



Optimization of Double-Skin Facades for High-Rise Buildings in Hot Arid Climates

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Abstract. Adopting technologies to a region requires careful consideration of its functional performance under the given climate. This study investigated how the performance of the double-skin façade (DSF) concept is affected by the materials used to construct the outer skin, i.e. transparent glass and opaque concrete and phase change material (PCM) impregnated concrete, and the amount of perforations or openings in the outer skin in a typical high-rise building under the hot arid climate of the UAE. Findings show that all DSF variants reduce solar gain reaching indoor conditioned spaces and provide an envelope of air in contact with conditioned spaces that is at a lower temperature than outdoor ambient. The combination of these effects provides savings in whole building annual cooling demands. These energy benefits are found to increase as the thermal mass of a DSFs outer skin increases. Whilst savings will be building specific, they can be expected to be in the region of 8% to 20% for a glass DSF, 15% to 45% for a concrete DSF, and 30% to 50% for a PCM impregnated DSF. Results show that increasing the amount of perforations up to 45.6% of external skin area has little impact on the extent of reduction in DSF cavity temperature for glazed and concrete DSF but it does have a significant impact on that of PCM external skins.

Keywords. *Double Skin facades, Passive cooling, Phase Change Material, Energy Efficiency*

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Introduction

The hot arid climate of the UAE results in the need for mechanical cooling in buildings for most of the year and this is expected to increase under projections of future climate change. With current typical outdoor ambient temperature above 25°C for 75% of annual working hours, relative humidity above 60% for more than 20% of hours, and solar radiation above 893W/m² for more than 15% of hours, the main heat gain sources driving the need for mechanical cooling include high conductive heat gain from high ambient air temperature surrounding the external surfaces of buildings and high levels of solar radiation being transmitted into conditioned indoor spaces (Shanks, 2016). With many high-rise buildings in the UAE exhibiting an ongoing trend of high glazing to wall ratios (Aboulnaga, 2006),

upward of 60%, the concept of the double-skin façade (DSF) could offer a way to passively reduce cooling demand in many high-rise building projects. DSFs offer the potential of reducing the temperature of air surrounding the external surfaces of conditioned indoor spaces below that of the ambient air, partly by flushing unwanted heat away from conditioned inner skins through natural ventilation means, and partly by reducing solar heat gain, both of which otherwise add to the heating up of the inner skins of indoor conditioned spaces. Considering that improving the thermal performance of DSF outer skins would reduce cavity temperature and thereby reduce conductive heat gain, whilst also providing a degree of shading from solar heat gain, the cooling impacts of a number of DSF constructions and

configurations have been investigated to determine the principal design considerations to be addressed in the application of DSF in the hot arid climate of the UAE.

Double-Skin Facades (DSFs)

There are many different types and configurations of DSFs. Key characteristics have been identified in classifications by BBRI (2015) and those reported by Arons (2000). These provide distinctions between DSFs on type and mode of ventilation, i.e. origin and destination of cavity air, cavity geometry, e.g. vertical and horizontal cavities, operability, e.g. openable elements and blinds, and materials of inner and outer skins.

DSF in Hot, Arid Climates

DSF technology is most commonly utilized in the temperate climates of Europe as a solution to reduce heating loads during cold winters and mild summers. However, some applications in warmer climates have been studied (Hashemi et al., 2010; Yagoub, et al., 2010) and found generally unfavorable performance but identified design and operation characteristics that would improve overall performance benefits of DSF.

According to Yagoub et al. (2010), the intensity of solar radiation and air temperature of the hot and arid climatic zone, results in cavity temperature to rise up to 70°C causing an increase in the cooling load of the building and also necessitating mechanical ventilation to cool the air gap to maintain the air gap temperature close to ambient conditions. The building analysis reported, which was the proposed design for National Holding Headquarters in Abu Dhabi, UAE, had no opening on the external skin to allow for natural ventilation. This would have played a significant role in the high air cavity temperatures reported and thereby poor potential cooling savings.

Hashemi et al. (2010) studied the thermal performance of DSF in Tehran, Iran, and found that cavity temperature in summer is almost always 1–10°C higher than the ambient temperature. It was also concluded that due to high ambient temperature and lack of ventilation, heat accumulated in the cavity during night-time leading to an increase in the cooling load. Suggestions given to optimize the performance of DSFs were

to allow for night-time ventilation and install shading devices to prevent overheating in the cavity during mornings. The airflow regime within the DSF cavity adopted in this study would have had a direct impact on the cavity air temperature and resultant impact on cooling. Over the course of a year, the Tehran climate differs from that of the UAE in that it has a cold semi-arid climate with average summer temperature being below 30°C.

These studies, amongst others, indicate that airflow in DSF cavities have a major impact on performance in hot and arid climates.

DSF Performance

Yellamraju (2003) evaluated the performance of DSFs on an office building in a hot climatic region of India. It was concluded that, although transparent layers decrease the overall U value of the façade system, the associated radiative and convective heat transfer increases the cavity temperature. Among the strategies studied, the ones involving transparent layers had reduced cooling load by only 4–10% below basecase, making it less viable. However, when the configuration involves an opaque external skin and transparent glazed inner skin, the cooling load was 13–28% lower than basecase. Fallahi et al. (2010) studied the performance of DSF with integrated thermal mass under the humid sub-tropical climate of Torino, Italy. It was found that a DSF system with outer skin of concrete and inner skin of glass reduced cooling load by 40% in summer over the basecase and performed better when compared to conventional DSFs with aluminum blind, conventional DSFs with two panes of concrete thermal mass material located within the cavity, and DSFs with inner skin of concrete and outer skin of glass.

