EXPERIMENTAL AND NUMERICAL STUDY OF THERMAL PERFORMANCE AND ENERGY SAVING BY USING HOLLOW LIMESTONE WALLS

Atif Ali HASAN[1], Riyadh Husni ALJAWAD[2], Kadhum Audaa JEHHE[3]

In order to reduce the usage of brick as a primary material in the Iraqi buildings wall construction, several models of hollow Limestone walls with a close or open-air gap, with one or more reflective surfaces (ANS H 35.1(2001,) thick. 0.5 mm) have been investigated in experimental and numerical studies (ANSYS-fluent V.16.2) in this paper. These models contain one air gap that forms between two limestone blocks or two air gaps between three limestone blocks to allow the air circulation inside the air gap so as to increase the resistivity of the wall at the midday hours (in case of open air gap). A comparison was made on the thermal performance between the suggested walls and the traditional classical wall, which consists mainly of a 240 mm thickness brick. The results showed that using three layers and two air gaps is more efficient in the electrical energy consumption for cooling purpose that is reduced by 36%.

Keywords: Limestone Walls, Hollow walls, Air Gap Walls, Reflective Surfaces.

1. Introduction

Although the revolution is observed in the technical world regarding the constructing materials, [1, 2] the classic brick continues to be widely used as an essential building material in the constructing. The percentage of buildings is constructed by the brick was 79% in Iraq [3]. That leads to consumption of high electrical energy for air conditioning. For example, the overall heat transfer Coefficient is about 1.514 $W/m^2C°$ for a wall that constructs the brick which has a thickness of 240 mm with the presence a finishing layer of cement from the outlet and an internal gypsum layer. While the weight of this wall is about 288 kg/m^2 and the mean cooling load that is needed in summer is about 37 kW/m^2 of wall area [4]. In addition, for reducing the thermal leakage by using the buildings

[1] Assist prof., Department of Machines and Equipment, Institute of Technology, Middle Technical University, Baghdad, Iraq, e-mail: atif56ali@yahoo.com
[2] Eng., Construction and Projects Division, Middle Technical University, Baghdad, Iraq, e-mail: reead000000@yahoo.com
[3] Lecturer, Department of Machines and Equipment, Institute of Technology, Middle Technical University, Baghdad, Iraq, e-mail: kadhumaudaa@gmail.com

designed by experience consultative is called as an architectural experience such as (Baghdad college building, Institute of technology in Baghdad). It has the air gap width at 120 mm [5-8], while some literature considered it at 50 mm [9] and anther considered it at 20 to 60 mm [10, 11]. Also, the closed air gap [12] and that air recirculation inside the space was studied by [13, 14] or by using the night ventilation or by inducing the moist and cold air into the gap [15, 16]. Other authors have studied the ability to heat the air [17, 18, and 19]. Finally, [20, 21] studied a constructed wall from the hollow bricks with air gaps. In this study, an experimental and numerical investigation of using single, double and triple of the limestone slab with one and two closed or opened air gap with aluminum foil sheets were considered. This work was performed in order to study the effect of nine models of the limestone walls on the thermal behavior, thermal resistance, electrical energy, and the heat saving percentage of these modified walls. Moreover, compared with the classical brick walls, from the working Iraqi market, the cost of the 1m^2 of the brick will become at 75000 ID/m^2, while, the cost of limestone slab has 85000 ID/m^2 (ID: Iraqi dinars), the weight of both is 290 kg/m^2.

