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Research Article

Thermal Performance Assessment of External Wall Construction for Energy-Efficient Buildings

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ABSTRACT

Building envelope such as external walls are still constructed from poor materials which results in higher heating and cooling loads thereby raising energy bills. Improving building energy efficiency with advanced technologies is being sought. In this context, a numerical study was conducted to solve the coupled heat transfers through a standard wall structure used in Libyan residential buildings. Different techniques were compared to reduce the thermal transmittance of the traditional wall structure for saving energy including the application of radiant shield, low-e coating, insulating filling and external insulation. The numerical results revealed that the thermal radiation inside the cavities of hollow block is important and accounts for 21% of total heat transfer, while conductive and convective heat transfer contributes by 65% and 14% from the total, respectively. The obtained thermal transmittance value of the common wall structure was considered as high as 2.33 $W/m^2 \cdot K$ due to lower resistance of wall elements. The adoption of 50 mm layer of expanded polystyrene insulation (EPS) to the exterior wall showed the best thermal performance with a reduction of thermal transmittance by 45%. On the other hand, filling the interior of cavities with EPS resulted in a 37% reduction of thermal transmittance compared to 20% of using 3 mm aluminum foil as a radiant barrier in the middle of the cavities. The last case was less effective with a reduction of almost 10% when a commercial coating of 0.4 surface emissivity was applied to the interior of cavities.

Keywords: assessment, building, code, energy-efficient, external, thermal, wall

INTRODUCTION

Building sector worldwide consumes a significant percentage of total electricity produced. For instance, buildings in Libya (residential and commercial) consumed about 50% from the total electrical energy and almost half of this is used for cooling in hot summers (El Bakkush et al., 2015). Awareness is being raised to implement energy efficiency building codes (EEBC) for energy savings. Across the US, it was reported that households can save about 1.8% of electricity, 1.3% of natural gas, and 2.8% of heating oil with the application of these energy efficiency codes (Koirala et al., 2013). The heat transfers through building envelope (walls, windows and roofs) is a key factor affecting the thermal comfort criterion and building energy consumption. Poor construction materials of building envelope require larger heating and cooling loads. There are many studies on using some efficient technologies and sustainable materials to improve energy performance of building envelope (namely, the external wall). Accuracy depends on the adopted approach to calculate the effective thermal conductance/transmittance (U-value) including the use of simplified analytical approach, detailed numerical simulation or experiment (Ismaiel et al., 2021). Bodalal (2010) numerically investigated the impact of building envelope construction materials on the thermal performance of residential buildings in Benghazi-Libya using three scenarios. The reference scenario was 12 mm layer of cement plaster followed by a 200 mm cement brick and a 12 mm layer of cement plaster. The second consisted of 12 mm cement plaster, 150 mm cement brick, 50 mm air gap, 100 mm cement brick, and a 12 mm layer of cement plaster. The third consisted of 12 mm layer of cement plaster followed by 250 mm cement brick and a 25 mm decorative color layer functioning as an insulation (mixture of cement and perlite) known as stucco. The results revealed that scenario 3 is the highest thermally efficient construction while the reference scenario, which is commonly used in Libya, was the least thermally efficient among the three scenarios and the walls, windows and roofs contribute by about 70%, 20%, and 10% from the total building fabric load, respectively. Suleiman (2011) estimated the thermal transmittance of external walls and ground floor for an old Libyan house built in 1970. The walls are constructed from limestone bricks joined by mortar covered by inner and outer layers of plaster without any insulation. The ground floor was made of soil enclosed in mortar with tile covering. The estimated transmittance values of external walls were reported to be as high as 3.03 and 5.26 W/m²·K, for soft and hard type bricks, respectively; and the adoption of insulating materials was recommended.

