

Thermal performance of advanced material in intelligent concave and convex building façade in the semi-arid climate of low-rise residential

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Abstract – Building energy consumption, creating a comfortable indoor environment, and enhancing building thermal performance, from construction until demolition, are the major issues nowadays. Various strategies and designs are used to obtain a comfortable environment. These issues are considered as factors of emerging fields of intelligent building. Sometimes, they do not require technology. Many old buildings offer intelligent features. Also, it is not supported to define the constructions that are not working well as intelligent buildings even if they are well equipped. Although various intelligent façades are seen worldwide, the context and climate vary from different places. However, few attempts to create them in semi-arid climates are available. The aim is to create a building that provides a more comfortable indoor environment with less energy demand using different advanced materials and showing its response, according to different concave and convex building façade. The subject will be done in three steps, firstly, reviewing the existing and recent studies that determine the factors affecting building thermal performance. Then, studying advanced material. Finally, it investigates the adaptation of the advanced material on the building façade in the low-rise residential building by testing samples of concave and convex building façade in the area. It will show how they perform thermally to get suitable concave and convex building façade. As a result, for the same climatic condition, the different shapes of the buildings will provide various thermal performances.

Keywords— Advanced material, convex and concave façade, energy consumption, thermal performance

I. INTRODUCTION

Nowadays, global energy consumption has become a problematic issue. Till now, non-renewable energy used in all sectors, such as the building sector, the transportation sector., Etc. It causes a dramatic environmental problem and depleting sources. For the sake of decreasing the rate of non-renewable energy,

researchers have suggested different methods in different disciplines, as well as trying to adapt and use renewable energy [1]. In the building sector, there are many proposed approaches to decrease the energy demand. However, modern buildings are becoming increasingly complex. So, it needs extra attention. For obtaining occupant comfort, modern building mostly depends on mechanical systems. Generally, they rely on non-renewable energy, which causes environmental degradation. Therefore, an energy-conscious design is needed to get a desired indoor environment with minimum non-renewable energy use. For this purpose, understanding the building and its climate are the main requirements. The building is exposed to the surrounding area through its envelope. Thus, the building envelope has a significant influence on the indoor environmental condition. So, architectural design has an essential role in obtaining human comfort inside the building. High energy consumption in a building relates to the uses of non-renewable energy, the climatic condition of the area, and non-optimal design criteria such as building orientation, the shape of the building, window to wall ratio of the building, as well as the material properties of the building envelope, Etc [2]. A recent study showed that almost 40% of the energy is consumed by building sectors. It is used for lighting, heating, cooling, and air conditioning [3]. Besides, energy consumption in the building is continuously increasing, as predicted by the international energy outlook [4]. On the bright side, the residential and non-residential building has the second-largest potentials in saving energy. New constructions can save 80% of their power during their operation if integrated design methods are used [5]. In many developed countries with a semi-arid climate, there are attempts to design buildings with energy-conscious design by using different shapes, advanced materials according to climatic conditions. Nevertheless, in many developing countries, particularly in Iraq in almost all sectors, there is no improvement in enhancing the use of renewable energy or proposing new strategies for minimizing energy demand. Mostly, the country depends on oil [6].

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Although the ambient environment is a reason for increasing building energy demand, architectural building envelope designs are regarded as a senior factor in maximizing the loss, if not considered a serious concern. Therefore, this study focuses on the building envelope design, especially the building façade. It manipulates the façade shape and material by implementing smart material on the concave and convex building facade. It is vital to find the relationship between the ambient environment and architectural building design to enhance thermal performance. Most of the concave and convex building façades are designed widely all over the world. However, the purpose of most of them is to promote their aesthetics instead of energy performance. Besides, most of the studies have addressed the energy performance of intelligent material on a flat façade [7]. This paper assesses the material's thermal performance on the concave and convex building façade through the computer-based methodology. A set of convex and concave building forms was modelled and used for simulation. For this purpose, the Ecotect simulation program is applied to study the role of smart material on concave and convex building façade in the semi-arid climate of Iraq. The research first goes through a qualitative methodology by focusing on intelligent buildings and materials on the façade also the factors affecting building thermal performance. Then, it will study the climatic condition of the area to get the quantitative analysis. This paper compares flat and curved shapes without and with integrating the smart materials. The study shows the effectiveness of the advanced