2. Experimental Methodology

The primary view from this research was constructed by building nine models of walls that are formed from a limestone (marble) which was available and was widely used in Iraq (as a solid). These models contain one or two air gaps inside the blocks to allow circulation the air inside at the midday hours (in the case of the open-air gap). Moreover, the air moves inside the gap at the night hours from the sunset to sunrise (in the case of the closed air gap). The two fans with the power of 15W were run by an electrical cell with a capacity of 30W that has dimensions of 300x800 mm that used to motivate the air inside the air gap as shown in Fig. 1

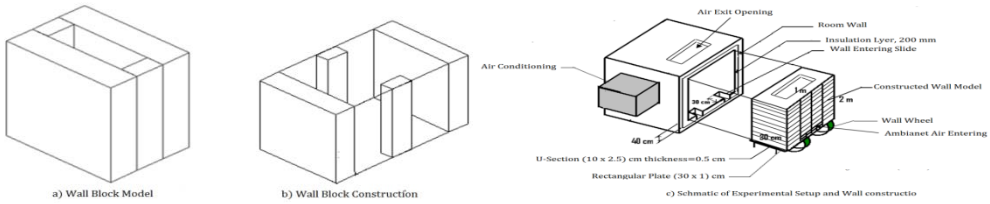


Fig. 1. Experimental Setup diagram and wall construction; a) Wall block model, b) Wall block construction, c) Schematic of experimental and wall construction.

The nine models, as given in Fig. 2, noted that the internal layer of gypsum is fixed in all nine models:

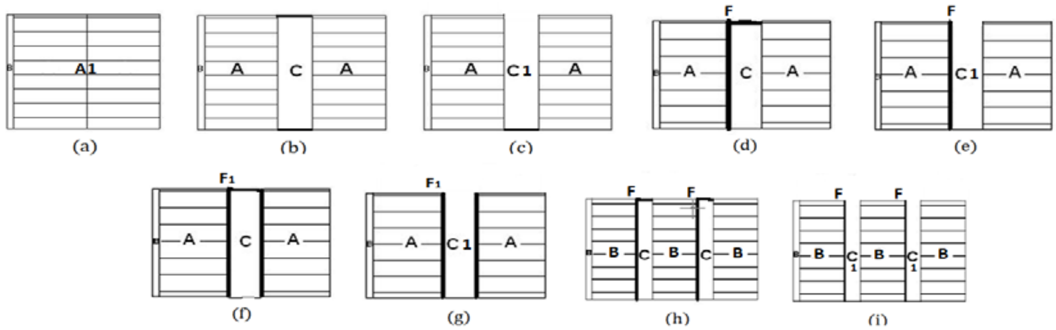


Fig. 2. Constructed modified walls models used in this study.
A_1=210mm, A=105mm, B=70mm, C_1 opened air gap, C closed air gap
F one side reflective plate, F_1 two side reflective plate

Study Variables and Limitation

To study the thermal behavior and temperature distributions in the walls, the three limestone slab with dimensions of (210 x 200 x 200 mm), (105 x 200 x 200 mm) and (70 x 200 x 200 mm) was used to build walls with air gap with a thickness of 50 mm (one or two air gap) by using aluminum reflective foil sheets (ANS H 35.1 (2001). These blocks are used in order to build a tested wall (1×2)m, the testing room (1×1×2)m, located on the third floor of a building constructed in Baghdad (latitude 32.2° North) and exposed to the environment as shown a Fig. 1, from inside, all room surfaces are insulated by polystyrene sheets (200mm thickness) except the tested wall, which is oriented to the East, Air-conditioning unit (ACU) has refrigeration capacity 3.5 kW which is employed to obtain standard comfortable condition (26.5 C° & 65% R.H.) [22]. The consumed electrical energy level from (ACU) is measured by electric energy meter in kW-hr. Air room temp (Tr), the internal face temp of the tested wall (Ti) is measured by a calibrated thermocouple and a digital thermometer, the environment temp. In shade (Tsh) and outer face of the tested wall (To) is measured by an auto digital thermometer. The experimental reading air is recorded from 5:00 AM to 7:30 PM, for twenty – one day in summer months (from May to September 2017). The free convection heat transfer coefficient (h) between the internal surfaces of the test wall into the room environment can be calculated as [23]:

$$h = 1.31(\Delta t_{i-r})^{1.3} \tag{1}$$

Then the cooling load wall (Q) will be equal to:

$$Q = h \times A \times (\Delta T_{i-r}) \tag{2}$$

To obtain the energy saving due to modification in conventional wall E in which electrical energy consume to preserve the comfortable condition in the tested room must be recorded, Energy Saving

$$\frac{\Delta E}{E}\% \tag{3}$$

The uncertain analysis is done for the quantity of heat transfer through the wall, and the maximum present obtained is (3.2 %) in this study.

