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Assessment of the Intermediate Cavity Impact on the Cooling Energy Performance of the Multi-Story Double-Skin Facade in Hot and Humid Climate (Kish Island)*

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ABSTRACT

The majority of the energy exchanges in buildings are dependent on or at least related to the exterior skin of the building. The exterior skins are the localities of the building's heat exchange with the peripheral environment, solar energy absorption, ventilation, and light and sound infiltration to the interior environment. These spots play an important role in energy savings in buildings. The double-skin facades have been considered a solution to create transparency, control the effect of the environment on the building, and its useful performance in terms of climatic consistency and energy consumption. Given the heat pileup problems stemming from the greenhouse effect of the intermediate cavity, especially in hot and humid climates; it was deemed necessary to carry out a study to figure out the optimum clearance between two skins to reduce energy consumption. The present study is conducted using information collection, simulation of case study with Design builder software, and analysis of the quantitative data obtained from the simulation of the studied buildings in the hot and humid climate of Kish Island. The multi-story DSF is simulated at various distances between the two skins to investigate the amount of cooling energy consumption. The research findings show the amount of cooling energy used at cavity intervals of 30 to 200 centimeters. The research theoretical foundation is laid on the idea that the southern front of the multi-story DSF, compared to the various types of DSF, has a considerable effect on the optimum conditions of the reduction in energy consumption. The results of this study indicate that the cavity depth plays an important role in the reduction of cooling energy, and a double skin facade with the depth of 50 to 70 centimeters is the optimum distance in reducing cooling energy consumption, compared to other intervals in the low-rise office building in the hot and humid climate.

Keywords: Double-Skin Facade, Intermediate Cavity, Consumed Cooling Energy, Hot and Humid Climate.

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1. INTRODUCTION

Energy saving in buildings and environmental pollution are two important concerns in architecture, which have attracted considerable attention. The façade, as a part of the construction associated with external factors, plays an important role in energy performance and comfort in
the building. In fact, the facade is the common element that forms the interior and exterior of the building, and hence it is responsible for several concerns such as heat loss, solar heat absorption, daylight, and daze control (Jafari, Khyrossadat, & Mirhosseini, 2017, p. 8)
The exterior skin of the building can be designed to meet different environmental, technological and structural, sociocultural, functional, and aesthetical needs. And, this requires the consideration of numerous factors, including the external environment and micro-climate conditions, interior environment, the spatial characteristics and residents' needs (Halawa, Ghaffarianhoseini, Ghaffarianhoseini, Trombley, Hassan, Baig, YusmahYusoff, & Ismaile, 2017, p. 3).
To regulate the interior environment of a building, a route is selected in the external wall to work with the weather, i.e. to respond to the heat, cold, ventilation and the natural light needs. This necessitates the determination of physical processes and plays a key role in the general building energy performance. Heat transmission controls the solar radiation and air stream, so the required conditions for the provision of daylight and ventilation should be balanced according to the proper thermal protection in proportion to the climatic conditions (Haggag, 2007, p. 290).
According to the tendency of modernism to remove walls, the use of glass was increased to maintain the building transparency. Knowing that the glass possesses low thermal resistance and this results in higher thermal energy wastage, the application of the double-skin façade, meanwhile reserving transparency, is a solution to energy saving, resulting in the higher efficiency of building walls (Halawa, Ghaffarianhoseini, Ghaffarianhoseini, Trombley, Hassan, Baig, YusmahYusoff, & Ismaile, 2017, p. 12) as well as allowing the regulation of heat, cold, light, and sound in such a way that the lowest amount of energy is used (Klein, 2013, p. 37). As underlined by Hendriksen, "transparency is most predominantly proposed as the most important architectural reason for the use of double-skin façade for its provision of close contact with the peripheral space" (Hendriksen, Sorensen, Svenson, & Aaqvist, 2000, p. 64).
Therefore, according to the aforementioned discussions and considering the importance and performance of the building wall and, in between, the effect of double-skin façade on the amount of energy absorbed, the main question of the study is whether the clearance between the two skins plays an effective role in the amount of energy use, temperature reduction and, finally, thermal comfort knowing the optimal performance of the multi-story double-skin façade in hot and humid climates.