occupant, and technology for human comfort through their response to the surrounding environment. There are several criteria for intelligent building, based on their material, skin, renewable resources, passive..., etc. [10]. Anshuman and Kumar specified the fundamental objectives of intelligent building systems. They categorized it into four categories. The categories are increasing environmental comfort, energy optimization, security, and automated building maintenance procedures [9]. Façade design plays a fundamental role in achieving the mentioned objectives if it is appropriately applied. Additionally, the smart building components are smart systems, smart envelopes, smart shapes, and smart people [2]. Buildings that can maintain their environment to suit the occupants can be regarded as intelligent buildings [11].

Designers, architects, and systems specialists are involved in creating intelligent façade [12]. In the long history of architecture, the facade was a social structure. Currently, building facades have become automatic intelligent because of the smart material and systems [9]. "Intelligent facade is not characterized by how much it is driven by technology, but instead that it depends on the rate of communication between three of the facades, the building services, and the environment" [13]. So, intelligent building façade adjusts itself to users and the weather conditions. Moreover, it protects the interior environment from undesirable climatic conditions and provides more comfortable conditions for the occupant.

III. ADVANCED BUILDING MATERIAL

There is no doubt that building participates in the pollution of the environment on a large scale. Therefore, many researchers focused on the many ways to decrease these pollutions by utilizing innovative building materials. The innovative building material is used to enhance environmental performance, profitability, and safety. New technologies and high-performance materials have been developed to meet these requirements.

Based on their components, construction materials are classified into five groups: ceramic, metal, glass, alloy, and polymer. These materials provide different performances and applications while used in the buildings [2, 14]. Building smart materials are defined in different ways. The broad definition of it refers to its achievement compared to traditional material. Smart or advanced material refers to all new materials exposed to different modifications to get a better result. It is a material that is different from other materials depending on its properties and functionalities, in terms of its mechanical properties, electronic properties, thermo-physical properties, Etc. [14]. Advanced material is divided into dynamic responses and fixed responses [2]. The first one acts as a living system capable of sensing and functioning according to the building's environment. The second one which the research focused on is named Nano-materials. It is a material with a nanometre-scale substructure [15]. It is a "Materials which have one or more external dimensions or an internal structure which can

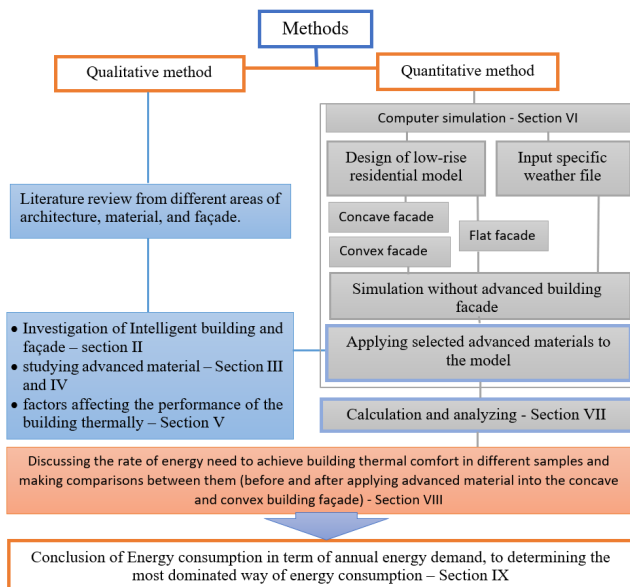


Fig. 1. Illustration of the research method.

material and building geometry on residential thermal energy saving. Figure 1 shows the outline of the research.

II. INTELLIGENT BUILDING AND INTELLIGENT FAÇADE

Recently there have been many publications issued about intelligent building and its definitions [8, 9]. There are more than thirty different definitions [10]. Overall, intelligent buildings combine ambient environment,

exhibit new properties compared to the same materials without the nanometric characteristics" [14]. Nanomaterial products by Nanotechnology improve the functionality of the materials [14]. Nano-products are broadly used for nearly all building components, elements, systems, structures, and materials such as steel, concrete, paints, and insulation materials. There are numerous types of Nano-products and materials created by the use of nanotechnology for different purposes. Nanomaterials have been created for various purposes. It is made for structural purposes, such as concrete and metal. It is used for increasing the durability of the material by protecting it from the outside environment, such as coated plastic by a special kind of growing chemical material called "Zirconia nanoparticles". It is also produced for the insulation purpose of both buildings' opaque and transparent parts [16] to resist heat flow. It is used for improving the lighting system, like a self-cleaning material, besides its benefit in grasping the solar energy and converting it to the other type of energy (photovoltaic cell). Based on the aim of this paper, nanomaterials are tested, which are used for insulation purposes.