Huang et al. (2013) conducted a study on building envelope retrofitting using thermal insulation of extruded polystyrene (XPS) and high reflectivity coating (environmental friendly acrylic polyurethane) in commercial buildings. The results showed that air-conditioning system cooling load can be reduced when extra insulation and high-reflectivity coating were used. 50 mm thickness of insulation board was satisfactory for economic saving in energy. Alghoul et al. (2016) studied the influence of insulation thickness of external walls of buildings on electricity prices in the city of Tripoli. The results showed that residents were not interested in insulating their homes due to the provision of subsidized electricity tariff of 0.015 $/kWh (2016 price). The annual potential savings was found to be 46.1 $/m² corresponding to 7.9 cm insulation thickness when actual electricity tariff was considered. Fogiatto et al. (2019) studied thermal transmittance reduction in hollow blocks using numerical two dimensional steady state analysis. Five scenarios were tested including; standard configuration without any form of insulation, low emissivity coating on the inner surfaces, cavities filled with insulating material, radiant shields in the middle of cavities, and baffles in the inner surfaces, respectively. The reduction in thermal transmittance was reported to be 68.9%, 44.3%, 22.2%, and 19.1% for polystyrene filling, radiant shield, baffles, and low emissivity coating, respectively. Fantucci and Serra (2020) experimentally assessed the thermal emissivity of different paints containing 0%, 20%, 40%, 50%, 60%, 80%, and 100% of aluminum, respectively. The results showed that emissivity can be reduced from 0.9 for conventional paint (0% of aluminum paint) to 0.6 for 100% of aluminum paint. This resulted in a 35% reduction of overall heat transfer coefficient when compared to non-insulated walls.

Al-Tamimi et al. (2020) used finite element analysis to redesign conventional hollow blocks in terms of optimum air cavities layout and they used rubber, polyethylene and perlite to cast lightweight concrete blocks. The results showed that the obtained optimum design reduced the thermal conductance by 21% and further enhancement was obtained when 30% of perlite used in casting the new concrete block. Alayed et al. (2021) investigated the thermal transmittance and thermal bridging in thermal envelope of Saudi Arabia dwellings. Simplified thermal resistance analogy methods and high precision finite element methods were considered. The first case used the best insulated block used in construction in Saudi Arabia. The second case also used insulated block but with 10 mm mortar joint, and the last case used insulated block with 10 mm mortar joints and structure element influence. The study results showed that the effective U-value in the first, second and third case was 0.48 W/m²·K, 0.71 W/m²·K, and 1.27 W/m²·K, respectively. One solution, proposed in this research to overcome the excessive heat loss without drastically changing the construction process was to apply a 55 mm layer of insulation to the external wall before rendering the façade. On the other hand, William et al. (2021) conducted techno-economic assessment of building envelope performance in different locations in Egypt. Different insulation materials were considered including XPS, polyurethane, glass-wool, and reflective paint. The results showed that the best energy saving was obtained when reflective paint is used followed by a layer of XPS. Other researchers explored the use of recycled materials to improve the thermal performance of building envelope. Krstić et al. (2021) conducted experimentally thermal performance assessment of a wall made of lightweight concrete blocks with recycled crushed brick and ground polystyrene as an aggregate. The mechanical properties of the proposed blocks were verified by (Markulak et al., 2018). The results showed that the thermal conductance of the proposed blocks are 13% and 46% lower than those of hollow clay blocks and hollow concrete blocks, respectively. On the other hand, Cortês et al. (2022) reported a 30% reduction of heating and cooling needs when green vertical systems made of cork were installed as an insulation layer to the building living walls. In this context, Libya is one of the countries that heavily relies on heating, ventilation, and air-conditioning systems due to the inefficient performance of building envelope. The external walls in such buildings are commonly formed from hollow concrete blocks followed by two internal and external layers of plaster without any type of insulation. With the current consuming behavior of Libyan households in the absence of an EEBC, programmed power cuts are unavoidable due to the increased demand of electricity (Mohamed et al., 2015). This outlines the objectives of this research; first, to investigate numerically the coupled heat transfer modes (conduction, convection, and radiation) through conventional external wall structure in Libyan buildings. Second, to reduce the thermal transmittance of the wall structure using some technologies including the application of radiant shield, low-e coating, insulating filling, and external insulation.

