Modelling and Simulation of Integrated Responsive Solar-Shading with Double Skin Facades in Hot Arid Climates

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Abstract

This paper tests the performance of a kinetic solar shading system in a double skin façade in a hot arid climate. The shading system is thermally actuated. Computational Fluid Dynamics (CFD) for modelling air flow and heat transfer in DSF is used. It combines RNG k-epsilon turbulence model with P1 radiation model. Shape Memory Alloys (SMAs) work with actuation temperature from 35-40°C. Simulation runs are carried to compare thermal performance of three cavity widths; 0.6, 0.8, 1.0m; and three solar-shading opening ratios; 30%, 50%, 70%; to detect the optimal settings to reduce direct solar radiation indoors. The 1m wide cavity with the screen located 0.10m from the outer glass and apertures between 30% to 50% in peak summer midday are recommended.

Introduction

The term ‘Kinetic skins’ has come to be used to refer to building envelopes capable of configuration changes due to their geometrical, material and mechanical properties (Adrover, 2015). Recent literature shows that most environmental kinetic facades are based on mechanically operated systems. A mechanical system, such as implemented in the facades of Al Bahar Towers in Abu Dhabi and Institut du Monde Arabe in Paris, has the disadvantage that it is complex to build, difficult to maintain and requires high energy consumption (Karanouh and Kerber, 2015; Meagher, 2015; Reichert et al., 2015). Lately, more attention has focused on soft mechanics to simplify mechanical designs utilized in kinetic skins.

Integration of smart materials for solar-shadings with Double Skin façade (DSF) systems may exhibit a potential to low-tech adaptive systems. Shape memory alloys (SMA) act as servo-actuators to design low-tech responsive skins. SMA as thermo-responsive actuators are introduced to use the radiative heat gains in the DSF as passive and renewable energy resources to activate the kinetic system. When the temperature in the cavity increases above the activation temperature of the SMAs, the SMA actuators change to its trained shape and trigger the solar shading system to reconfigure.

A number of recent findings are reported in the literature pertaining to the thermal performance of double-skin facades. Double-skin facades (DSF) have the potential to reduce energy consumption and maintain thermal comfort (Velasco et al., 2017). The energy consumption used to maintain indoor comfort represents a range from 70% to 80% of total energy consumption in hot arid climates in commercial buildings and DSF is predicted to reduce indoor cooling loads between 12-30% based on size and configuration of the building (Hamza, 2008; Hamza and Qian, 2016). A movable solar-shading device is usually installed in the intermediate space of the DSF for thermal controls and can significantly improve the building energy behaviour throughout the entire year (Gratia and De Herde, 2007; Wong et al., 2008). The thermally actuated shading system needs to be positioned at the highest temperature gradient in the cavity. Studies undertaken by (Hamza and Underwood, 2005) shows that the highest temperature gradient is closer to the outer layer of the DSF cavity. Further CFD simulations were carried out (by the first author) and supports the positioning of the system closer to the outer layer of the DSF to achieve temperatures needed to activate the shape memory materials.

Computational Fluid Dynamics (CFD) has proven to be a useful tool on the study and optimization of DSF. Coupling Radiation and turbulence models has always been a problem addressed by researchers in different ways (Table1). Some researches couple BS simulation with CFD while others depend on coupled thermo-fluid-dynamics problems using sub-models of Radiation and turbulence. (Manz et al., 2004) coupled Surface-to-surface radiation model with revised k-ε turbulence model to assess the cavity performance and compare it with experimental database. (Coussirat et al., 2008) used (Manz et al., 2004) well documented experimental database to validate CFD code and compare different radiation and turbulence models. From the results, the RNG k-ε turbulence model and standard k-ε turbulence models seem to perform better than the other turbulence models while the P-1 radiation model seems to better predict the temperature of the solid surfaces present in the double façade. The problem is identified as heat transfer by conduction/radiation for solid surfaces and convection in the air fluid in the cavity. The importance of radiation phenomena in the heat transfer mechanism present in these surfaces is greater than the contribution of the conduction and convection phenomena. The P-1 radiation model proved its superiority in solving (RTE) easily and with little CPU demand (Coussirat et al., 2008).
Most of the studies simplified the problem using two-dimensional simulations. (Liao et al., 2005) used the conjugate heat transfer to study a two-dimensional CFD model. Other researchers, such as (Velasco et al., 2017) and (Parra et al., 2015) simulated a three-dimensional model for the whole cavity. (Coussirat et al., 2008) limited the three-dimensional model to a cell size to compute the turbulent mixing appropriately with the proposed geometry. (Safer et al., 2005; Baldinelli, 2009) compared the two & three dimensional simulations with experimental results and found that the three-dimensional simulations are more accurate while the two-dimensional model lightly underestimates the flow rate. To make a balance between accurate simulations and a method that would allow for more complex geometries of shading screens, a three-dimensional simulation is proposed for a vertical section with 0.4 m deep and assigned symmetry condition for both sides.