2. LITERATURE REVIEW

The application of DSF is an interesting solution to control solar heat gain and thus enhance the energy-efficient design of the glazed buildings, in addition to aesthetics aspects (Qahtan, 2019, p. 2).
There are various definitions of the DSF System.
Oesterle et al. gave the most comprehensive definition of DSF. For the author, a double skin façade consists of amulti-layered façade envelope, which has external andinternal layers that contain a buffer space used for controlled ventilation and solar protection (Ahmed, Abel-Rahman, Ali, & Suzuki, 2016, p. 84).
Slenz defines DSF as "a façade structure that incorporates two transparent surfaces separated by an intermediate cavity that is used as an air canal".
Many studies on DSF were carried out in different climate regions to examine the appropriateness of the system in enhancing the indoor environment of the glazed buildings. The study investigated the energy performance of DSFs in two different climates, i.e. temperate and warm regions. The west facings of DSFs were compared. The study concluded that DSFs are more suitable for temperate climates than the warmer one. It also found that DSFs are capable of almost 50% energy savings in temperate and 16% in subtropical climates (Qahtan, 2019, p. 2). It is deemed logical to choose it for hot weather because the main goal is to keep the heat outside. Heating the inter-skin space and then ventilating the hot air, much of the solar energy can be prevented from entering the residence space (Klein, 2013, p. 146). The use of DSF has been mostly considered for reducing or depreciating the solar heat absorbance coefficient (Farrokhzad & Nayebi, 2014, p. 66).
The function of the DSF, as a passive solar system, encompasses elements similar to the constituents of the greenhouses and the only difference is that the intermediate cavity is not livable. The sunlight hitting the exterior skin will be partly reflected, absorbed, or led through. The solar rays passing through the exterior skin are absorbed by the interior skin, and at that point, the temperature goes up. Then, it is emitted in various directions. After a while, the temperature of the exterior glass wall increases due to absorbing the beams of the intermediate cavity as well as part of the sunlight. Now, part of these absorbed beams is emitted on both sides of the glass, and part of this irradiation is entrapped in this way, resulting in the increase of the temperature of the interior space air due to the transitional conduction between the walls and the inter-skin air.
The varied types of DSFs common in practice reflect the need to make a balance between thermal performance, visual comfort, and varying climatic conditions. The main differences lie in the spatial configuration of the two skins, the depth of the air cavity (ranging from

200 mm to more than 200 cm), the way this cavity is ventilated (either by natural or mechanical ventilation, or by a combination of both); the type of glazing used for each of the skins and the integration of shading devices into the system (Aleksandrowicz & Yezioro, 2018, p. 1).

Double-skin façade is comprised of the following layers:

1) External glass: these glasses are usually single-glazed, hardened; they are offered in thicknesses higher than the other glasses. The exterior façade can be completely made of glass (Afshin mehr, Aref, & Shanesaz, 2015, p. 79).

2) Internal glass: this layer can be made of glass in parts; it is usually made of double-glazed insulated glasses and/or laminated glass that can better reflect light. These glasses can be opened or shut by the user, so it is possible to naturally ventilate the interior space of the building (Ibid, p. 79).

3) The intermediate air-filled cavity between the two glasses: the cavity between the two skins can be ventilated completely naturally or mechanically. The width of the separating space usually ranges from 10cm to 2m and such breadth is most effective when the façade acts as a supporter (Mulyadi, 2012, p. 25).

4) Solar Shade Equipment: the vast use of glass in the exterior skin means that direct access to the solar light causes a larger deal of sunlight to enter the interior spaces. This causes the discomfort of residents and disorders their activities during the hot seasons of the year. The most ordinary way of protecting the building against direct sun radiations is to install the shades in the intermediate cavity between the two layers of the façade (Ibid, p. 18).

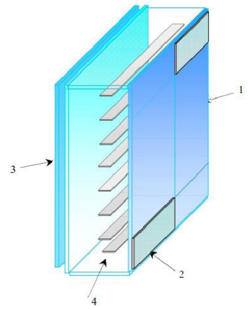

Fig. 1. An Overview of the Double-Skin Facade: 1) Exterior Single-Glazed Hardened Glass Skin; 2) Manual or Mechanical Baffles; 3) Interior Usually Double-Glazed Glass Skin (with Low E Coverage); and 4) Shading System Installed on the Intermediate Cavity between the Two Skins
(Lembo, Marino, & Lacava, 2009, p. 198)

2.1. The Depth of the Inter-Skin Space (Cavity Depth)

Façade depth takes various values. In the existing buildings, most often the ranges are from 200mm to 1400mm in a face-to-face manner between the interior and exterior skins. There are three dominant styles for this depth. In the compressed style, the distance between the two skins is in a range between 200mm and 500mm. In the second style, the clearance is regulated so that the surfaces in the façade slit can be distinguished. The third style, or the so-called wide style, is about a meter or broader. In this style, the slit space can be also utilized as a fire exit duct. In fact, the latter style is an extension more similar to an atrium-like space (Afshin mehr, Aref, & Shanesaz, 2015, p. 79).