3. Mathematical Formulation

The geometry description of the 2D rectangular section of the studied limestone wall with a single air gap was presented in Fig .3. The fluid properties are assumed to be constant except for the density variation that is treated according to Boussinesq approximation. The present flow is considered steady, laminar, incompressible, and two-dimensional [24]

The formulation of buoyancy-induced problems is solved according to the basic conservation principles that described the fluid movement, these equations were the conservation of mass, momentum, and energy, and they can be presented via ANSYS-Fluent v.16.2 in air fluid regions, [25]

Continuity equation,

$$\nabla.(\rho\vec{v}) = 0 \tag{4}$$

Momentum equation, $$v.(\nabla.v) = -\frac{1}{\rho_{ref}}\nabla\rho + v_{ref}(\nabla^2.\vec{v}) + \vec{g}\left[1-\beta(T-T_f)\right] \tag{5}$$

Energy equation, $$\nabla.(\vec{v}\rho T) = \nabla(\frac{k}{c_p}\nabla T) \tag{6}$$

In solid regions, the energy transport equation has the following form:

$$\frac{\partial}{\partial t}(\rho h) + \nabla.(\vec{v}\rho h) = \nabla.(k_{eff}\nabla T) + S_h \tag{7}$$

The appropriate dimensionless form of the boundary conditions summarized by Fig. 4 used to solve equations (1) to (4) inside the cavity is given as:

At the inlet; $U=U_o$, $V=0$, $\theta=\theta_i$

Boundary condition of the convective (CBC) at the outlet: $P=0$, $U=0$, $V=0$, $\frac{\partial p}{\partial n}=0$

At the heated blocks wall, $\theta=1$

At the left, top, and bottom walls: $\left.\frac{\partial\theta}{\partial X}\right|_{X=0} = \left.\frac{\partial\theta}{\partial Y}\right|_{Y=1,0}$

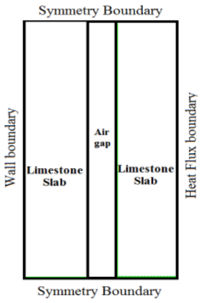
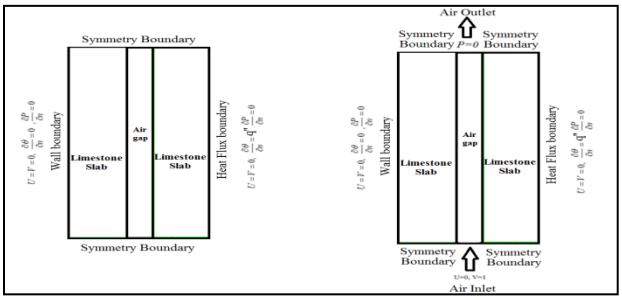


Fig. 3. Dimension diagram of the rectangular cavity



a) Closed Air Gap b) Opened Air Gap

Fig. 4. Schematic Diagram of the Boundary Conditions

In this numerical study, the finite volume method was considered in order to discretize the above governing equations in the solid and fluid domain. By using the implicit line by line Gauze elimination scheme and the pressure-velocity coupling (SIMPLEC algorithm) [26], the discretization equations transformed the system of elliptic partial differential equations into a system of algebraic equations. The relaxation factors used for velocity components, temperature, and pressure are given by 0.8, 0.9, and 0.3, respectively. The region near the walls, the uniform grid with refinements is used. The computational grids are staggered for the scalar variables and not staggered for the scalar one as presented in Fig. 5. The model is terminated when the mass, momentum, and energy for each simulation are evaluated over the course; residuals drop below 10^{-7}. Moreover, in these numerical simulations, the convergence criterion for temperature, pressure, and velocity is [27]:

$$Error = \frac{\sum_{k=1}^{i}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\zeta_{i,j,k}^{t+1}-\zeta_{i,j,k}^{t}\right|}{\sum_{k=1}^{i}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\zeta_{i,j,k}^{t+1}\right|} \leq 10^{-7} \tag{8}$$