Most of the previous studies limited the computational domain dimensions to contain a single storey double skin cavity to minimize the computational timing and the problem resolved.. The present paper will include a description of the computational domain, boundary conditions, numerical method and computational mesh.

Model descriptions

The numerical setup used for this study was implemented on three stages. The first model replicates Baldinelli (2009) open configuration case to validate the used method and compare the results of surface temperature, and air cavity temperature. The second models studied the DSF cavity with different cavity widths, 0.6, 0.8, 1.0 meter respectively. A set of simulation runs are carried for the cavity without solar shadings to study its thermal performance and measure the air temperature needed to activate the solar-shading system. The thermal performance of the DSF air cavity is function of its type of ventilation. Thus, an assessment of the cavity conditions for both unventilated and naturally ventilated cavities is carried to compare their thermal performance. These simulations tested the three previously stated widths for both naturally ventilated and unventilated DSF. Then the third set of models intended to study the surface temperature of the inner wall relative to screen opening ratios (ranges from 30% to 70%) to detect the opening range required to prevent interior over-heating

A comparison was carried between the full detailed and the simplified solar-shading as shown in figure 3. The performance is compared in terms of inner and outer surface temperature, air cavity temperature and air velocity. The cases were tested as a point in time simulations on a peak summer day, 15th of july, at 12pm.

All cases were modelled in Rhino and exported as step files to be further processed in Ansys software package.

Geometrical model

For the purpose of the study, a vertical section of 0.4 m deep for one storey south-orientated DSF is studied numerically with and without solar shading as shown in Figure 1. The dimensions of the geometrical model were set to 2.8 m height, 0.4 m depth and three different cavity widths of 0.6, 0.8, 1m respectively. The system consists of an external glass surface, an air gap, a responsive shading screen with different opening ratios, an inner air gap and a single pane 6 mm internal glazed surface. The outside air is drawn from the bottom inlet of the cavity at 0.1m and the outlet of 0.1m at the top of the façade configuration as shown in Figure 1.

<table>
<thead>
<tr>
<th>Authors (year)</th>
<th>Study (Generic /Applied)</th>
<th>Configuration 3D/2D</th>
<th>Presence or absence of external environment (Modelling: Indoor only or coupled Indoor and outdoor)</th>
<th>Turbulence modelling</th>
<th>Radiation modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mauz et al., 2004) *</td>
<td>Generic &amp; Applied</td>
<td>2D</td>
<td>Indoor Modelling</td>
<td>Revised k-epsilon turbulence model</td>
<td>Surface-to-surface radiation model</td>
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<tr>
<td>(Liao et al., 2005)</td>
<td>Generic &amp; Applied</td>
<td>2D</td>
<td>Indoor Modelling</td>
<td>Realizable k-epsilon model</td>
<td></td>
</tr>
<tr>
<td>(Safer et al., 2005)</td>
<td>Generic</td>
<td>2D &amp; 3D</td>
<td>Indoor Modelling</td>
<td>Realizable k-epsilon model</td>
<td>No radiation model</td>
</tr>
<tr>
<td>(Coussirat et al., 2008) *</td>
<td>Generic</td>
<td>3D</td>
<td>1 cell thickness</td>
<td>Indoor Modelling</td>
<td>RNG k-epsilon model (recommended)</td>
</tr>
<tr>
<td>(Baldinelli, 2009)</td>
<td>Generic &amp; Applied</td>
<td>2D &amp; 3D</td>
<td>Indoor / coupled Indoor and outdoor</td>
<td>k-epsilon model with enhanced wall function</td>
<td></td>
</tr>
<tr>
<td>Pasut and De Carli, 2012</td>
<td>Generic</td>
<td>2D &amp; 3D</td>
<td>Indoor / coupled Indoor and outdoor</td>
<td>RNG k-epsilon model with enhanced wall function and k-omega SST</td>
<td>No radiation model</td>
</tr>
<tr>
<td>(Parra et al., 2015)</td>
<td>Generic</td>
<td>3D</td>
<td>Indoor Modelling</td>
<td>RNG k-epsilon model</td>
<td>P1 radiation model</td>
</tr>
<tr>
<td>(Varughese and John, 2016)</td>
<td>Generic</td>
<td>2D</td>
<td>Indoor Modelling</td>
<td>k-epsilon model</td>
<td>Discrete Ordinate Model</td>
</tr>
<tr>
<td>(Velasco et al., 2017)</td>
<td>Generic</td>
<td>3D</td>
<td>Indoor Modelling</td>
<td>RNG k-epsilon model</td>
<td>P1 radiation model</td>
</tr>
<tr>
<td>(Li et al., 2017)</td>
<td>Generic &amp; Applied</td>
<td>2D</td>
<td>Indoor Modelling</td>
<td>RNG k-epsilon model</td>
<td>Discrete ordinates (DO) model</td>
</tr>
</tbody>
</table>
DSF Parameters

