thermal admittance has been calculated based on assuming the internal environmental temperature is varying and the external environmental temperature is constant. It was calculated using a set of matrices including density, heat capacity, thermal conductivity, and thickness (see CIBCE Guide A [21] for more explanation). Admittance for one-dimension heat flow can be calculated using the thermal diffusion equation (Eq. 8):

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho C_p}{\lambda} \frac{\partial T}{\partial t} \tag{8}$$

where T is the temperature (°C), x the distance in direction perpendicular to wall's surface (m^2), ρ the density (kg/m^3), C_p the specific heat capacity (J/kg K), λ the thermal conductivity (W/m K), t the time (s). The dynamic thermal admittance parameters calculation is deeply explained elsewhere [14,21].

Table 3
R- and *U-values* for the studied walls fabrics configurations.

		Bearing leaf	*R-value*	*R*-value*	*U-value*	*U*-value*
Existing wall system		Stone	0.59	0.58	1.69	1.73
		Clay brick	0.53	0.51	1.89	1.97
		Concrete block	0.39	0.38	2.56	2.61
Internally changed	Timber sheathing instead of plastering (5.1.1)	Stone	2.62	2.61	0.38	0.38
		Clay brick	2.56	2.54	0.39	0.39
		Concrete block	2.43	2.43	0.41	0.41
	Timber sheathing without gypsum (5.1.2)	Stone	2.57	2.56	0.39	0.39
		Clay brick	2.51	2.49	0.40	0.40
		Concrete block	2.37	2.37	0.42	0.42
Externally changed	Ferrocement instead of cement mortar as an external cladding layer (5.2.1)	Stone	2.60	2.59	0.38	0.39
		Clay brick	2.53	2.51	0.40	0.40
		Concrete block	2.40	2.39	0.42	0.42
	Ferrocement with timber instead of plastering (5.3.1)	Stone	4.63	4.62	0.22	0.22
		Clay brick	4.57	4.55	0.22	0.22
		Concrete block	4.43	4.43	0.23	0.23
	Ferrocement with timber instead of plastering and without gypsum (5.3.2)	Stone	4.58	4.57	0.22	0.22
		Clay brick	4.51	4.49	0.22	0.22
		Concrete block	4.38	4.38	0.23	0.23

* With mortar binding effect.

5. Thermal resistance of the existing and modified configurations

Thermal performance has been evaluated based on thermal resistance and thermal transmittance. Although *R-value* is the inverse of *U-value* (as presented in Eq. 7), it was thought that it is beneficial to present both of them for more clarity. Table 3 shows that for all configurations the stone fabric wall (system (a)) provided the highest thermal resistance (lowest thermal transmittance). This could be highly attributed to the thickness of this fabric (400 mm) in comparison with the other fabrics (clay brick is 240 mm and concrete block is 200 mm) and to less extent to the stone thermal conductivity and density in comparison to the concrete block as seen in Table 2. It is clear that the configurations contain air-cavity/ies have much higher thermal resistance regardless the other leafs thermo-physical properties and thicknesses. For example, the increases in *R-value* for configuration 2.3.2 were more than 6, 7, and 10 times for stone, clay brick, and concrete block systems, respectively, in comparison with the existing configuration (see Table 3). The relatively high differences in the *R-value* enhancement could be high likely attributed to the original differences in both λ and walls thicknesses. Such increase in *R-value* is mainly attributed to the air thermo-physical properties in comparison with the other materials. Despite of the configuration 2.3.1 provides the highest *R-value* followed by configuration 2.3.2, the difference is not significant in comparison to the cost of the gypsum layer. This result was noted with configuration 2.1.2 in comparison with configuration 2.1.1, which suggests that gypsum layer could be removed as far as thermal performance is concerned.

Interestingly, it was noted that when the configuration contains double air-cavity (when the external cavity was included), the *R-value* was almost doubled for all configurations in comparison with each corresponding one. This increase could be explained by the transferred heat energy from the outside (sol-node) to the inside (environmental node) would be faced by the air-cavity layer before reaching the load-bearing leaf, i.e. less heat will be transferred by conduction due to λ value for the air. Table 3 shows that cement mortar as a binding material has no significant effect on the thermal resistance (R^**-value*) of the studied wall configurations and could be neglected. Therefore, its effect on dynamic thermal admittance properties has not been considered in addition to simplify the calculations.