The basic operation of a DSF is due to the stack effect that occurs in the cavity. Inside the cavity, the air is heated by a heat transfer phenomenon that promotes a difference in the density of the air circulating: the heated air is expelled through the upper opening of the device and the fresh air enters the cavity through the lower opening. The entrance and expulsion of the air in the cavity of the façade can occur naturally or mechanically with the use of fans and exhaust fans (Souza, Souza, & Rodrigues, 2018).

Sterly offers a broad explanation of the performance of and the airflow in the cavity in relation to the structural factors: “there is a considerable pressure drop only when the cavity between the façade walls is not deep (below 40cm) otherwise the intermediate space does not offer much resistance to air current” (Poirazis, 2004, p. 39).

Since the interactions and effects of various elements on one another influence the performance of the cavity, modeling and simulation of the cavity between the double-skin façade is a complex task.

From the results of the modeling works, it can be concluded that the depth variations have a considerable effect on the quality and velocity of the airstream inside the cavity. In a case where the heat convection coefficient of the glasses is controlled and the double-skin façade is correctly insulated, depth changes of the intermediate cavity space can bring about a difference of about 6ºC to 10ºC for various depths. On the other hand, in unventilated DSF, as well, the more the intermediate cavity depth, the more the air volume needed to be heated by the radiations passing through the exterior wall (using the greenhouse effect). This can per se lead to the lowering of the temperature inside the cavity. However, it does not mean the improvement in the DSF performance because it disorders the thermal performance of the skin under cold conditions.

Of course, to determine the optimum depth, it has to be noted that the height, as well as the length of the skins, are of great importance in determining the cavity depth. In the meanwhile, the dimensions of the space connected to the DSF, as well, influence the performance of these facades to a large extent. Moreover, making a decision on the cavity depth is also subject to the effects of such other cases as:

• Enough space for shading equipment and structural elements should be provided.

• The interior space of the cavity should be accessible for washing and repairs.

• The cavity should not act as a duct for dispersing pollution or fire expansion to the other floors.

It has to be noted that each project has its own specific depth in relation to the conditions, heights. and the volume of the air therein. Therefore, an optimum balance should be created between the height and depth in DSF so that the inflammation could be prevented (Hadian pour, Mahdavi Nejad, & Bemanian, 2014, p. 36).

2.2. Research Background

There is a scarcity of research on the design of double-skin facades in hot and humid climates. According to the advantages of using such a system in controlling the building front in such countries as China, Malaysia, and the countries in the southern margin of the Persian Gulf, there is a growing body of research in progress on DSF in these countries. Considering the appropriate situation and climatic similarities in Kish Island, these studies can be benefitted in designing building facades in these regions.

Gratia and De Herde (2007) examined the cavity temperature at intervals of 30, 60, 120 and 240 cm using the TAS software in Belgium, and concluded that the temperature in the deep cavity was slightly less than the double-skin facade with a lower depth (Gratia & De Herde, 2007).

Pekdemir et al. (2012) explained that the depth of the DSF cavity is significantly affected by the excessive heat function in the cavity. Also, the climate has a greater effect on the cavity depth or its classification (Spastri, Noble, Kensek, & Choi, 2015, p. 839).

In a study on the natural ventilation of the DSFs in hot and humid climates, Mulyadi concluded that the naturally ventilated DSFs are effective in minimizing the heat absorption in respect to single-skin facades and that the clearance between the interior and exterior skins is an important factor in reducing the heat conduction and absorption by 50% (Mulyadi, 2012, p. 119).

In a study using Fluent software, Rahmani et al. (2012) have studied the depth of DSF at intervals of 30, 50, 100 and 150 cm in Malaysia and concluded that increasing the size of the cavity to one meter reduces solar reception in the building, and also, it reduces the efficiency of the DSF (Rahmani, Kandar, & Rahmani, 2012).