IV. NANO INSULATION MATERIAL

Nanotechnology creates a unique material that is uncommon in its properties, and nanomaterials are one of these achievements [7]. There is constant progress and achievements in Nano-insulation material products, especially in the 21st century. In general, there are four types of Nano-insulation material, which are Expanded polystyrene products within graphite powder additive, Aerogel insulation material, Nanoparticle-based vacuum insulation panels, and Nano-ceramic thermal insulation coatings [16]. Expanded polystyrene products, including graphite powder additives, are products used on both walls and roofs. The thermal conductivity of expanded polystyrene products with graphite powder additive, 20% lower when compared with traditional expanded polystyrene products [16]. The second one is used in the transparent parts of the building [2, 16]. Vacuum insulation products are used in non-transparent parts of the building. It gives better insulation performance compared to conventional materials. It is available in different shapes according to its application, like insulation panels and sandwich panels. Vacuum insulation panels are more flexible to be installed in any part of the building, such as facades, roofs, floors. The fourth type is Nano-ceramic thermal insulation coatings. It has many properties such as flexibility, non-toxic, resistible to fire, washable, environmentally friendly, and creates a membrane that infills cracks. It can stick on different surfaces such as concrete, plaster, and metal [16, 17].

V. FACTORS AFFECTING THERMAL PERFORMANCE OF BUILDINGS

The definition of building thermal performance is the procedure in which energy transfers between the building and its surrounding [18]. The heat exchange between the inside and outside of the building is a factor in building energy flow. It is directly related to the thermal properties of the material and the area of the structure [19]. Thermally, the quality of a building depends on the amount of energy that the building needs in the year to provide occupant thermal comfort [20]. Many concerns should be taken into consideration to get the ideal building thermally. One of them is a suitable building form, which can be made by creating the balance among the shape of the plan, floor area, the height of the building, and surface area to volume ratio. It is not easy to find the optimum forms unless the main factors are taken, such as form, orientation, material, and climatic consideration [21]. Notably, selecting an appropriate building configuration and orientation can decrease 40% of energy consumption [8]. Many factors are affecting building thermal performance. They are the design variables, material properties, weather data, and building usage [18].

Design variables such as building shape, shading, and orientation of the building. The outer skin of the building isolates inside and outside the building. Thus, selecting a suitable building form according to its context and orientation can control total heat exchanged between inside and outside. Any change in the building's shape influences the pattern of wind flow and the ratio of incidental solar radiation on the structure. Building shading plays a vital role in decreasing or increasing building energy consumption in semi-arid and Mediterranean climates. The material properties of the envelope also have a significant impact on heat gain and the overall heat transfer coefficient. So, selecting materials for building envelopes should be carefully studied because they must be decided based on specific requirements, especially thermophysical parameters of the materials [18]. Also, the climatic condition influences building energy performance. It needs many special precautions to achieve a comfortable living. In this study, semi-arid (Steppe) was used. It is characterized by hot, long summers and low rain in the winter [22].

VI. METHODOLOGY

Coping building envelopes with the surrounding environment has an immense effect on reducing energy consumption while maintaining high levels of indoor environmental quality. It can be examined with the use of

building performance simulation [28]. The paper used the term curvature to describe the degree of concavity of the curved facades. It depends on the dimensions of the cross-section. The dimensions are height, depth, and width [29]. Several vertical stripes are used to generate convex and concave shapes in the software. The more precise result could be obtained by increasing the number of vertical strips [30]. The simulated plan area is 100 m² with 0.1 and 0.2 curvature. Figure 2 shows the degree of curvature in both concave and convex building façade and the base model (same building area, window area, different building façade shape).

The building was designed with the same building volume and area with three different materials and shapes. The shapes are flat, concave, and convex front façade in several degrees. Four different samples of the wall were designed, as shown in Table 1.