These examples, reporting the significant energy benefits of DSFs with a concrete outer skin, indicate that combining an opaque outer skin with a glazed or transparent inner skin is the most effective DSF approach in hot climates. However, it is important to remember that with this combination the wider architectural benefits of a glazed inner skin, such as view and daylighting, are directly negated by an opaque outer skin. This negative implication can be ameliorated by having perforations in an opaque outer skin

which would enable some degree of daylighting and views from indoor spaces. In this context, our study investigated how the type of external skin materials and proportion of perforations affect DSF cavity temperatures and whole building cooling demand.

Methodology

As the performance of DSF is a function of the air-flow and heat transfer occurring in the façade cavity, an ideal model of a naturally ventilated DSF for the region will be one that has significant air movement within the cavity at a temperature below the outdoor ambient. Two main factors dictate the scale of these parameters, namely, geometry and thermal properties of the external skin. Where computational fluid dynamics (CFD) account for drivers of air movement at a fixed point in time dynamic thermal simulation is also needed to account for the time varying transfer of heat. Therefore, calculated outputs from dynamic thermal simulations, conducted in internationally validated thermal model software IES-VE Apache, were checked against CFD modeling results of the worst-case hour in a year to determine the suitability of results. To produce the hourly annual dynamic results of cooling demand, heat gains, and temperatures, air movement up through the DSF cavity were modeled as bulk airflow driven calculated hourly dynamics of temperature difference, wind speed and wind direction. These temperature and air velocity results were compared to results generated from CFD modeling to check suitability of the dynamic modeling. Cooling and ventilation energy modeling of conditioned indoor spaces were based on an idealized HVAC system with open-top cooling where there is no limit to the capacity of cooling in each space such that the space design temperature was always reached, this was considered to represent the maximum cooling load for common occupant density and ventilation standards.

The CFD based IES-VE Microflo was used to calculate cavity air velocity (airflow); inner and outer skin surface temperature as well as cavity air temperature distributions for a peak cooling hour for three of the model variants. The boundary conditions for the Microflo modeling were generated and imported from the ApacheSim

simulations. The standard k- ϵ turbulence model was adopted across the modeled variants as the flow within the DSF cavity was predicted as featuring transitional and more turbulent flows, with medium to high Reynolds numbers. The geometry meshing for the CFD models was achieved in Microflo, which uses structured non-uniform rectilinear Cartesian grid. The available grid quality control is the aspect ratio and the highest acceptable aspect ratio by the solver is 50:1. The highest aspect ratio of the study models was 18:1, which is well within the acceptable range of the software. The CFD results were used only as a check of the dynamic thermal simulation results.

DSF Study Models

The following three sets of DSF constructions and configurations were modeled, each having an inlet at ground floor level and outlet at roof level in addition to any perforations in the outer skin across the height of the DSF:

- Model 1 - Glazed Outer Skin (5 variants having different proportions of perforations)
- Model 2 - Concrete Outer Skin (5 variants having different proportions of perforations)
- Model 3 - PCM Impregnated Concrete Outer Skin (5 variants having different proportions of perforations)

Although the performance of a DSF would be sensitive to the size and shape of both the inlet and outlet, the impact of variations in these are beyond the scope of the study reported here. The geometry of a DSF impacts directly on the nature of airflow and heat build-up in the cavity. The DSF configuration that offers the greatest opportunity to reduce cooling demand, by having a cavity temperature that is lower than outdoor ambient, is one with compact surface shape and area for heat absorption and unobstructed air movement through the height of the cavity to flush out built up heat.

Cavity depth is a primary factor that controls the rate of ventilation, and the amount of heat retained in the DSF system. According to studies conducted by Rahmani et al. (2012) and Regazzoli (2013), the optimal cavity depth at which the cooling load of the building is placed is at least

between 1,000–1,200 mm. Hence a cavity depth of 1,000 mm is adopted for the high-rise multi-story DSF for this study and this is modeled as being completely naturally ventilated (see Figure 1).

Airflow and temperature characteristics of the cavity are subject to constant change based on the ambient weather conditions and estimating the overall annual impact of these, through dynamic thermal simulation, is one of the central objectives of this study. Hence, to explicitly account for these dynamics or changes, the cavity is modeled as a “room” with no internal heat gains. However, in dynamic thermal simulation software, as individual rooms within the model are assigned with a single calculation node at which the temperature of the whole room is averaged, this would produce results that do not directly account for the temperature variation occurring throughout the height and width of DSF cavities and an average constant temperature would be assumed for the cavity, leading to inaccuracies in calculated annual cooling demands. To ensure that the temperature and airflow dynamics are accounted for, the cavity is separated vertically and horizontally into zones at each floor level via “holes” in order to ensure unobstructive airflow. The airflow between these

zones is automatically calculated, within the dynamic thermal simulation as a function of changing temperature and pressure differences. CFD analysis was conducted on three of the DSF study models to briefly check air velocity, direction, and temperature distributions supported the dynamic thermal simulation results. These were conducted for the west facing DSF elevations under the peak weather condition of 15:30 on July 23, as this was a worst-case scenario in terms of DSF performance, i.e. highest average cavity temperature. Each CFD model used a standard $k-\epsilon$ turbulence model with hybrid discretization. Hybrid discretization is one of the three solver schemes available within Microflo and is used for the DSF study models as it evaluates the relative ratio of convection and diffusion to apply upwind or central differencing method as suitable to produce solutions. The standard $k-\epsilon$ turbulence model was adopted, for computational efficiency, as airflow within the DSF cavities are considered to range from medium to high turbulence due to the amount of external skin perforations. The surface heat transfer coefficients for each surface of the model are program calculated as per the thermal properties of the assigned construction materials. The initial conditions for DSF cavity temperature were set at 25°C and velocity at 0 m/s were set for the CFD models to begin the iterative solution.