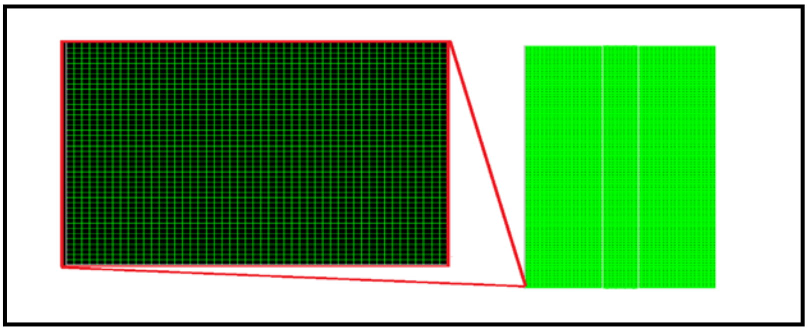


Fig. 5. Meshed computational domain.

4. Results and Discussion

The aim of this study is the knowledge of the effect of presence of the multi air gap with aluminum sheet foil in a limestone slab walls. The results are presented as in Table 2.

Table 2

Results of the measured parameters of the present study

Model Symbol	T_{sh} C°	T_o C°	T_i C°	ΔT C°	T_i-T_r C°	*Cooling load kW	* Season consumption electrical energy kW.hr	* Saving in electrical energy kW.hr	Saving percentage %
A	37.8	46.7	42.2	4.5	15.7	115	391	---	---
B			40.0	6.7	13.5	93.0	319.5	71.5	18.30
C			40.2	6.5	13.7	95.8	325.7	65.3	16.7
D			39.8	6.9	13.3	92.1	313.14	77.86	19.9
E			39.99	6.71	13.5	93.93	319.4	71.6	18.3
F			38.1	8.6	11.6	76.8	261.1	130	33.3
G			38.3	8.4	11.8	78.6	267.2	123.8	31.7
H			37.7	9.0	11.7	73.3	249.2	142	36.3
I			37.99	8.71	11.49	75.8	258	133	34.0

* all the values were calculated per m^2 wall area

Effect of Air Gap

Table 2 lists the overall results. The results showed that the temperatures along the interior wall are 40.0°C for closed gap and 40.2°C for the open gap. When using the modified wall of models C, the airflow that is induced in the air gap in the midday period will defect the heat transfer from the environment to the room, while the thermal load caused in the room was 94.0-95.8 kW for the wall of the closed and opened respectively. Also, the electrical heat used to remove the thermal load and to maintain the room under standard thermal comfort was 319.3-325.7 kW.hr, respectively. The opening of the air gap in the day and letting the air come inside will lead to increase the cooling load by 1.8kW and increase the electrical energy by 6.2 kW.hr for the summer season. Therefore, the savings will be about 71.5-65.3 kW.hr as compared to the limestone wall for hollow wall with closed and opened respectively, but the percentage for the energy reduction will be about 18.3-16.7 % for the same conditions.

Effect of Single Reflective Sheets

Table 2 showed that the mean wall temperatures were 39.8-39.99°C for the wall of the one sheet with closed and opened air gap respectively. The difference of temperatures across the wall was 6.9-6.71°C for close and open-air gap respectively, but the temperature differences on the wall room and the room temperature were 13.3-13.5°C in the case of close and open-air gap respectively. Furthermore, the amount of thermal load inside the room and the amount removed 92.1-93.93 kW, and electrical cooling energy for the unit was 313.4-319.5 kW.hr for the summer season, and the percent of saving energy was 19.9-18.3 % as compared to the solid wall. Therefore, the electrical energy was 77.86-71.6 kW.hr as compared to the solid wall.

The consumption of electrical energy for models, D and E was compared to models, B and C is about 6.36-6.3 kW.hr in case of closed and opened air gap, respectively. Therefore, the presence of a single reflective aluminum sheet will save the electric energy which about 6.3 kW.hr. The reflective aluminum sheet has high thermal conductivity, and the high temperature difference was low inside the air gap.