Radhi et al. (2013) simulated an example in the UAE with natural ventilation at intervals of 50,70, 100, 120 and 150 cm with the Design Builder and Fluent software, and stated that narrow cavities strengthen the effect of the chimney, and the movement of the stronger air leads to the extraction of more hot air through the cavity. On the other hand, the depth of the large cavity (more than one meter) reduces the effect of the chimney, and the heat transfer increases near the internal rooms, thus the depth of the cavity between 70 and 120 cm can create a balance between the air output and heat transfer in the interior (Radhi, Sharples, & Fikiry, 2013, p. 186).

According to the review of studies carried out in hot and humid climates, it can be concluded that there is no study on the effect of various depths of the intermediate cavity on energy consumption (cooling) in hot and humid climates. Thus, relying on the prior research indicating the optimal performance of the southern front of the DSFs, the present study deals with the role of the DSFs' intermediate cavity depth in reducing energy consumption following which the optimum distance between the skins will be also examined.

3. METHODOLOGY

Determining the distance between the interior and exterior skins and the most appropriate to obtain the highest productivity is largely dependent on the quantitative research method. In this study, the simulation method and case study have been used to examine the optimum distance between the two skins. To do this, simulation instruments were applied to assess the effect of various distances between the two skins on the amount of energy consumption in a building. The first step taken in this study is to collect the information required for advancing the research on the study topic. The information includes climatic data of Kish Island and the information related to the studied building. The simulation software applied in the present study is Design Builder which is a software package used for performing thermal analysis on a building and it measures the effects of the environmental factors on the building; also, it can calculate the amount of energy consumed per hour, day, month and year based on the climatic information. Energy-Plus Analyzer Engine is used in this software and zonal numerical methods are applied to solve the energy equations.

3.1. Simulation

To investigate the optimum distance between the two skins, the case sample was simulated in a single-skin façade and then modeled in a double-skin façade in a distance range of 30cm to 200cm. Next, the energy consumption rate was evaluated. Then, the various investigated distances were compared to select the optimum depth in terms of energy consumption.

The followings are amongst the conditions and presumptions taken into account in the modeling:
1) The modeled DSF is of the multi-story type that was evaluated to be installed in the southern front.
2) The glass and masonry specifications were considered fixed based on the current statuses of the project site.
3) The openings were also considered fixed and shut.
4) The Cavity Ventilation of double skin façade in case studies is natural.

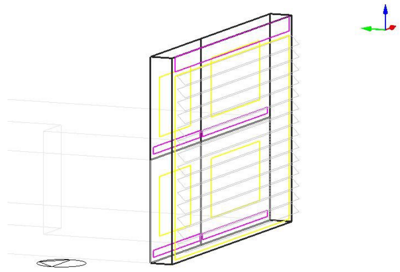

Fig. 2. Air Inlet and Outlet Valves in Simulation

Furthermore, to facilitate the study and analysis process as well as the comparison of the various distances, air entry and exit were considered in the form of static air buffer for natural ventilation.
In the present study, the Kish Climate File was written using the Meteonorm software. Therefore, hourly weather information, along with latitude and longitude, is provided in the form of a suitable climate file (Epw File) as an input for the Design Builder software. In order to solve the equations in the desired time step, the necessary analyzes are performed.

3.2. Case Study

The studied buildings, with an administrative land-use, are located in the northern and eastern regions of Kish Island, along a north-southward and east-westward stretch and they have windows in four fronts. The simulations were conducted for the southern front.

Table 1. Features of the Residential Facilities System

Energy Sources	Electricity for Cooling and Natural Gas for Heating
Utilities System (HVAC)	Condensation chiller for cooling, hot water coil for heating
Lighting	An average of 250 LUX (for cor-ridors 150-200 /for rooms 300-400 LUX)
Ventilation of the Interior	0.7 Ac/h
Time of Use	7 - 16 on Saturdays and Sundays. 7 - 13 on Thursday

Table 2. Architectural and Physical Features of Case Studies

Specifications	Building 1	Building 2
Plan Geometry	Rectangle	Rectangle
Plan Proportions	2.7	1.7
Plan Dimensions	31.2×11.6	20×11.5
Space Layout Plan	Free	Free
Height of Floors	3.5 m	3.5 m
Number of Floors	G+2	G+4
Floor Level	360.7 m2	230 m2
Rotation Direction	North-South	East-West
Skeleton and Core Type	Concrete	Concrete
Number of Users	100	110
Occupancy Level of Users	918 m2	993.7 m2
Occupancy Density	0.11	0.11
The Heat Produced by Office Equipment (Printers)	11.7 w/m2	11.7 w/m2
Air Changes per Hour	0.7 ac/h	0.7 ac/h