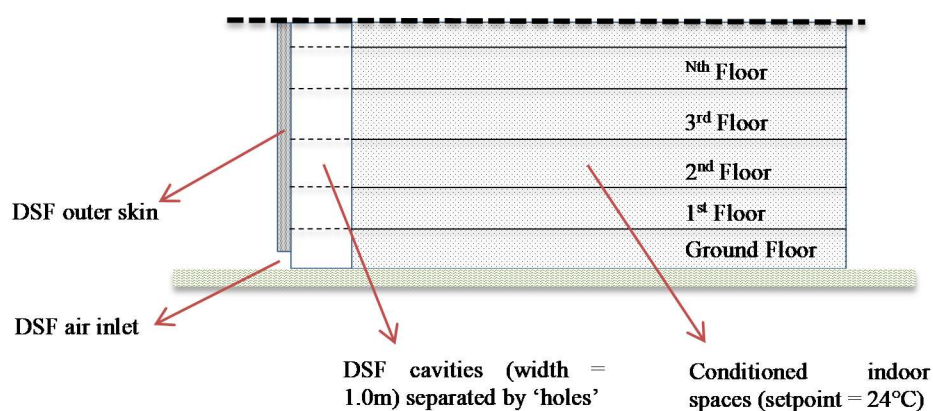


Figure 1: Sample cross section of common DSF model construction (not to scale)

Model 1 - Glazed Outer Skin (no perforations in outer skin)

A conventional DSF was built with the aim to achieve energy efficiency without compromise on the use of glass. Hence, the first external skin to be examined under the climatic conditions is glass. As mentioned, a high-rise multistory DSF with cavity depth of 1,000 mm is used for this study. Air inlet and outlet of dimension 30 x 1 m (l x h) is provided at the bottom and top of the DSF as shown in Figure 2. The outer skin glazing has a U-value of 1.56 W/m²K, SHGC of 0.47, visible light transmittance of 71%, outside reflectance of 0.072, and net R value of 0.813 W/m²K.

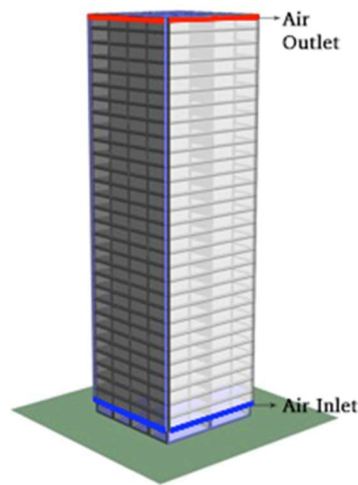


Figure 2: DSF general configuration (air inlets & outlets)

Model 2 - Concrete Outer Skin (perforations in the outer skin)

To analyze the impact of increasing thermal mass of the external skin, concrete skin configurations with varying percentages of perforations were made as shown in Table 1 and Figure 3.

Aerated concrete was adopted as the exterior skin having thermos-physical properties of thickness 100 mm, density 500 kg/m³, specific heat capacity 840 J/kgK, and thermal mass 21 kJ/m²K.

Model 3 - PCM Impregnated Concrete Outer Skin (perforations in the outer skin)

The third model variation is based on increasing the thermal capacity of the external skin from the previous model. For this purpose, concrete skin is impregnated with PCM. Due to inability of IES-VE to simulate the exact nature of PCM, i.e. its latent heat capacity and phase change as result of ambient temperature, an alternate way to model the skin was adopted. Kendrick and Walliman (2007), proposed a method called the “conditioned cavity method” to dynamically simulate the latent heat storage capacity of PCM in IES-VE. In this method, a cavity representing the PCM material is placed adjacent to the space being conditioned by PCM. The cooling set point in the cavity is set at the melting point temperature of the selected PCM with a limited cooling capacity as dictated by its latent heat storage capacity. This method is used to simulate the latent heat storage capacity of the PCM impregnated concrete skin in this model variation. In our current study, this cavity has been denoted as the “PCM dummy room.”

Table 1

DSF model variants

Model variants	Number of individual perforation in outer skin	Perforations proportion of total outer skin area (%)
1.0, 2.0, 3.0	2	1.9
1.1, 2.1, 3.1	30	11.5
1.2, 2.2, 3.2	28	18.8
1.3, 2.3, 3.3	32	22.2
1.4, 2.4, 3.4	590	37
1.5, 2.5, 3.5	238	45.6

PCM impregnated aerated concrete blocks are an available building material having a latent heat capacity of 110 kJ/kg and a melting point of 26°C. The amount of PCM impregnated into the concrete requires careful consideration as it affects the mechanical properties of the concrete mixture. Hence, only 5% (by mass) of PCM is contained within the modeled aerated concrete blocks (Halúzová, 2015).