6. Dynamic thermal properties of the existing and modified configurations

6.1. Existing wall configurations

Table 4 shows that the wall system that constructed using concrete block has higher *Y*-value followed by stone wall. This was expected as the wall configurations are same except the bearing-leaf as dense material such as concrete block has higher thermal admittance than lighter material like clay brick (see Table 2) [24]. It is known that the materials/construction elements that have higher *Y*-value could mitigate the indoor temperature fluctuations, which mainly depends on thermal conductivity and specific heat capacity of the used materials. This could also be explained by the thermal diffusivity of stone, clay brick, and concrete block (see Table 2),

Table 4
Thermal dynamic properties of the studied wall systems (3% error).

		Y (W/(m^2 K))	ϕ (h)	f (–)	Ω (h)	F (–)	Ψ (h)	U (W/(m^2 K))
Existing wall systems	S-a	5.05	1.13	0.12	12.97	0.42	1.82	1.69
	S-b	4.62	1.37	0.36	8.28	0.49	1.72	1.88
	S-c	5.14	1.14	0.43	6.72	0.41	1.92	2.52
Configuration 5.1.1	S-a	5.05	1.14	0.04	14.63	0.42	1.82	0.38
	S-b	4.59	1.33	0.12	10.21	0.48	1.65	0.39
	S-c	5.21	1.05	0.17	8.38	0.39	1.86	0.41
Configuration 5.1.2	S-a	5.04	1.14	0.04	13.78	0.42	1.82	0.39
	S-b	4.62	1.30	0.15	9.24	0.48	1.66	0.40
	S-c	5.29	1.07	0.20	7.59	0.39	1.95	0.42

where the material having higher thermal diffusivity can reach thermal equilibrium with its ambient environment faster than that has lower thermal diffusivity [19]. The thermal admittance time lag Ø, which represents the time difference between the timing of the peak heat flow at the internal surface of a construction member and timing of the peak internal temperature, i.e. it is the time between the response and the inducement, was higher for clay brick wall over the other two walls.

Thermal decrement factor, *f* describes the rate of heat flow from the exterior surface of a constructional element, as well as describes 'thermal mass' of a fabric construction member. It is normally used to represent the reduction in temperature gradient formation (as a function of time) across a construction member due to heat storage within that member. It was theoretically stated that walls that having smaller decrement factor is more effective at suppressing temperature swings, i.e. when *f* approaches zero better thermal stability (thermal comfort) can be achieved for an envelope (e.g. building) [26]. This factor is directly linked with its time lag ω, which is the time delay between the internal temperature peak and the peak heat flow out of the external surface. In this study, as Table 4 shows that there is an inverse relation between the thermal decrement factor and its time lag, which means that the wall with higher *f* can store less heat, i.e. higher thermal transmittance *U-value* (less thermal resistance) as Table 3 shows. Stone walls have provided lower *f* followed by clay brick wall and concrete block (see Table 4), i.e. the first has better thermal comfort.

Surface factor, *F* (dimensionless), represents the ability of a surface element to gain heat by absorbing the incident radiative heat. From Table 4, it can be seen that the difference in surface factor between stone and concrete block wall is much less than that for clay brick one. This could be attributed to the density and thermal conductivity, where they are both closer for stone and concrete block in comparison with clay brick, as tabulated in Table 2. Table 4 shows that the surface factor time lag, ψ (h), has an inverse relation with *F-value* and a positive one with thermal effusivity (β) (see Table 2), which describes the time lag between the timing of the peak heat flow entering the surface of wall configuration and peak heat flow leaving the surface and moving into the internal environment, e.g. room. It is worthwhile to note that there is no systematic relation between *U-value* and *Y-value* as seen in Table 4. In spite of *Y*-value and *U*-value have the same units, it is possible to have different construction elements with the same *U*-value but different thermal damping properties as measured by the *Y*-value, i.e. *U* is the rate of heat transfer across a construction component, whereas *Y* is the rate of transfer to the fabric [21].