The thermal properties of the materials investigated and

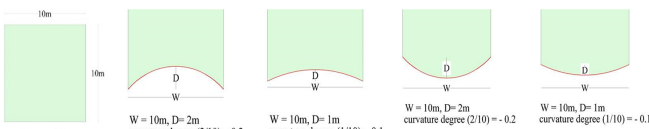


Fig. 2. Degree of curvature in both concave and convex building façade and the base-model (same building area, window area, different building façade shape).

TABLE I

WALL MATERIAL DESIGN; ITS THICKNESS DERIVED FROM [16, 17, 31]

Model 1 (m1)	Model 2 (m2)	Model 3 (m3)	Model 4 (m4)
1.5 cm Cement plaster	1.5 cm Cement plaster	1.5 cm Cement plaster	0.2 cm Nano-ceramic Thermal Insulation Coating
12 cm Brick masonry	12 cm Brick masonry	12 cm Brick masonry	1.5 cm Cement plaster
5 cm Polystyrene foam	5 cm Vacuum insulation panel	5 cm Expanded polystyrene products +graphite powder additive	24 cm Brick masonry
12 cm Brick masonry	12 cm Brick masonry	12 cm Brick masonry	1.5 cm Gypsum plaster
1.5 cm Gypsum plaster	1.5 cm Gypsum plaster	1.5 cm Gypsum plaster	

studied depend on the previous studies. Table 2 shows the types of nano- insulation material and conventional insulation material used.

The research used four main orientations (South, East, North, and West). Some of the Iraqi cities are located under a semi-arid climate. Erbil city was selected. It is one of the largest cities located in the semi-arid zone of the country. Rainy and cold winters and dry and hot summers are the characteristics of the studied area. The annual temperature is 21.85 degrees, and the air temperature reaches 49 °C on the hottest day [32].

VII. RESULTS

This study gives the results and discussions of the thermal analysis of houses having one story with different façade, insulation materials, and orientations. The layers of the wall are cement plaster+ masonry brick +insulation material + masonry brick +gypsum plaster. All the layers

TABLE I
PROPERTIES OF NANO-INSULATION MATERIAL AND CONVENTIONAL INSULATION MATERIALS USED. THE VALUES DERIVED FROM [16, 17, 31]

Type	Density- kg/m ²	Specific heat- kj/kgK	Thermal conductivity – W/MK
Conventional insulation material	36	1130	0.033
Vacuum insulation panel	300	800	0.010
Expanded polystyrene products including graphite powder additive	30	1130	0.033
Nano-ceramic Thermal Insulation Coatings	300	1080	0.014

are fixed in the models, and only the insulation layer is changed to (Polystyrene foam, Vacuum insulation panel, expanded polystyrene products with graphite powder additive, and Nano-ceramic thermal insulation coatings). ECOTECT simulation program with the Erbil weather file was used to obtain the results. The study examined the simulation results in steps. The study first analyzed Nano-insulation and conventional insulation materials and four different curvature façades and flat façade in four main orientations. Finally, all obtained data were compared.

A. Simulation result of the material

The difference between polystyrene foam and expanded polystyrene products with graphite powder additive, representing M1 and M3, respectively, is low. The difference between them is around 2%. Furthermore, houses with conventional insulation material (M1) consume more energy than Nano-insulation material (M2). Thermal consumption of the structure with conventional insulation material is 7.5% lesser than a non-insulated coating. This percentage changes according to the orientation the value becomes higher. The thermal load of conventional insulation material for 0.2 concave façade with northern direction is 16% lesser than when compared with non-insulated coating.

B. Simulation result of orientations

According to the flat façade, the best orientation is south. However, for all curved models, the north orientation is the best one because it decreases cooling load in summer. These curvatures minimize solar radiation on the façade in summer. Also, the Western orientation is determined as the worst one in all the models, as demonstrated in Figure 3. The Western orientation gets high solar radiation in summer and a lower rate in winter, so it needs a higher cooling load in summer and a higher heating load in winter than other orientations. The percentage of thermal load in the North is 8% less when compared with the West. Thus, because it has minimum exposure to solar radiation in the summer season, it needs a minimum cooling load.