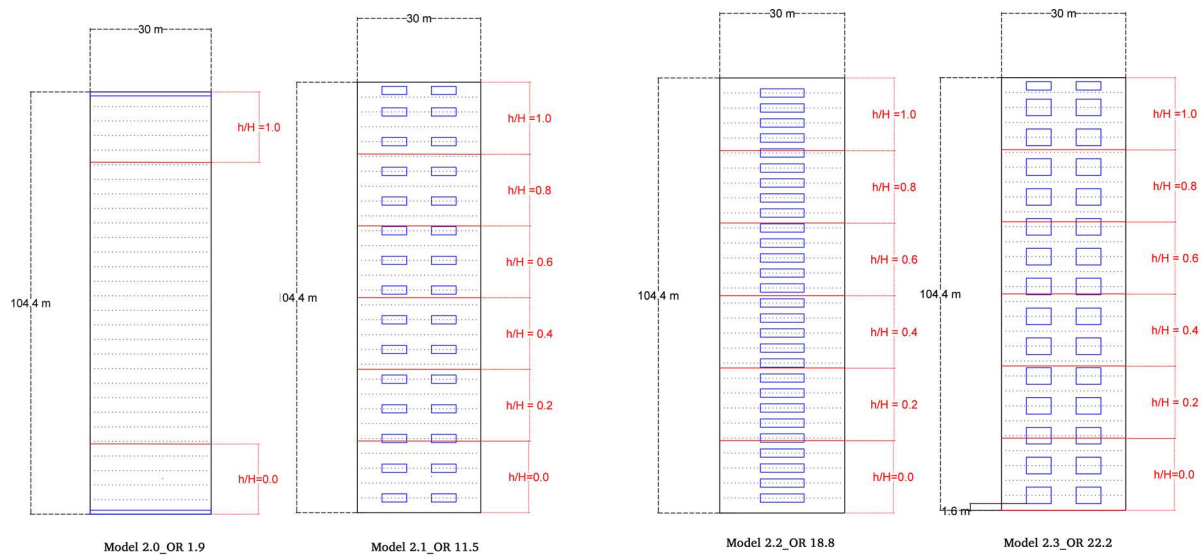


Figure 3: Sample of outer skin perforation variants

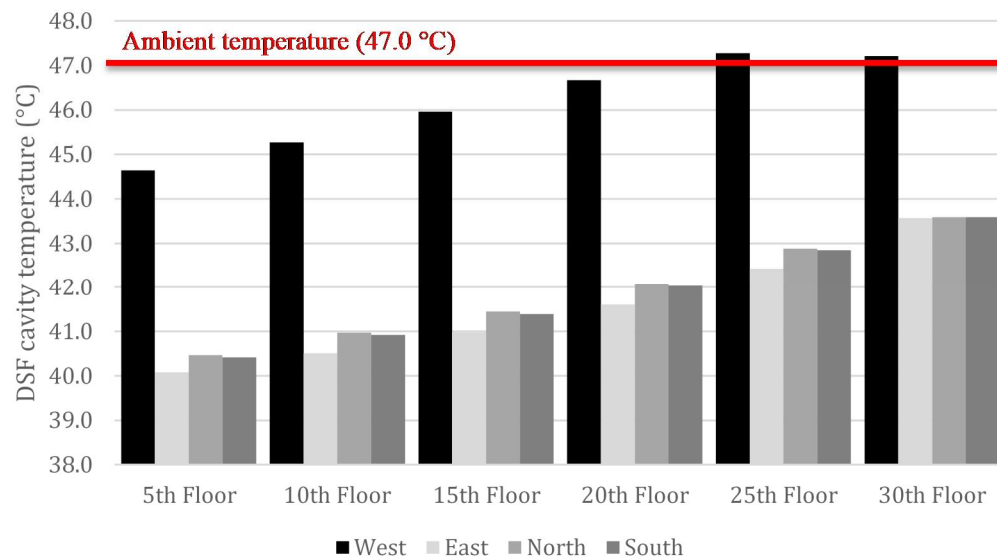


Figure 4: Model 1 glazed outer skin – DSF average cavity temperature for each orientation and floor

The latent heat capacity of the concrete skin with the selected PCM is calculated as follows:

Density of aerated concrete = 500 kg/m³ and volume of concrete layer is 104.4x (l) x 30 (b) x 0.1(h) = 313.2 m³. Therefore the mass of PCM in aerated concrete at 5% = 7,830 kg with a latent heat storage capacity of PCM = 110 kJ/kg. Therefore, the equivalent total latent heat storage capacity of the PCM impregnated outer skin = 239.25kWh. The latent heat storage capacity is

set as the cooling setpoint, i.e. when cooling is switched on, for the “PCM dummy room” that represents the PCM impregnated aerated concrete block outer skin. In this modeling approach the “PCM dummy room” has 239.25 kWh of free cooling which becomes available when the “PCM dummy room” reaches 26°C and once this cooling is consumed, any further heating from conduction, convection, or radiation has the effect of

heating and thereby increasing the temperature of the “PCM dummy room.”