Fig. 3. The Southern Front of the Studied Samples

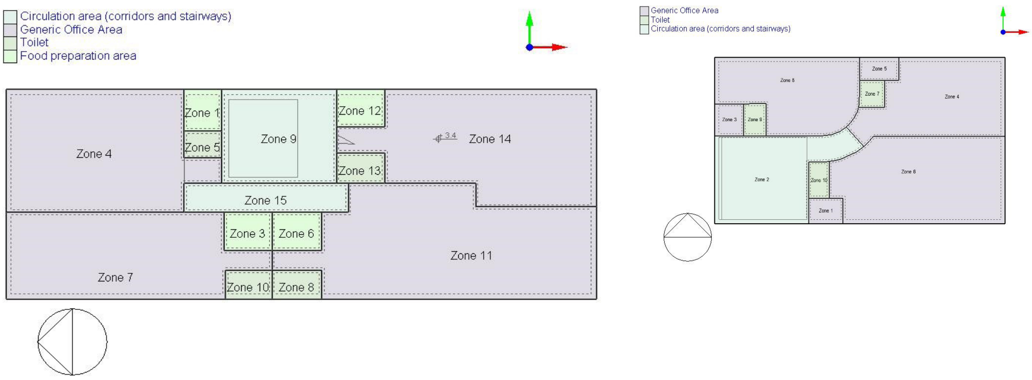

Fig. 4. Building Plans, Thermal Zones Modeled in the Design Builder Software for Case Studies

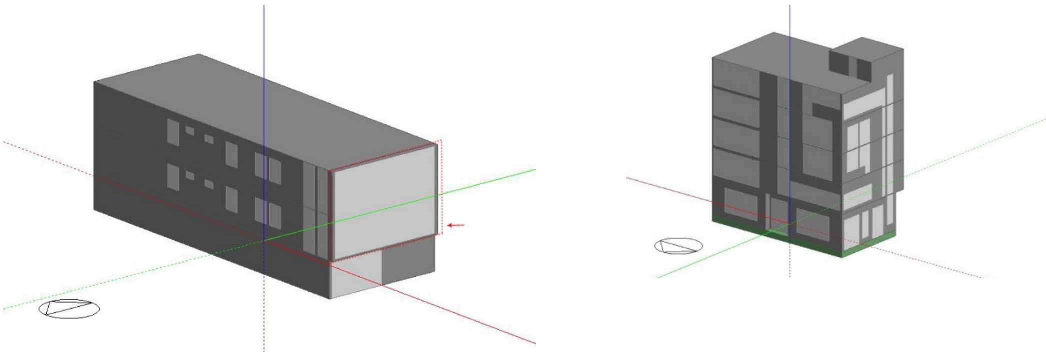

Fig. 5. Schematic Drawing of the Space between the Two Skins in the Software on the Southern View of the Building

4. ANALYSIS

According to the prior history of the modeled samples, the multi-story double-skin façade was considered fixed. In the present study, the studied multi-story DSF was investigated in terms of cooling energy consumption by changing the intermediate cavity distance in a range from 30cm to 200cm.

4.1. The Cooling Energy Consumption Rate

As it can be seen in Table (3), the cooling energy consumption is 169.73 kwh/m2 in the multi-story DSF with a 50-centimeter depth in building 1 and 227.62 kwh/m2 in the multi-story DSF with a 70-centimeter depth in building 2, which are the lowest cooling energy consumption rates obtained for the studied distances in both buildings. Also, considering the energy consumption rates in the single-skin façade, the highest reduction in cooling energy usage is observed in a 50-centimeter depth for building 1 and a 60-centimeter depth for building 2.

Table 3. The Amount of Cooling Energy Used in the Double-skin Facade at Various Intermediate Cavity Distances Ranging from 30cm to 200cm

Cavity (cm)	Cooling Energy Building 1 (kwh/m2)	Cooling Energy Building 2 (kwh/m2)
Single Skin	178.35	241.81
30	171.3	228.67

Cavity (cm)	Cooling Energy Building 1 (kwh/m2)	Cooling Energy Building 2 (kwh/m2)
40	170.8	228.21
50	169.73	227.84
60	170.05	227.73
70	170.21	227.62
100	170.96	227.71
140	171.68	228.12
200	172.24	228.65

As it can be seen in Table (3), in cooling energy consumption, the difference between the single-skin and double-skin facades with a distance of 50 centimeters is 8.6 kwh/m2 in building 1 and 14.2 kwh/m2 in building 2.