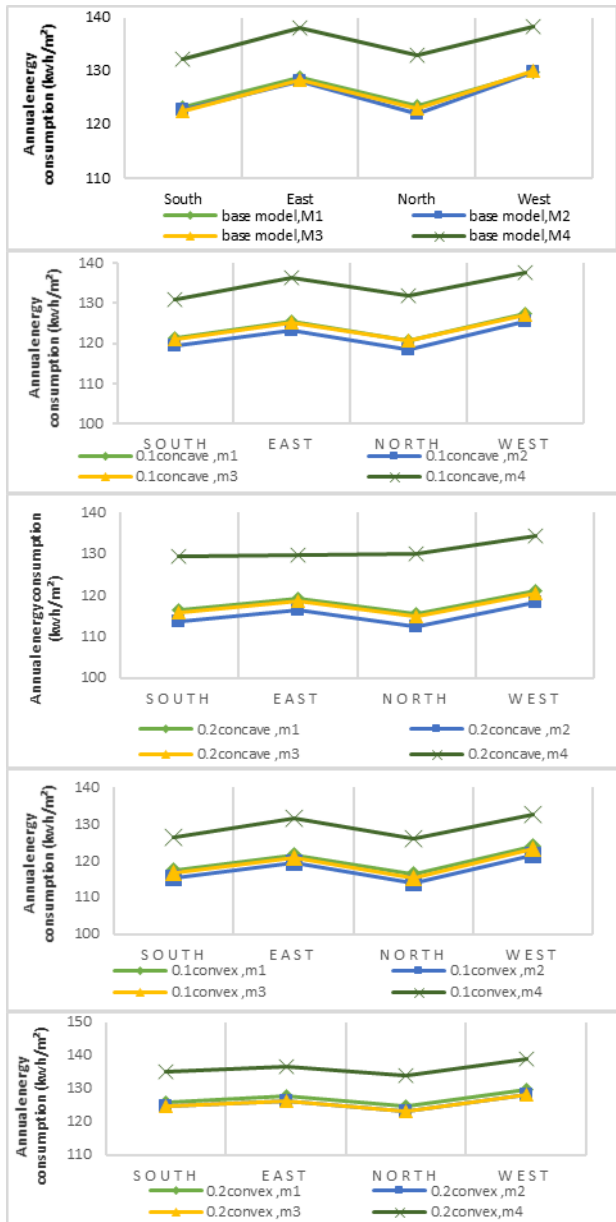


Fig. 3. Energy performance of different insulation material in a different orientation, Flat façade, 0.1 concave façade, 0.2 concave façade, 0.1 convex façade, 0.2 convex façade, respectively.

C. Simulation results according to the seasonal period

Generally, in the semi-arid climate of Iraq, the cooling demand is around 61% higher than heating. Furthermore, Figure 4 illustrates the differences between the heating and cooling loads in different façade shapes and orientations. Thermal load in each season varies according to its direction according to the sun. For the cooling period, the best orientation is North, while during the summer, south orientation requires minimum energy demand.

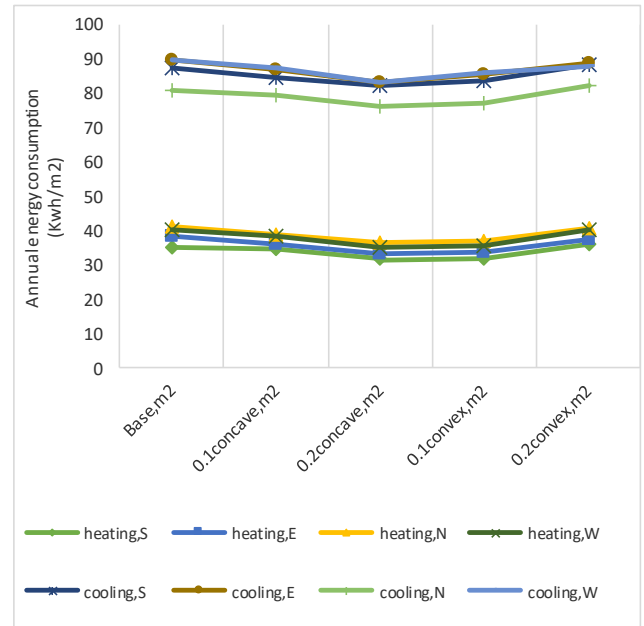


Fig. 4. Differences between the heating and cooling loads in different façade shapes and orientations.