Results and Discussion

The main areas of focus in this study are the performance of the various DSF constructions and configurations, in terms of DSF cavity and inner skin surface temperatures, and the impact of these on the annual whole building cooling demand. These are investigated for the typical UAE weather year and the peak cooling hour, i.e. the hottest hour in a typical year, which is at 15:30 on July 23.

DSF Performance

DSF cavity temperature varies depending on orientation. A west-facing DSF exhibits the highest cavity temperatures, i.e. the poorest performance, throughout its height and breadth on the peak cooling day when outdoor ambient is 47.0°C (see Figure 4). Due to this, the west-facing DSF, having lowest reduction in cavity temperature beyond outdoor ambient, is taken as the main focus of further results analysis albeit all dynamic thermal model variants have the same DSF variant on all elevations as that on the west.

For a west-facing DSF, a fully glazed outer skin, i.e. Model 1 (1.9% perforations), does provide a reduction in cavity temperature on lower floors but this benefit is reduced in the top half of the DSF, i.e. floors 15 to 30 (see Figure 5A). The reduced cavity temperature at lower floors is considered to be due to the buoyancy effect moving warm air from low level toward the upper levels. This reduces convective and conductive heat transfer to the inner glazed skin resulting in lower inner skin surface temperatures at low level as illustrated by the peak cooling day CFD results for an external skin perforation of 11.5% (see Figure 5B). As warm cavity air reaches the upper level outlet, the temperature is closer to and exceeds that of the ambient air on the other side of the outlet. This temperature difference alone would drive airflow out of the cavity through the outlet but with external wind pressure counteracting this to some degree the outflow is reduced resulting in an accumulation of heat. A similar condition is observed between floors 10 to 20. The scale of this effect will be dependent on wind direction, wind velocity, and the size and characteristics of the upper outlet.

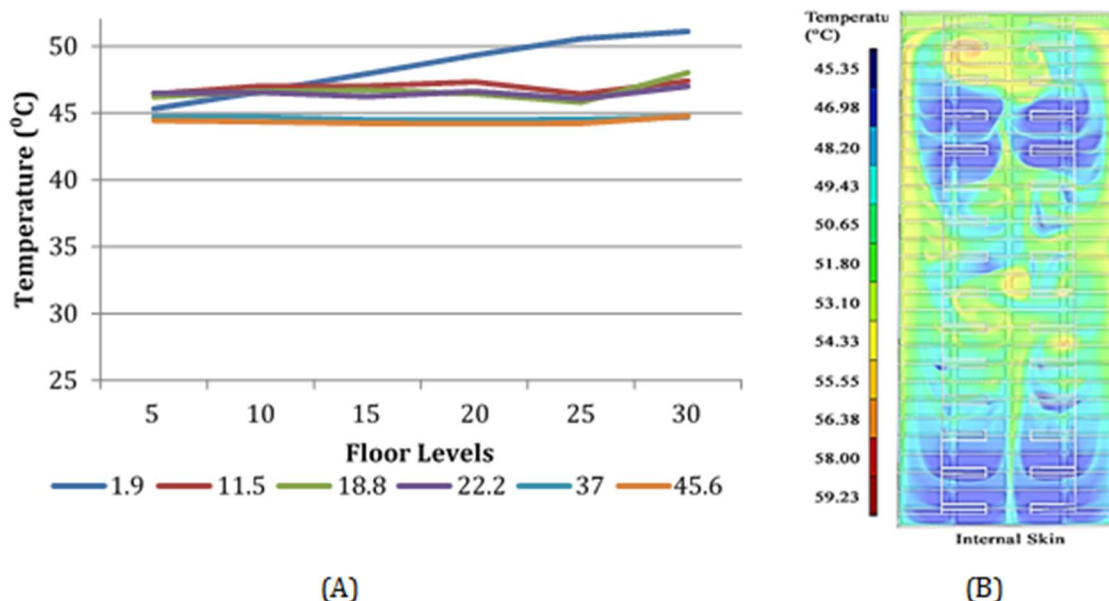


Figure 5: (A) Glazed DSF average cavity temperatures; (B) Glazed DSF inner skin temperature distribution (percent external skin perforations = 11.5%)