Effect of Double Reflective Sheets

The thermal behavior of the hollow limestone wall is presented in Fig. 6 and in Table 2. The results showed that the presence of the double sheet would lead to decrease the temperature along the interior wall of the room by 38.1-38.3°C, and the temperatures across the wall were 8.6-8.4 °C. The temperature difference between the interior surface wall and the room temperature will reduce inside to 11.6-11.8°C in case of using closed and opened gap, respectively. The effect of double reflective aluminum foil sheets on the thermal load inside the room to remove was about 76.8-78.6 kW.hr for the summer season. The percentage for the energy saving was increasing to 33.3-31.7 % from the consumption of the solid wall where the energy electrical energy was 130-123.8 kW.hr for closed and opened air gap respectively.

Nevertheless, the amount of energy saving as compared to the wall with a gap and without reflective sheet for models B and C, the saving reaches 58.4-58.2 kW.hr for closed and opened air gap respectively. However, the amount of electrical energy as compared to the presence of the single reflective sheet models of D and E and the models of F and G were between 52.4-52.2 kW.hr. The results showed that the effect of the presence of two reflective sheets along the interior walls of the air gap is the best.

Effect of Triple Limestone Slab

The thermal behavior for the modified wall from three slabs of limestone and two air gaps with a thickness of 25 mm were plotted in Fig.6 and Table 2. For models of I and J, the results showed that the departures of the wall into three sections would lead to a decrease in the temperatures along the interior wall of the gap to 37.7-37.99°C for cases of closed and opened air gap respectively. The temperature difference across the wall was 9.0-8.71°C for cases of closed and opened air gap respectively, and the temperature difference between the interior surface wall and the room temperature was at 11.2-11.49°C. Therefore, the conditioning load reduced to 73.3-75.8 kW, and this lead to decrease the energy that demanded to remove the cooling load of the room to 249-258 kW.hr. Also, the differences in the electrical energy in case of the solid wall were 142-133 kW.hr that will lead to the reduction percentage became at 35.6-34.8%. When compared with the wall of the single air gap with single reflective sheet models D and E, due to the departure, the gap will cause to generate a double thermal resistance for convection inside the wall section and this lead to decrease the overall heat transfer coefficient and reduce the energy transferred to the room. Also, we found that the saving was in the range of 64.14-61.4 kW.hr.

Numerical Results

In the numerical and simulation part of this study, [25] was used in order to solve the governing equations for the conduction and convection heat transfer inside the wall models structure for the nine models with and without the air gap and with and without the reflective aluminum sheets foil, where the convection model for without aluminum foil was used in the case of using the air gap and the radiation model was used to solve the case of using the aluminum foil.

The result presented in Figs. 7 to 10 presented the temperatures and velocity distributions inside the wall structures and inside the air gap to declare the effect of using aluminum foil on the interior wall of the air gap. Also, it described the effect of open and closed on the amount heat transferred across the wall that exposure to the constant heat flux of the solar sun ration simulated by 900 w/m^2 and the interior condition wall was fixed at 26.5°C.

Fig. 7 showed that the heat transfer inside the air gap was by conduction due to stagnation of the air inside the closed air gap and low velocity of the air inside the gap this lead to decrease the convection heat transfer and when using the aluminum foil. It leads to reflect some of the heat towards the gap and increased the thermal resistance of the wall and decreased the heat towards that room. The results showed that using the aluminum foil to cover the internal surface of the gap would lead to reduce the heat retransfer by12% as compared to the first case of without foil. Also, we can note that the velocity distinction inside