Fig. 7 illustrated that the internal environmental temperature is almost same for stone and clay brick systems, which is found to be higher for concrete blocks system under same conditions. This means that better thermal comfort (thermal stability) could be achieved with stone and clay brick systems in comparison with concrete block one. The internal surface heat flux for stone and concrete block walls was close peaked at 7 W/m^2 K in comparison with clay brick wall that has 5 W/m^2 K. Such behaviour could be explained by their thermo-physical properties as previously mentioned. The external heat flux for the studied walls exhibited almost same trend as internal heat flux. Generally, the results of the existing systems indicated that thermo-physical properties of the used construction materials have greater influence on the studied behaviour than walls thickness, although the walls thickness has a clear impact.

6.2. Configuration 2.1.1

Table 4 shows that all the walling systems have generally same trend, in terms of their dynamic thermal behaviour, in comparison with corresponding existing wall system. Where, there is no significant difference in terms of *Y-values* and its time lag for each corresponding one, however, the decrement factor values were significantly decreased in comparison with corresponding system. This reduction was associated with a significant increase in decrement factor time lag. Such behaviour could be mainly attributed to the effect of air-cavity and sheathing timber thermo-physical properties in comparison with the removed plaster layer in terms of both thickness and properties, as seen in Table 2. There was no significant difference in the surface factor and its time lag, where *U-value* was sharply decreased in comparison with these values for the existing systems. In systems (a) and (b), the *U-value* was dropped for almost fifth, while this value was 16% for system c with reference to the corresponding system in the existing walls configurations.

From Fig. 8, it can be seen that, both internal surface heat flux and internal environmental temperature have almost same trends and even values with reference to the existing configurations. However, the external surface heat flux was zero for the first 3 h and then marginally increased peaking at about 0.2 W/m^2 K in comparison with about 1 W/m^2 K for the corresponding configuration in the existing system (see Fig. 7). This shows that the air-cavity has a much more effect on the heat transferred from outside to inside than the bearing-leaf materials and thickness. This could be highly attributed to air thermo-physical properties in comparison to plaster layer as shown in Table 2.

6.3. Configuration 2.1.2

The effect of removing gypsum layer was not significant on *Y-value* and its time lag in comparison with same existing wall system as seen in Table 4. The decrement factor values were significantly decreased, for more than a half, in comparison with the corresponding existing wall configuration and slightly increased with reference to configuration 2.1.1 as shown in Table 4. This reduction was associated with an increase in decrement factor time lag for about an hour, whereas it was about 2 h in the previous configuration (see Table 4). This behaviour is mainly attributed to the effect of air-cavity and sheathing timber thermo-physical properties and thicknesses in comparison with plaster and gypsum layers. It was noted that there was no significant difference in the surface factor