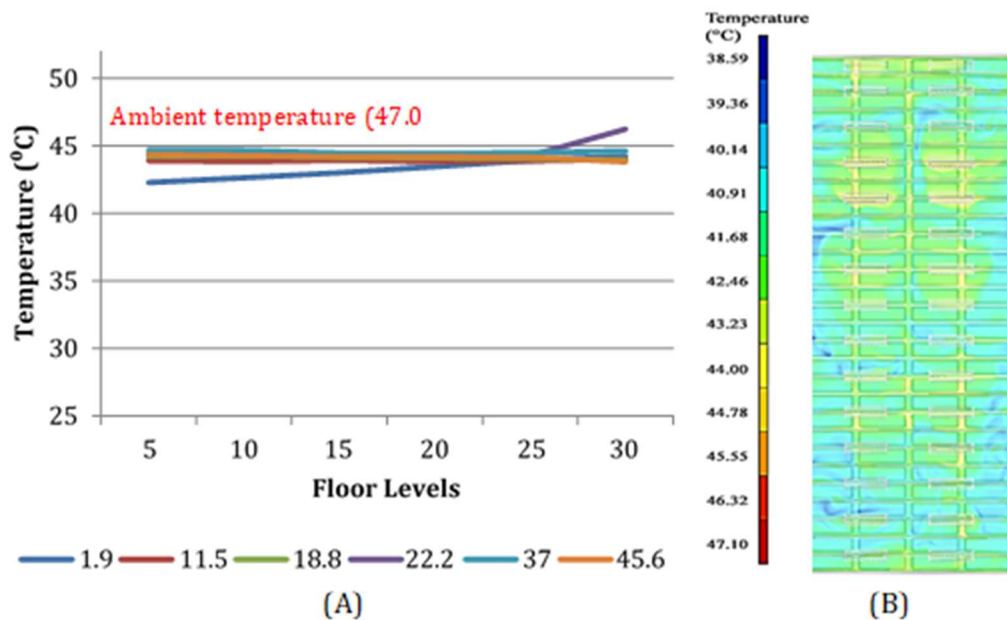


Figure 6: (A) Concrete DSF average temperatures; (B) Concrete DSF inner skin temperature distribution (percent external skin perforations = 11.5%)

As expected, the concrete DSF results in cavity temperatures marginally lower than the glazed DSF for all external skin perforations variants apart from the 37% and 45.6% variants, where no additional benefit is found (see Figure 6A). This lack of improved reduction in cavity temperatures for 37% and 45.6% variants is considered to be due to the dominance of wind driven air movement and turbulence caused by these variants' larger areas of perforations in the DSF outer skins. However, the extent of additional reduction in cavity temperatures, beyond that found for a glazed outer skin, is marginal, e.g. of the order of 5% or less at mid floors (e.g. 46°C glazed outer skin compared to 44°C concrete outer skin). Therefore, in terms of a DSF providing an envelope of cooler cavity air around conditioned indoor spaces, concrete has only a marginal advantage over glazing as a DSF external skin, under the configurations studied. It should be remembered that concrete outer skins, being opaque, will have additional benefit over glazed outer skins in terms of reducing solar gain reaching DSF inner skins. It is considered that DSF cavity temperatures for the variants external skin perforations of 22.2% or less could be reduced further through adopting larger opening areas of the low-level inlet and high level outlet.

As having no perforations in an opaque concrete outer skin would make a fully glazed inner skin entirely redundant, the results show that increasing the proportion of external skin perforations has greater benefit in glazed DSF than in concrete DSF variants. This is indicated by the differences in average cavity temperatures between the perforations variants of these two outer skin materials, i.e. there is marginally greater differences between floor level average cavity temperatures with glazed outer skin than there is with a concrete outer skin up to perforation ranges of 22.2%. This is considered to be due the inner cavity-facing surface of the glazed outer skin reaching marginally higher temperature than that of the concrete outer skin due to having less heat storage capacity.

Interestingly, although increasing the external skin perforations tends to stabilize cavity temperatures across the height of the 30-story glazed DSF, overall it can be considered that such increases in external skin perforations, i.e. from 11.5% to 45.6% for both DSF external skin materials, have negligible impact on overall DSF performance in terms of providing an envelope of cooler air around a building. As noted earlier, there will be impacts from these types of variations on shading from solar gain, which will be discussed later.

The comparatively higher cavity temperature at the 30th floor with 22.2% perforations, for both glazed and concrete DSF, and the unexpected drop at the 30th floor with 45.6% perforations, for the concrete DSF, suggests a relationship between the amount of outer skin perforations and upper outlet size. However, considering this will be highly building specific, investigating it further is beyond the scope of this study.

Of all the DSF constructions and configurations investigated the PCM based DSF, i.e. Model 3, provides the greatest reduction in cavity temperature (see Figure 7A). This DSF consistently results in cavity temperatures 10K or lower than that of the best performing concrete DSF, i.e. Model 2 variants, and up to 16K lower than a conventional fully glazed DSF, i.e. Model 1 variants. However, unlike the Model 1 and 2 variants, results indicate there is a clearer optimum proportion of perforations as larger proportions of 37% and 45.6% result in higher cavity temperatures than the rest. Similarly, the effect of upper outlet characteristics combined with external wind pressure acting on all perforations is

greater as indicated by the unexpected higher (i.e. perforations 1.9%, 11.5%, 22.2%, and 37%) and lower (i.e. perforations 18.8% and 45.6%) cavity temperatures at the 30th floor level. This issue is further supported by the generally uniform inner skin temperatures up to the high-level outlet where the temperature is greatest (see Figure 7B).

DSF Impact on Annual Whole Building Cooling Demand

The basecase building has an annual cooling demand intensity of 262.23 kWh/m²yr as estimated by thermal dynamic simulation. This is considered as being a reasonable model when compared to similar cooling intensity findings of similar UAE high-rise buildings reported in the literature, e.g. Shanks (2016). All the DSF construction and configuration variations investigated resulted in a reduction of annual whole building cooling intensity. These reductions or savings ranged from 8.7% for a glass DSF with 45.6% perforations in the outer skin to 49.9% for a PCM DSF with 1.9% perforations in the outer skin (see Figure 8).