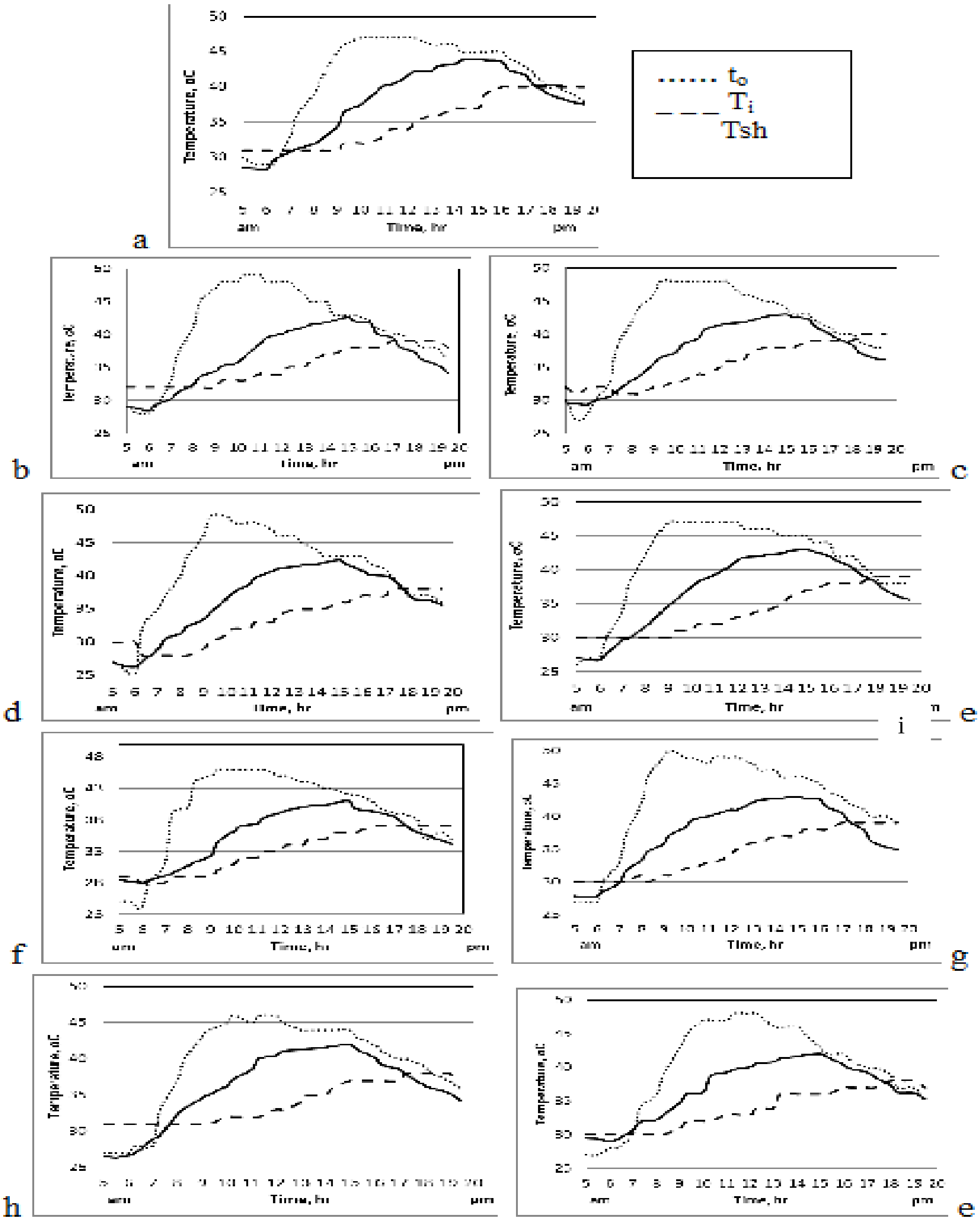


Fig. 6. Hourly thermal behavior for wall models of; a) Solid Wall, b) Hollow wall with closed air gap c) Hollow wall with open air gap, d) Hollow wall with closed air gap and single reflected sheet, e) Hollow wall with open air gap and single reflected sheet, f) Hollow wall with closed air gap and double reflected sheet, g) Hollow wall with opened air gap and double reflected sheet, h) Triple layer wall with two closed air gaps and single reflected sheet, i) Triple layer wall with two opened air gaps and single reflected sheet, t_o external face temp., T_i internal face temp., T_{sh} environment temp.