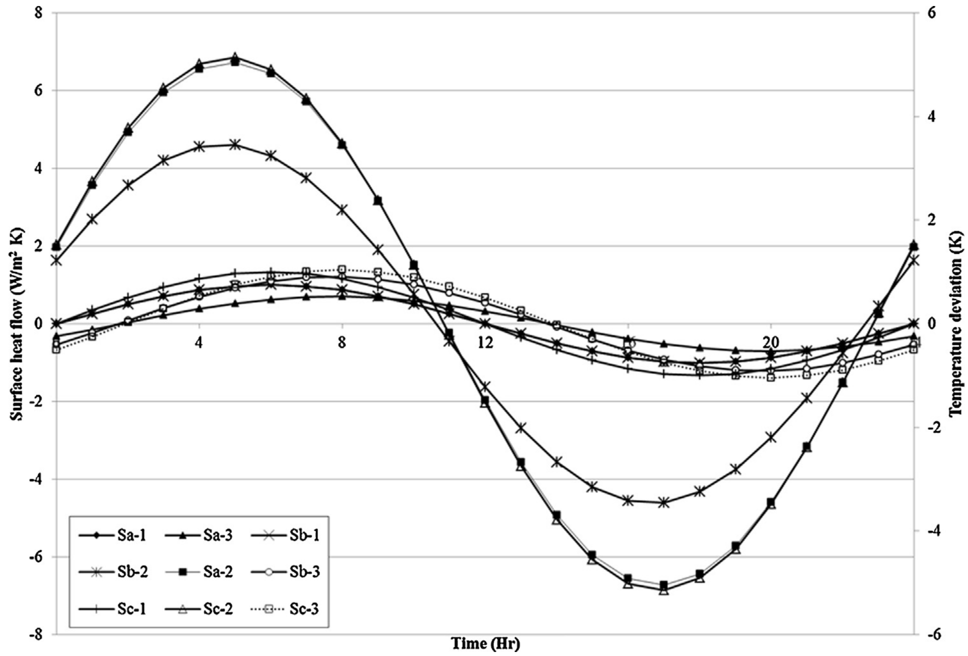

Fig. 7. Surface heat flow and internal environment temperature fluctuation for the existing configuration.

and its time lag whereas *U-value* was sharply decreased in comparison with these values for the existing systems. The difference in this reduction between configurations 2.1.1 and 2.1.2 could be mainly due to gypsum layer influence, which can be removed as it has no significant effect in comparison with its cost and environmental impact in terms of using the version materials and the heat used to manufacturing this construction material.

Fig. 9 shows that the highest internal surface heat flux was found to be with system (c) (concrete block) (7 W/m^2 K) followed by system (a) (~6.7 W/m^2 K), whereas it was just 3 W/m^2 K for system (b). This could be attributed to the effusivity and diffusivity values as shown in Table 2 where it was higher for concrete block followed by stone. The internal environmental temperature was found almost identical for systems (a) and (b) and those have values lower than that for system (c). Inversely, external heat flux was observed to be higher for system (b) than that for systems (a) and (c) that are almost same. Again, such behaviour is highly attributed to thermo-physical properties of load-bearing leaf materials in addition to their thicknesses.

6.4. Configuration 2.2.1

Table 5 shows that *Y-value* sharply decreased in comparison with the existing systems (see Table 4), where it dropped for more than a half when the ferrocement layer and the air-cavity were applied. This reduction is associated with a more than double

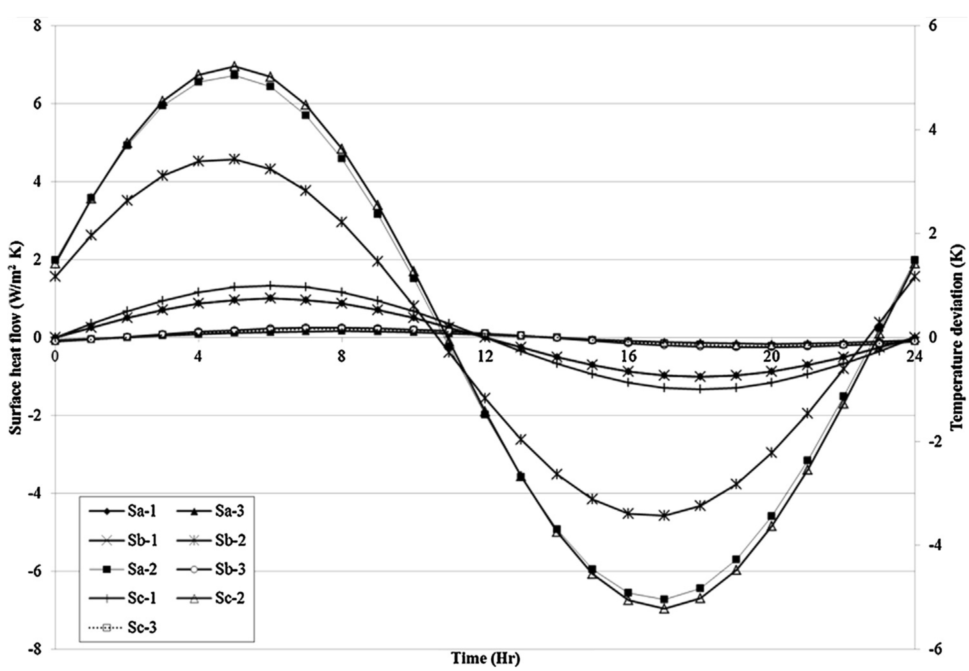

Fig. 8. Surface heat flow and internal environment temperature fluctuation for configuration 5.1.1.