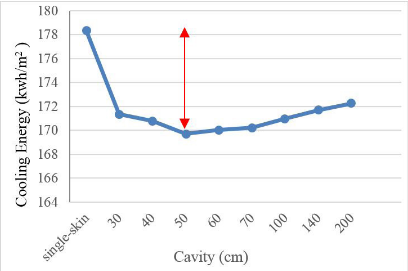

Fig. 6. The Diagram of Cooling Energy in a Range from 30 cm to 200 cm in Building 1

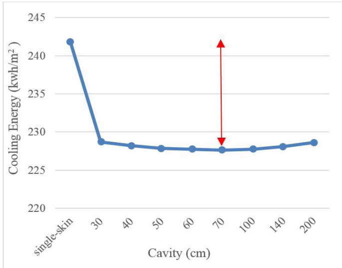

Fig. 7. The Diagram of Cooling Energy in a Range from 30 cm to 200 cm in Building 2

As Figure 6 shows, in building 1, the amount of cooling energy decreases as the distance increases from 30 to 50 centimeters and it increases as the distances increases to greater than 50 centimeters. In building 2, the amount of cooling energy decreases as the distance increases from 30 to 70 centimeters and it increases as the distances increases to greater than 70 cm. Obviously, the difference between the intervals of 30-200 cm is very negligible in building 2.

As can be seen, by changing the skin depth, the cooling energy consumption changes in both case studies, although the amount of change is negligible. To achieve the optimal distance relative to the depths of 50 and 70 cm in building 1 and 2, respectively, the amount of this change is 1.57 and 1.05 kwh/m2.

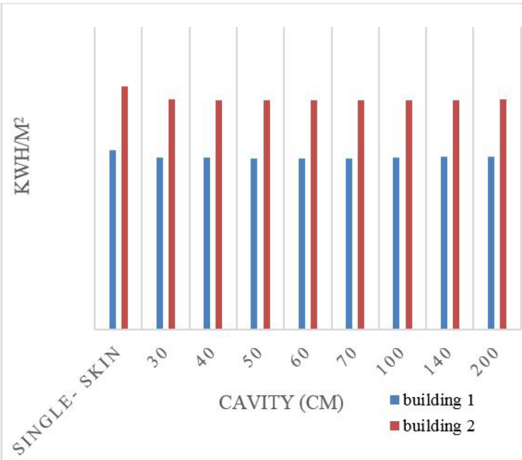

Fig. 8. The Amount of Cooling Energy Consumption in Building 1 and 2

According to a study on the depth of the cavity in the UAE by Radhi et al. (2013), the results obtained from the fact that at intervals of 70 and 120 cm, the transfer of heat decreases, as well as the simulation of case studies in Kish Island, it can be concluded that the results of the simulation are correct.

5. CONCLUSION

According to the modeling performed for the case studies, in the section of energy consumption ranges for the southern front of the multi-story double-skin façade, the results were studied based on the Psychrometric chart and climate file of Kish Island Standard and Analysis from Climate Consultant for Kish Island.

For the single-skin façade in the southern front, the amount of energy consumption in building 1 and 2 was 178.35 and 241.81 kwh/m2, which decreased by 8.6 and 14.2 kwh/m2 upon the use of DSF in multi-story buildings with the intermediate cavity depth of 50 and 70 cm, respectively.

Generally, by creating a double-skin facade, the amount of cooling energy in the hot and humid climate is reduced. This decrease with the cavity of 50 centimeters was 6.55 kwh/m2 (3.7%) in building 1 and 13.1 kwh/m2 (5.4%) in building 2. The amount of cooling energy consumption seems to depend on the height of the double-skin facade and the number of building floors, and the use of a DSF is affordable in buildings taller than 11 meters.

Therefore, according to the studies undertaken in this regard, it can be concluded that using the double-skin façade in a multi-story administrative building can considerably affect energy consumption rates with no need for heating and cooling installations in the hot and humid climate. In the meantime, studying the use of the double-skin façade with various intermediate cavity depths ranging from 30 to 200 cm in the southern front indicated that in terms of the energy consumption reduction, the cavity depths of 50 to 70 cm, as compared to the other distances, play a more effective role in reducing cooling energy. The exact amount of this distance depends on the height of the building, air suction, and the effect of the stack.

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