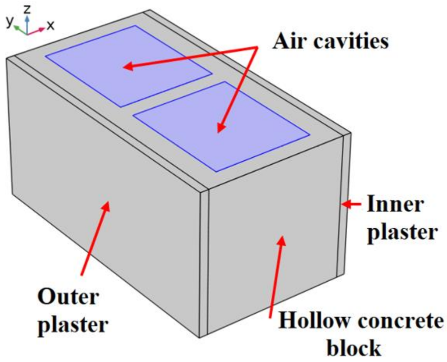

Figure 1. Computational domain

FINITE ELEMENT ANALYSIS

Finite element analysis was conducted in this work using COMSOL Multiphysics® v. 5.5. (COMSOL, 2018) to solve the three-dimensional steady state conjugate heat transfer equations in external wall structure of the building envelope. The computational domain of conventional external wall is composed mainly of standard hollow concrete block (200×400×200 mm) and two layers of plaster (12 mm of thickness) as depicted in **Figure 1**.

Table 1. Thermophysical properties of used materials in simulations (ASHRAE, 2017)

Material	Specific heat, C_p (J/kg·K)	Thermal conductivity, k (W/m·K)	Density, ρ (kg/m³)	Emissivity, ε
Plaster	840	0.72	1860	-
Brick	900	1.11	2300	0.9
EPS	1,450	0.05	11.5	-
Aluminum	900	238	2,700	0.07
Low-e coating	-	-	-	0.4

Table 2. Convective heat flux boundary condition parameters

B.C.	h (W/m²·K)	T_{ext} (°C)
Indoor surface	8	24
Outdoor surface	25	24+ΔT

The air inside the cavities which promotes the free convection mode of heat transfer was treated as laminar non-isothermal flow over the investigated range of temperature difference (Rohsenow et al., 1998). As temperature difference exists between inner and outer surfaces of the wall, the buoyancy term is added to the Navier-Stokes equation.

Continuity equation: $\rho\nabla.\mathbf{u} = 0$

Momentum equation:

$$\rho(\mathbf{u}.\nabla)\mathbf{u} = -\nabla p + \nabla.\mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}\mu(\nabla.\mathbf{u}) + \rho\mathbf{g}$$

where **u**, is the velocity vector and p is the pressure. The constant **g** is the gravitational acceleration, ρ and μ are the temperature-dependent density and dynamic viscosity, respectively. Energy equation is solved to calculate heat transfer in the air and solid materials.

Energy equation: $C_p\mathbf{u}.\nabla T = \nabla.(k\nabla T)$

All thermal properties for air are temperature-dependent inside COMSOL environment (COMSOL, 2018). While the thermophysical properties of materials used in simulations are listed in **Table 1**.

Thermal radiation inside cavities is accounted for in the current simulations using *surface-to-surface radiation model.* The detailed description of the model can be found in (COMSOL, 2018). All boundary conditions were carefully set in the present model. It is worth noting that setting two isothermal boundary conditions on the outer and inner surfaces of the wall neglects the thermal resistance of outdoor and indoor air. Therefore, convective heat flux is applied on the two surfaces of the wall as

$$q_0 = h.(T_{ext} - T)$$

where, T_{ext} is the temperature of external air surrounding the wall surfaces (indoor and outdoor). The indoor air temperature is controlled by air conditioning system. The outdoor air temperature is varied in simulation from 5°C to 25°C above indoor air temperature. **Table 2** summarizes values used in simulations. Remaining external walls are treated as adiabatic.