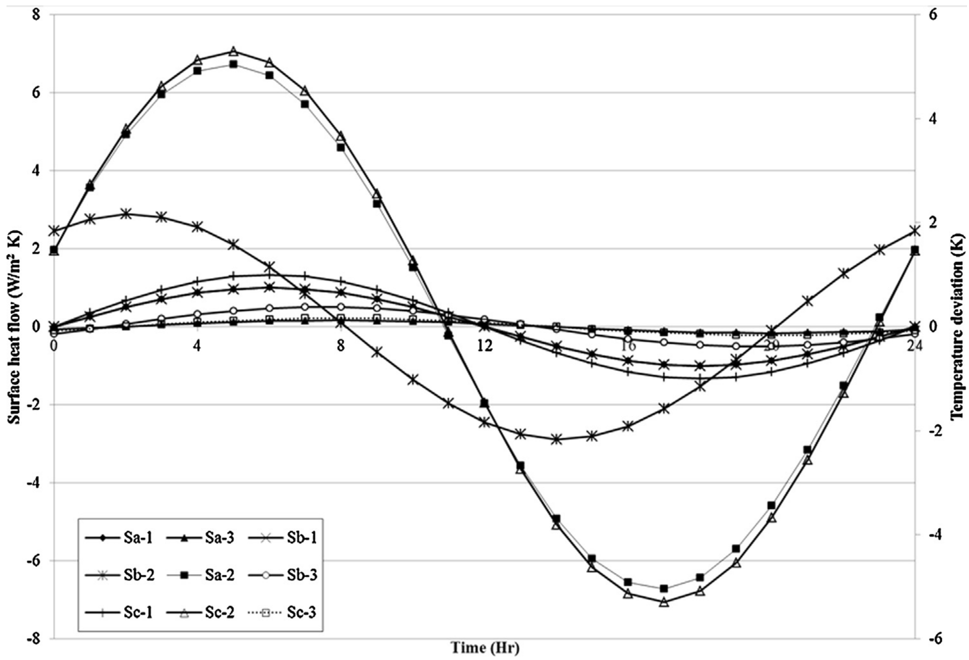

Fig. 9. Surface heat flow and internal environment temperature fluctuation for configuration 5.1.2.

increase in its time lag if compared with the corresponding configuration wall system. Interestingly, the *Y-value* is exactly same for all three systems, regardless the load-bearing leaves (stone, clay brick, or concrete block) and there was no significant difference in its time lag. Such behaviour is highly attributed to the air-cavity involvement and to less extent to the ferrocement layer as the differences in the thermo-physical properties between the cement mortar and ferrocement is not significantly large. In other words, the effect of air-cavity on the thermal dynamic behaviour for the three systems is much more than the effect of the load-bearing leaf type. This could be mainly attributed to the air thermo-physical properties (see Table 2). As, in Iraq, the outer temperature is much higher than that internal one (over the most year), the transferred heat from the sol-air node to the environment node will be theoretically faced by the air-cavity before the bearing leaf materials. This could improve the thermal insulation of the traditional external wall systems which is still dominant for the aforementioned reasons.