D. Simulation result of façade Shapes

Façade shapes provide the different thermal performance of the buildings due to the different periods and patterns of the incident solar radiation on the façade. As a result, it produces a variety of shading patterns on the facades. So, the shading leads to a decrease in cooling load in summer and increased heating in winter. Concave façade decreases thermal loads in the buildings, and the decreasing gets to its minimum by increasing the degree of the concave curve from 0.1 to 0.2, so it can be said that concave façade with 0.2 degrees has minimum energy performance when compared with others as shown in Figure 5.

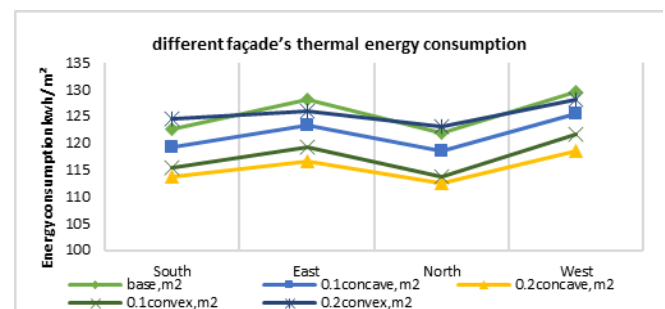


Fig. 5. The thermal performance of different façade shapes with four orientations

Due to the increasing shading area, it decreases cooling load in summer, which plays a vital role in the overall thermal performance of the houses. 0.1 convex façade more efficient than 0.1 concave. But by increasing the degree of curvature from 0.1 to 0.2 the efficiency of the façade will be opposite. In a way that the efficiency of 0.2 convex will be lower than flat façade especially in north and south orientation. Therefore, a convex façade shape with 0.2 degrees is assumed to be the worse shape compared with the others.

VIII. DISCUSSIONS

Occupant comfort varies in the building like visual comfort, acoustic comfort, lighting and safety, but this paper focused on thermal comfort by evaluating thermal energy demand. Generally, when the types of insulation material change, comfort level changes too. It depends on its thickness and thermal properties. The best nanomaterial insulation is a vacuum insulated panel. It means that by using the Vacuum insulation panel, the overall thermal property changes for the better. It enhances inside building comfort. The less effective Nano-insulation material is nano-ceramic thermal insulation coatings. Even so, its thermal performance is lower than conventional insulation material due to its thickness. The conventional insulation material of Polystyrene foam is around 5 cm, but the maximum thickness of the Nano-ceramic thermal insulation coating is only 2 mm. By increasing the degree of curvature of the concave façade, the performance of building thermal performance improves. It relates to the increasing self-shading during hot days during the cooling season. Annual energy demand increases if the curvature of the convex facade changes from 0.1 to 0.2 because it is more exposed to the surrounding environment.

By modifying the shape of the front elevation, housing energy demand changes as well. It means that the façade shape has a significant effect on the energy demand of the houses. If concentrating on the seasonal thermal energy demand, the desired orientation for winter and summer is south and north, respectively, because of the rate of incidental solar radiation on the façade. In the southern orientation, the building gets maximum solar radiation that decreases heating energy demand on the houses. The contrast is true for cooling demand. There are no doubt designers and architects use strategies to decrease thermal energy consumption in the building, like installing shading devices, window design, and many other techniques. This research focuses on the thermal energy demand of the houses. So, a more detailed conclusion on the building shape has been investigated. The study analysed the building geometry based on the shading pattern on the façade. It is shown in Figure 6. The way of shading varies according to the degree of curvatures. At 9 AM flat façade was exposed to the sun radiation. While curvature façades are more protected from sun rays than flat façade, more desirable in the long summer days. The

shading in 0.1 curved façades is almost the same for the convex and concave front elevation. The same is true for the 0.2 curved façade. The inner curved façade is more efficient thermally than the convex façade because it protects the building from the warm and cold wind in summer and winter. High degree of outer curved façade is less efficient than flat façade although the façade is more protected from solar radiation. The outer curved façade is more exposed to the undesirable wind in the winter and summer season.