The mesh is composed primarily of tetrahedral elements, with a boundary layer mesh applied on the fluid side of the cavity walls to resolve the velocity and thermal gradients near the walls. Three mesh sizes with total number of elements counts for 18,688, 31,106, and 77,862 were tested. The intermediate size was selected with a deviation of less than 1.5% in U-value when compared to the finer mesh. Based on the finite element method, the discretized governing equations of fluid flow and heat transfer (continuity,

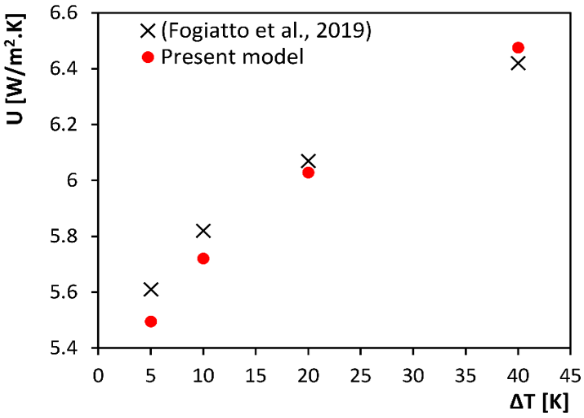

Figure 2. Comparison of numerical model results of thermal transmittance with reference (Fogiatto et al., 2019)

momentum, and energy equations) are solved by segregated solvers using iterative methods which require less memory compared to direct solver in a fully coupled mode. The algebraic multi-grid solver with parallel sparse direct linear solver as a pre-conditioner provide robust solutions for large CFD simulations (COMSOL, 2018). All simulations were performed on Intel® core™ CPU i7-3632QM PC runs at speed of 2.2 GHz with 16 GB RAM memory.

Model Verification

Various studies on thermal performance of building envelope (external walls) were reviewed in the present work. With the current 3D numerical model methodology, assumptions and dimensions, it is not possible to find matching results to compare with. Therefore, 2D simulations were performed at different differential temperatures to compare the results of thermal conductance with the results obtained from reference (Fogiatto et al., 2019). Similar physical domain and boundary conditions were carefully set up for comparison. Good agreement was found as shown in **Figure 2** with maximum deviation of 2%.

This gives confidence in the numerical model and its methodology to carry out simulations. On the other hand, it is believed that the current 3D numerical model is a good representative of the physical problem when compared to the 2D computational domain specially when gravity is considered in the right direction (z-axis) of the 3D air cavity in the hollow concrete block and the cavity vertical walls are correctly selected as in the real construction.

Simplified Method for U-Value Calculations

When predicting the thermal performance of building envelope, steady state R-value is commonly used which is the sum of *thermal resistances* of a composite wall. The thermal transmittance of the material (U-value) is based on The

Table 3. Materials used in the building envelope (external wall) (ASHRAE, 2017)

Material	Conductivity, k ($W/m \cdot K$)	Thickness, L (mm)	R-value ($m^2 \cdot K/W$)	U-value ($W/m^2 \cdot K$)
Plaster in and out	0.72	12	0.016	2.67
Hollow concrete block	1.11	200	0.18	
Outside air film	-	-	0.04	
Inside air film	-	-	0.125	