The thermal decrement factor was also sharply decreased for almost a half and this reduction is associated with an increase in its time lag for about 2 h for all systems in comparison with the existing walling systems. This could be explained by the effect of the air-cavity in reducing the peaks between the heats that leaves the external surface and the external temperature which could be due to the air thermo-physical properties. The surface factor increased, as seen in Table 5, due to the thermo-physical properties of ferrocement layer in comparison with the cement mortar in addition to air-cavity influence. It is clearly that the reduction in *U-value* for all systems is much more than that for *Y-value*. This could be justified by the effect of this configuration on reducing the transferred heat from external environment to the internal environment higher than that on the heat leaves the internal surface. The internal environmental temperature was same for systems (a) and (b) and they were much lower than that for system (c), as Fig. 10 illustrated. This could be mainly due to the compensation of wall thickness and λ value where stone has higher λ than clay brick as demonstrated in Table 2, but the larger thickness of system (a) (40 mm) has compensated for the thickness of system (b) (240 mm). Unlike internal surface heat flux, as it was same for systems (a) and (c) and they were more than that for system (b), which could be attributed to the thermo-physical properties that presented in Table 2. It peaked at the second hour and hour thirteen at ∼6.5 W/m^2 K. Indeed the external heat flux for system (a) was the lowest over the others ones, however, all of them were fluctuated within 1 W/m^2 K.

6.5. Configuration 2.3.1

The effect of replacing the plaster layer by air-cavity and timber sheet on the *Y-value* and its time lag can be neglected in comparison with configuration 2.2.1. Nevertheless, when these values

Table 5
Thermal dynamic properties of the studied wall systems (3% error).

		Y (W/(m^2 K))	*ϕ* (h)	*f* (–)	Ω (h)	*F* (–)	Ψ (h)	*U* (W/(m^2 K))
Configuration 5.2.1	S-a	2.38	4.04	0.05	15.06	0.89	1.18	0.38
	S-b	2.38	4.09	0.17	10.54	0.80	1.18	0.39
	S-c	2.38	4.08	0.23	8.85	0.89	1.18	0.42
Configuration 5.3.1	S-a	2.38	4.08	0.01	16.73	0.89	1.18	0.22
	S-b	2.38	4.09	0.02	12.42	0.89	1.18	0.22
	S-c	2.38	4.08	0.03	10.43	0.89	1.18	0.23
Configuration 5.3.2	S-a	2.38	4.08	0.01	15.88	0.89	1.18	0.22
	S-b	2.38	4.09	0.03	11.43	0.89	1.18	0.22
	S-c	2.38	4.08	0.03	9.66	0.89	1.18	0.23

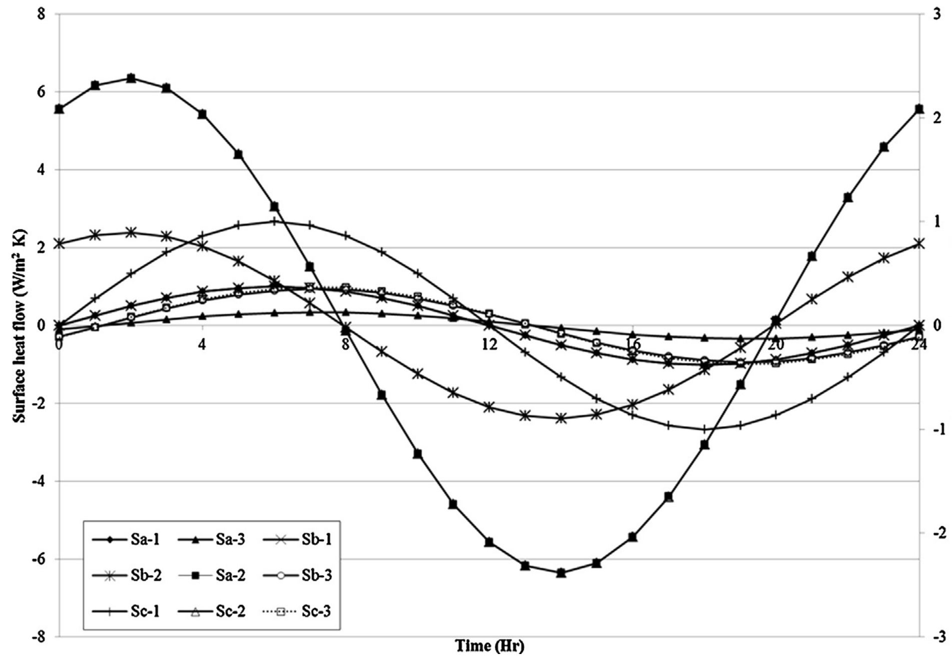

Fig. 10. Surface heat flow and internal environment temperature fluctuation for configuration 5.2.1.