IX. CONCLUSIONS

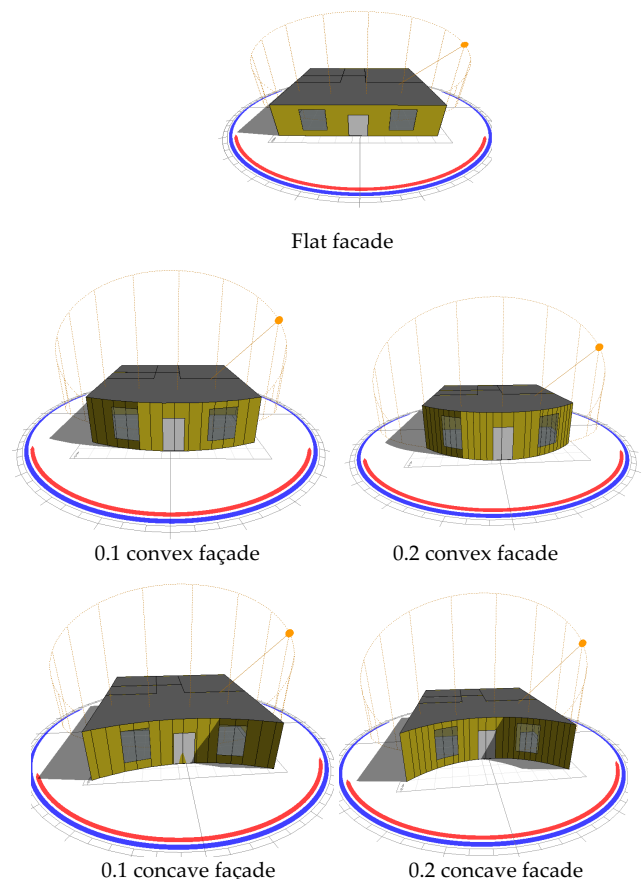


Fig. 6. Shading pattern on the façade at 9 AM on the hottest month of the year.

As mentioned earlier, many factors influence building thermally: design variables, material properties, weather data, and building usage data. The study has selected one point in each factor: curved façade, wall insulation material, and semi-arid climate on low-rise residential buildings. Through the review and examination of this research, energy consumption is an important issue nowadays. There are many efforts in minimizing thermal energy consumption. Architectural design is regarded as one of the efforts.

Based on the results from the thermal analysis of the models, it can be concluded that the thermal consumption of the building changes by changing the insulation materials, orientation, and façade shape. The Nano insulation material is generally more efficient than conventional insulation material except for Nano-ceramic thermal insulation coatings, which give maximum thermal

load due to its thickness. Moreover, the most efficient material is a vacuum insulated panel.

Orientation plays a vital role in decreasing the total thermal load. According to the curved shapes, the North orientation is preferred over the others because it needs low cooling demand. Semi-arid climate characterized by long, hot summers, Northern building orientation has a lower chance of gaining solar heat. However, for a flat façade, a south orientation is preferred. Moreover, The West orientation is considered the worst because it needs higher cooling and heating demand. Building energy demand increase with an increasing degree of convex curvature because of the negative effect of shading on the façade. Convex façade with 0.2 degrees needs a maximum thermal load. A higher inner curved façade requires a lower thermal load because of the positive effect of shading on the front façade. A concave façade with 0.2 degrees provides a minimum thermal load.

This research suggests that in a semi-arid climate, the inner curved is better than flat and outer curved façade. Nano-insulation material is better than conventional ones. In the steppe climate, the houses should be designed according to the summer season. This climate has a long summer with a very high temperature and a short winter period with moderate to cold weather. In the final, façade shape, material, and orientation are the main factors in saving energy in the entire life cycle of the buildings. With the thermal energy design, exposure to solar radiation and wind play a prominent role. For steppe climate, more self-shading and less wind exposure during hot and cold seasons of the year are essential. The air became too hot in the summer season and too cold in the winter season.

For future study, the effect of Nano-insulation of the curved shape in different climates could be examined, especially in cold and humid climates. They have distinct weather characteristics which might change the result. Likewise, different building types could be investigated, like seasonal buildings such as schools and large-scale structures. Unlike houses, school buildings have winter operations. It means the heating load plays an essential role in saving energy rather than the cooling load. Moreover, examining lighting energy demand can be investigated with different curved buildings.

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