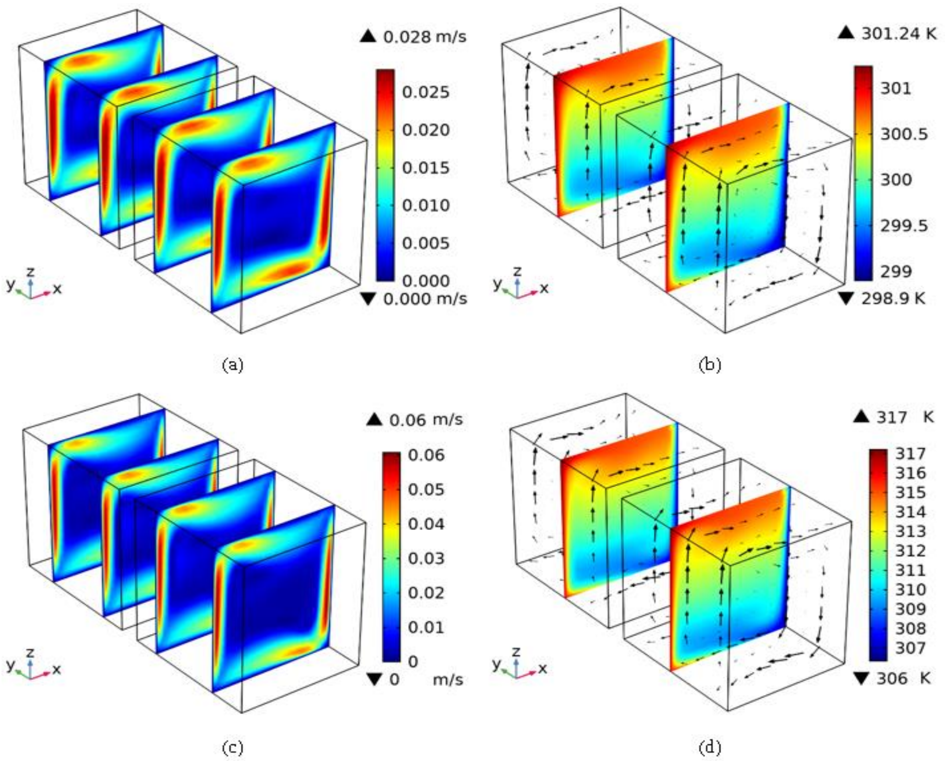

Figure 3. Velocity and temperature distributions in the cavity at ΔT=5 K (a, b) and at ΔT=25 K (c, d)

reciprocal of R-value. The calculated R-value and U-value are listed in **Table 3** for the construction materials used in building external walls in Libya.

$$U = \frac{1}{\sum R_{th}}$$

This gives an adequate reference of thermal transmittance value to be compared with those obtained from simulations for different techniques. However, the current numerical model results are expected to be more accurate than those of simplified method as free convection and thermal radiation inside cavities are considered.

RESULTS AND DISCUSSION

Velocity and Temperature Fields in Cavity

As the external surfaces of the wall structure are maintained at high temperature (left side) and low temperature (right side), buoyant flow is driven in the cavity due to density variation of the air. The velocity and temperature distributions in the cavity are shown in **Figure 3** at temperature difference, 5 K and 25 K. The maximum velocity and temperature of air circulation inside the cavity increases from 0.028 m/s and 301 K (**Figure 3 (a)** and **Figure 3 (b)**) to 0.06 m/s and 317 K (**Figure 3 (c)** and **Figure 3 (d)**) with increasing the temperature difference from 5 to 25 K. Although the air is not a good conductor, it cannot prevent heat transfer by convection and radiation in the cavity. Therefore, one way to reduce the thermal transmittance of the wall structure is controlling the convective and radiative heat transfer inside the cavity

Influence of Thermal Radiation

The simulations were initially carried out by solving all coupled heat transfer modes for several temperature differences between external surfaces of the wall structure. Then, five runs were performed without considering the thermal radiation in the cavities. The results of U-value at different temperature differences were presented in **Figure 4** for comparison between the two cases. It can be seen that the U-value increases almost linearly with the increase in temperature difference for both cases compared to the overestimated constant value obtained from U-value equation. On average basis, the U-values compare to 1.92, 2.33, and 2.67 as depicted in **Figure 4**. With a relatively high surface emissivity of the concrete walls inside the cavity at maximum temperature difference (25 K), thermal radiation is responsible for 21% of total heat transfer (**Figure 5**) through the wall structure and cannot be ignored. The total convective heat transfer contributes by 14% of the total. The significant portion (65%) goes to the conductive heat transfer which highlights the importance of thermal insulation for better performance of building envelope.