compared with existing systems, a considerable reduction has occurred as seen in Tables 4 and 5. This configuration led to a sharp decrease in the thermal decrement factor and a significant increase in its time lag in comparison with configuration 2.2.1. This reduction was associated with a significant decrease in *U-value* in comparison to both configuration 2.2.1 and the existing systems, as shown in Tables 5 and 4. This behaviour could be mainly attributed to the air-cavity involvement and its location, where it appears that externally located air-cavity is more efficient than internally located for a same configuration, as previously explained. No significant differences have been noted for the internal environment temperature, internal and external heat flux in comparison to configuration 2.2.1 as Fig. 11 illustrated. This could support the previous hypothesis, i.e. externally located air-cavity has much more effect on the studied behaviour than the replaced plaster layer with timber sheet and internally located air-cavity.

6.6. *Configuration 2.3.2*

This configuration has shown almost same results as configuration 2.3.1 with some negligible exceptions as Table 5 demonstrates. The only exception which is worthwhile to be highlighted is the decrement factor time lag that is decreased by almost an hour in comparison with configuration 2.3.1, which could be due to removing gypsum layer. This behaviour is due to the aforementioned reasons. The general reduction in *Y*- and *U-values* in addition to *f* in

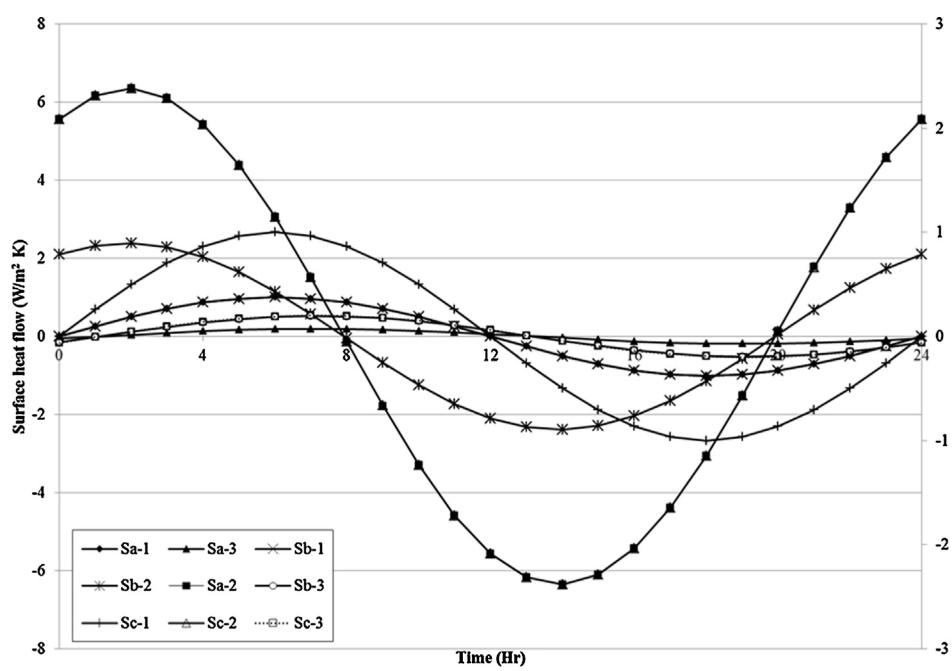

Fig. 11. Surface heat flow and internal environment temperature fluctuation for configuration 5.3.1.