The open-air gap is presented in Fig. 8. It can be noted that the benefit of presence of air movement inside the air gap, and this will lead to increase the convection heat transfer and to increase the thermal resistance with and without using the aluminum foil. This will lead to a reduction in the heat that transfers to the room. Finally, the case of using two air gaps inside the modified wall and its effect upon the thermal insulation of the tested room. Figs. 9 and 10 showed that the temperatures decreased by 32% at the same condition of the numerical and experimental solution before the open gap but the open gap with aluminum foil will give 45% for closed air gap by 51% in case of open gap and use two aluminum foils along the interior surfaces wall of the air gap. From the Fig. 10, we can note that the usage of two gaps with two aluminum foil will give a reduction in the velocity distributions and the air will become more and more stagnate inside the air gap that near the room due to reducing the heat that transfers towards this gap and there is no convection inside it.

5. Conclusions

The results obtained from the present work can be concluded as follows

1) The usage of double limestone slab with air gap was the best than the solid limestone for reducing electrical energy which was consumed for purpose cooling.
2) The usage of double limestone slab with two closed air gap was the best than the open gap (the saving percentage is 18.3% 16.7% opened gap).

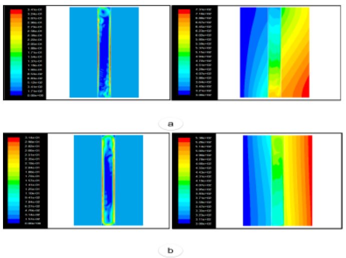


Fig. 7. Effect of using closed air gap; a) Hollow wall with one closed air gap without reflected aluminum sheet, b) Hollow wall with one closed air gap with reflected aluminum sheet.

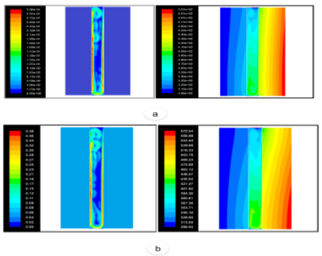
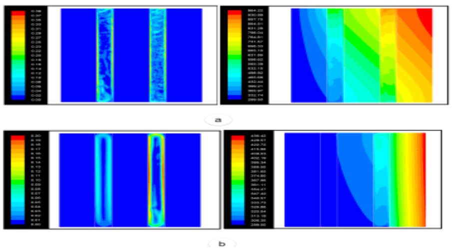
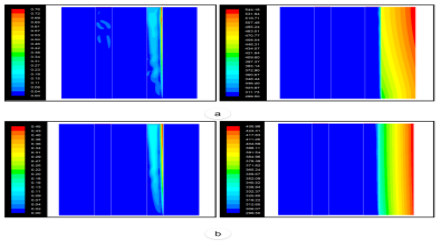


Fig. 8. Effect of using opened air gap; a) Hollow wall with one opened air gap without reflected aluminum sheet, b) Hollow wall with one opened air gap with reflected aluminum sheet.



Temperature Distribution

Fig. 9. Effect of using tow closed air gap; a) Hollow wall with two closed air gaps without reflected aluminum sheet, b) Hollow wall with two closed air gaps with reflected aluminum sheet.



Temperature Distribution

Fig. 10. Effect of using tow opened air gap; a) Hollow wall with two opened air gaps without reflected aluminum sheet, b) Hollow wall with two opened air gaps with reflected aluminum sheet.

3) Presence of reflecting aluminum foil sheet along the interior walls of the gap will give a good saving and insulation results (one side 19.9%, two sides 33.6% saving percentage).
4) The case of using three limestone slabs with two air gap that covered by reflecting aluminum foil was the best one thermally and high heat reduction and thermal insulation (the saving percentage 36.3%, closed gap34% opened gap).
5) The use of available natural materials such as; the limestone will be considered a good choice but with using an insulated space.
6) It is recommended leaving the usage of the traditional brick (solid-hollow) in the construction of the modern buildings.

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