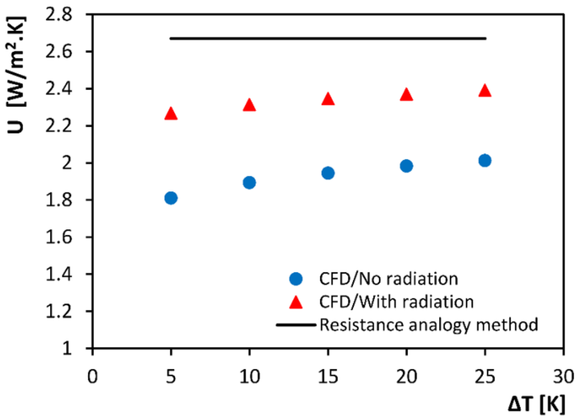

Figure 4. Influence of thermal radiation in cavity on thermal transmittance (comparison of radiation effect at ΔT=25 K)

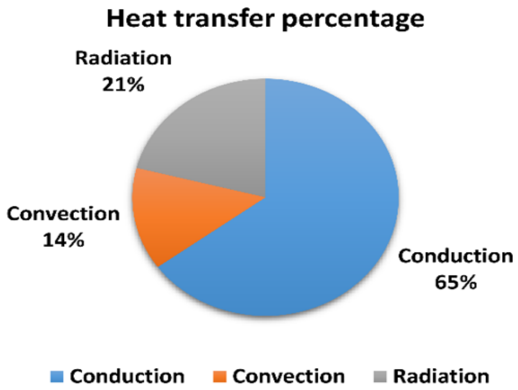

Figure 5. Influence of thermal radiation in cavity on thermal transmittance (heat transfer percentage through wall structure at ΔT=25 K)

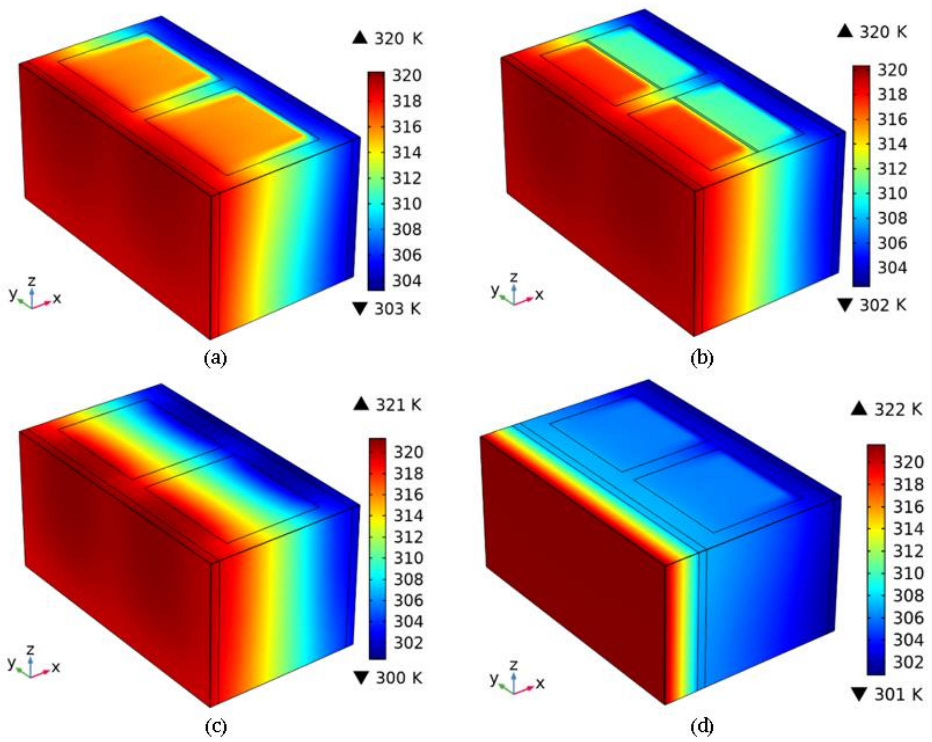

Figure 6. Surface temperature distribution, (a) low-e coating, (b) radiant shield, (c) EPS filling, and (d) exterior EPS