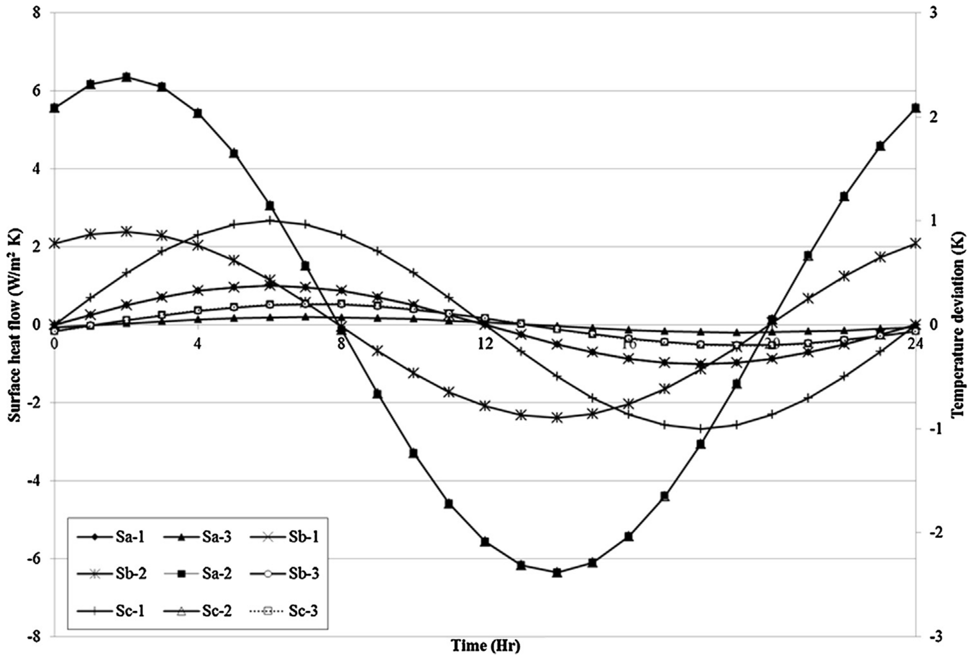

Fig. 12. Surface heat flow and internal environment temperature fluctuation for configuration 5.3.2.

comparison to the corresponding existing and internally changed configuration (see Tables 4 and 5) is due to double air-cavity existing (internally and externally). This was explained by the effect of air thermo-physical properties as previously mentioned. The effect of removing gypsum layer on the internal environment temperature, internal and external heat flux can be neglected in comparison to configuration 2.3.1 as Fig. 12 illustrated, which once again confirmed that air-cavity involvement is the dominant factor over other changed/removed layer due to air thermo-physical properties. Based on the results of thermo-dynamic behaviour, both configurations 2.3.1 and 2.3.2 exhibited almost same behaviour. However, as in configuration 2.3.2 the gypsum coating layer has been removed, this one can be counted the best configuration from both economic and thermal behaviour.

7. Conclusions

It appears that the wall thickness has greater effect on thermal resistance/transmittance than thermal conductivity of the load-bearing leaf of the studied existing wall systems. The results showed that the stone wall provided the highest thermal resistance followed by clay brick and concrete block walls, respectively. Image analysis technique that used in calculating the cement mortar binding area (2-D image processing) as a percentage to the whole wall stated that it has no significant effect on the walls thermal resistance of the studied wall systems. Generally, the configurations contain air-cavity/ies have much higher thermal resistance than existing wall systems regardless the other leafs properties including the load-bearing leaf type. This could be highly attributed to the air thermo-physical properties in comparison to other used construction materials.

Gypsum layer was found to have no significant effect on both thermal resistance and thermal dynamic properties; therefore, it could be removed as far as thermal performance is concerned, which could be economic/environmental added value. Interestingly, it was noted that when the configurations contain double air-cavity (internally and externally), *R-value* was almost doubled for all configurations in comparison with each corresponding systems. Both configurations 5.3.1 (internally and externally air-cavity inclusion in addition to replacing the plaster layer by timber sheeting) and 2.3.2 (same previous one in addition to remove gypsum layer) have similarly behaved in terms of thermo-dynamic and thermal resistance. However, configuration 2.3.2 can be nominated to be used gypsum layer can be removed without significantly affecting the thermal performance. Accordingly, this configuration with stone load-bearing leaf is recommended to be used whenever possible followed by clay brick wall fabric.

Acknowledgment

The author greatly thank Dr. Matthew Hall/Division of Materials, Mechanics, and Structures at The University of Nottingham for his help in conducting this work.

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