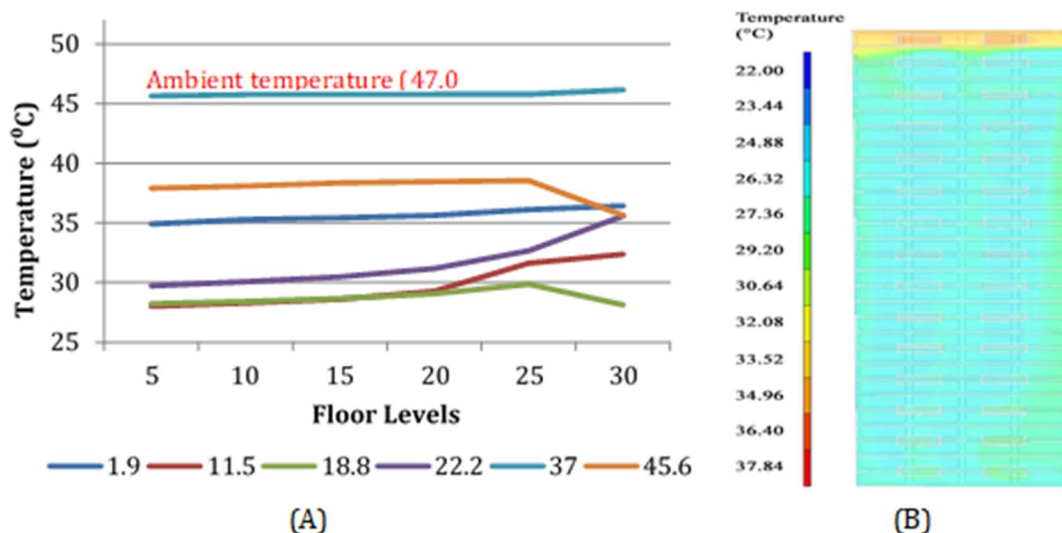


Figure 7: (A) PCM DSF average cavity temperatures; (B) PCM DSF inner skin temperature distribution (percent external skin perforations = 11.5%)

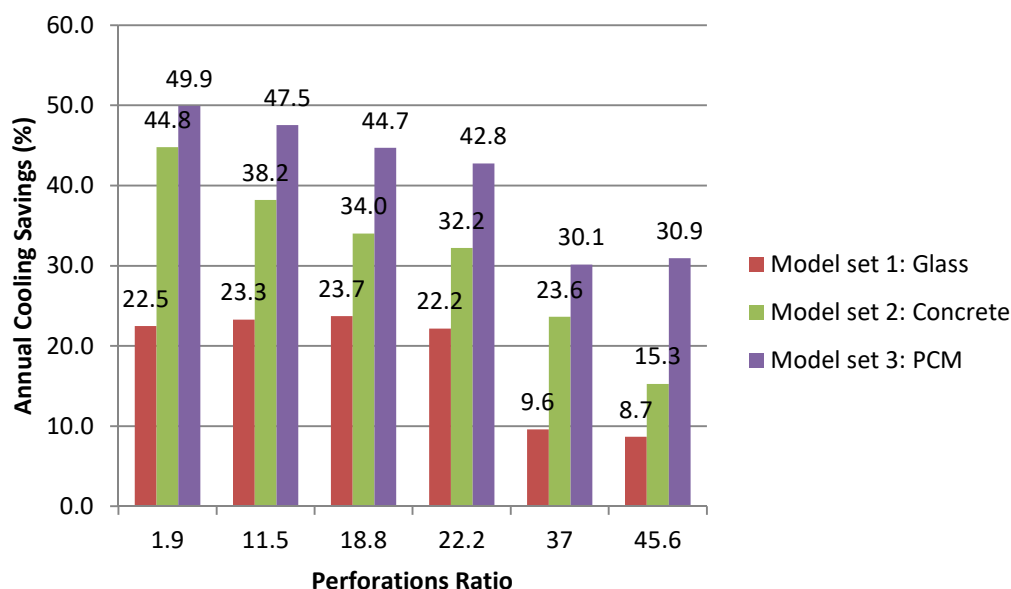


Figure 8: Annual cooling demand savings for model variants

Generally, annual cooling saving decreases as the amount of external skin perforations increases (Figure 8). Due to the modeling approach taken in this study, such reductions in annual cooling savings can only be due to reductions in solar gains reaching indoor conditioned spaces, i.e. behind the DSF, and reduced temperatures in DSF cavities. Therefore, considering that increasing external skin perforations has little impact on glazed and concrete DSF cavity temperatures yet do tend to impact overall annual cooling savings, the results indicate the dominant benefit of glazed and concrete DSF is shading from solar heat gains.

The primary difference between the modeled concrete and PCM external skins is the capacity to absorb heat from the DSF cavities, where PCM has a higher capacity. This combined with the differences in DSF cavity temperatures between these two outer skin materials being in the range of 10K or approximately 25% and their differences in annual cooling savings being from 10% to 50%, the results indicate that the advantages of opaque PCM over opaque concrete DSFs are driven by the enhanced heat absorption of PCM producing lower DSF cavity temperatures. This finding illustrates the value and importance of

maximizing the heat storage attributes when using an opaque external skin for a DSF in the UAE's hot arid climate.

Glass DSFs are found to provide clear savings in annual cooling demand with little variation in savings as the outer skin is perforated, or opened up, until perforations go beyond 22%. As expected, opaque concrete and opaque PCM DSF's provide greater savings than glass DSFs, but these cooling energy benefits reduce as the outer skins are opened, i.e. external skin perforations increase.