Results of Thermal Transmittance Reduction

Different techniques were compared to reduce the thermal transmittance of the traditional wall structure for saving energy including the application of radiant shield, low-e coating, insulating filling and external insulation. The surface temperature distribution is depicted in Figure 6 for all scenarios. It is clear that the significant part of heat flux occurs in the x-direction.

However, the application of 50 mm layer of expanded polystyrene insulation (EPS) to the exterior wall resulted in the highest reduction in thermal transmittance by 45% compared to the basic wall structure as shown in Figure 7. This is due to the increased thermal resistance of the insulating material. Normally, the optimum thickness is determined from cost analysis. However, a thickness of <50 mm tends to be cost-effective for both heating and cooling (Alghoul et al., 2016; Evin and Ucar, 2019). The second scenario is filling the interior of cavities with EPS. The air cavity is no longer exists to convict heat naturally and more resistance is added to the heat flow resulted in reducing the thermal transmittance by 37%. The third case is the integration of 3 mm aluminum foil as a radiant barrier in the middle of the cavities. The air flow is confined into smaller cavities with lower circulation velocity and the low emissivity of the foil reduces the radiative heat flux which helps reducing the thermal transmittance by 20%. The last case was less effective with a reduction of almost 10% when a commercial coating was applied to the interior of cavities in this study. The surface emissivity of the coating used in this study was 0.4 which is based on the experimental work of Fantucci and Serra (2020). On the other hand, most low-e coatings with surface emissivity <0.4 in the literature (Fioretti & Principi, 2014) are only theoretically verified.

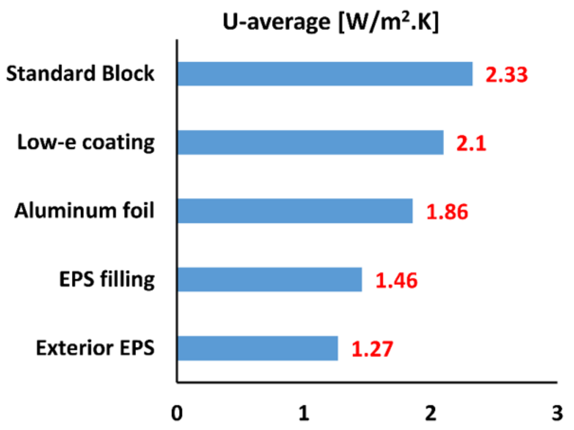

Figure 7. Average thermal transmittance values for all scenarios

CONCLUSION

A three-dimensional numerical analysis was conducted on thermal transmittance reduction of external building walls in Libya for saving building energy. The model methodology was verified with prior experimental studies. The results showed that the thermal performance of the current wall structure is inefficient due to the lower thermal resistance of construction materials. Four techniques were proposed to reduce the higher thermal transmittance of the wall structure. The best thermal performance was obtained when 50 mm layer of EPS was applied to the exterior wall with a reduction of thermal transmittance by 45%. The second best solution was to fill cavities with EPS resulting in a 37% reduction of thermal transmittance compared to 20% of using 3 mm aluminum foil as a radiant barrier in the middle of the cavities. Finally, the adoption of commercial low-e coating with its surface emissivity of 0.4 to the interior of cavities reduced the thermal transmittance almost by 10%. In terms of energy savings, more research is required on using recycled materials as insulating fillings to lower thermal transmittance of building walls.

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Availability of data and materials: All data generated or analyzed during this study are available for sharing when appropriate request is directed to corresponding author.

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