Whilst reducing cavity temperatures goes some way to reducing cooling demand, reducing solar radiation reaching the skin of indoor conditioned spaces, i.e. the inner skin of a DSF, provides significant energy benefits. A glass DSF is the least effective at reducing the amount of these solar gains and commonly results in enabling up to three times as much solar gain to reach indoor conditioned spaces than opaque concrete DSF or opaque PCM DSF (see Figure 9). As there is a clear dependence of a buildings annual cooling savings on such solar gains in the hot arid climate of the UAE (see Figure 10), the ability of a DSF to reduce these gains is important.

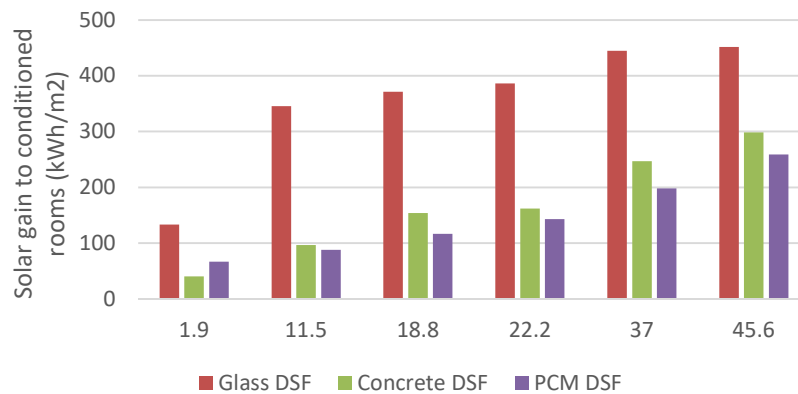


Figure 9: Solar gain reaching DSF inner skin for each model variant

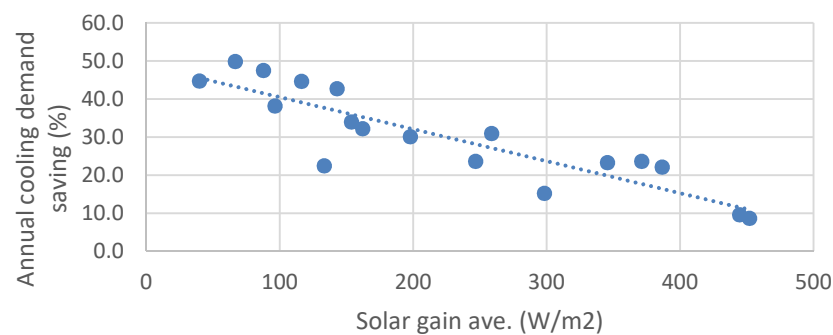


Figure 10. Influence of solar gain on annual cooling demand savings across all DSF model variants

These effects, as well as the variations of the results shown below, are sensitive to the proportion of perforations in the outer skin, the thickness of the outer skin in terms of thicker skins, e.g. concrete, providing more shading, the physical position of the perforations in relation to glazed elements of the indoor conditioned rooms, and sun position. These latter factors could be readily harnessed to tune the layout and positioning of perforations to the solar and visual field of any particular building and site.

Conclusions

DSF is an advanced and relatively mature façade concept used in many different temperate and cool climates to provide heating and cooling savings at different times throughout the year. Other studies reported in the literature show it can have potential to provide cooling savings in more

extreme climates, such as the hot arid climate of the UAE. This study supports this latter overall view of potential in the extreme climate of the UAE and further provides evidence of the importance of opaque and high-heat storage capacity DSF.

The study finds that DSFs do provide savings in annual cooling demands, from 8.7% to 49.9%, in high-rise buildings under the hot arid climate of the UAE.

Whilst a glazed outer skin does provide useful reduction in cooling demand, i.e. from 8.7% to 22.5%, the scale of this is on average half as much as that provided by opaque concrete, i.e. 15.3% to 44.8%, and a third as much as PCM, i.e. 30.9% to 49.9%, outer DSF skins. The increased thermal mass provided by a PCM impregnated DSF outer skin results in the greatest cooling demand savings of 49.9%. This additional benefit of thermal

mass is a key finding for DSF in hot arid climates and should be a central design consideration.

Perforating outer skins will be an important design issue for opaque DSF of concrete or PCM impregnated concrete. Generally, as outer skin perforations are increased, annual cooling savings reduce and the majority of this reduction is due to increased solar gain reaching the surface of indoor conditioned spaces. Opening up or perforating DSF outer skins does reduce the impact on cooling demand but with outer skins perforated up to 45.6% savings remain significant, e.g. 15.3% concrete and 30.9% PCM, albeit they are typically reduced by approximately half, due to reduction in shading from solar gains reaching the surfaces of indoor conditioned spaces.

As savings are mainly due to a reduction in solar gains reaching the surface of indoor conditioned spaces, i.e. inner skins of a DSF, and, to a lesser

extent, by reducing the temperature of air in contact with these surfaces, i.e. DSF cavity air, much of the cooling benefits of DSF could be potentially achieved by lower cost external shading systems.

All DSF configurations investigated had the common problem of accumulation of heat at the upper levels. It is possible that this negative impact could be ameliorated by careful sizing and opening design of inlets and outlets, all of which will be building and site specific. The DSF concept does lend itself to architectural expression and the findings of this study, e.g. DSF performance varying depending on orientation, cavity temperature being relatively independent of amount of outer skin perforations for glass and concrete DSF, and heat storage capacity being a significant factor on DSF annual cooling savings, present relatively few limitations for tuning DSF in response to whole building architectural objectives.

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