A parametric study is proposed to analyse the impact of cavity width on the temperature profiles in the cavity on the inner wall. It has been stated in the literature that decreasing the cavity width, increases the heat gains as it reduces the global heat transfer coefficient of the module (Velasco et al., 2017). The study analysed the impact of the solar-shading screen aperture or opening percentage on cavity temperature and the inner wall surface temperature. The proposed kinetic modules as shown in figure 2 is abstracted to simple square apertures with openings 30%, 50% & 70% percent to cut down the computational cost and use this primary data for further refinement of the system. Then a comparison is carried between the performance of the simplified 3D model and the 3D full detailed model as shown in Figure 3.

Figure 1: Vertical section of the DSF with 40cm depth.

Table 2. Simulation Parameters

<table>
<thead>
<tr>
<th>Space Parameters</th>
<th></th>
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<td>Climate Zone</td>
<td>Hot Arid</td>
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<td>Orientation</td>
<td>South-oriented</td>
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<tr>
<td>DSF type</td>
<td>Corridor type</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity’s width</td>
<td>0.6, 0.8, 1.0 m</td>
</tr>
<tr>
<td>Aperture size</td>
<td>30%, 50%, 70%</td>
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</table>

Material Properties

Physical and optical properties for the DSF elements used in all the study cases. Layer thicknesses were assigned in the studied model following common practices in architecture.

Table 3. Physical properties of DSF elements

<table>
<thead>
<tr>
<th>Façade Element</th>
<th>ρ (kg/m^3)</th>
<th>Cp (J/kg·K)</th>
<th>k (W/m·K)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>2.700</td>
<td>900</td>
<td>0.8</td>
<td>6 mm</td>
</tr>
<tr>
<td>Internal wall</td>
<td>1400</td>
<td>800</td>
<td>0.6</td>
<td>250 mm</td>
</tr>
<tr>
<td>Slab</td>
<td>2240</td>
<td>960</td>
<td>0.8</td>
<td>250 mm</td>
</tr>
<tr>
<td>Fabric screen</td>
<td>585</td>
<td>1624</td>
<td>0.16</td>
<td>6 mm</td>
</tr>
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</table>
Location and Climzatic Conditions of the DSF
The south oriented DSF located in Cairo, Egypt (30.044° N – 31.34° E). Climatic data for outdoors temperature for a peak summer day (15th of July) at 12:00 pm was taken from open-access databases.

Modelling and simulation
Three-dimensional geometries were created in Rhino and then the meshes were built with ANSYS ICEM CFD. Then, the numerical models and simulations using the software package from ANSYS were processed.

Meshing
The meshing was built with ANSYS ICEM CFD and mesh selection was based on case-by-case basis. Hexahedral cells were selected in the cavity without solar-shading cases while tetrahedral cells were selected for the cases with solar shadings. A refined mesh around all solid surfaces was set in order to model the thermal boundary layers created at the solid-fluid surface contacts. Prism layers (Tetra meshing) is not efficient for capturing shear or boundary layer physics. Using inflation elements along surfaces efficiently increases boundary layer resolution perpendicular to the wall, allowing you to capture these effects. With ANSYS ICEM CFD, mixed prism and tetra generation is automatic and intelligent, creating prism layers near the surface while maintaining the ease and automation of Tetra mesh. Mesh independency tests were done through series refinements to select the optimal size. The mesh used for the 1 m without solar-shading was 1,149,600 hexahedral cells, while the mesh used for the cavity with full detailed solar-shading reached 16,476,700 tetrahedral cells.

Boundary conditions and solver set-up
The study was conducted through three-dimensional (3D) modelling using CFD code Ansys Fluent® v18.1. At present, the commercial CFD code allows coupled thermo-fluid-dynamics problems to be solved using turbulence and radiation sub-models. Some recent studies (Coussirat et al., 2008; Parra et al., 2015; Velasco et al., 2017) have recommended k-epsilon turbulence model and P1 radiation model for better performance prediction. The full buoyancy effect in the RNG k-epsilon turbulence model was turned on during the simulations. The Enhanced Wall Treatment was adopted for the RNG k-ε model. Air was chosen as the simulation fluid, for which the constants were available in the software database. The fluid was set to be incompressible ideal gas and in a turbulent flow regime to make variables temperature-dependent. Solution scheme was set as PISO pressure–velocity coupling due to its suitability for buoyancy-affected flows.

Numerical convergence of the model was checked based on the normalized numerical residuals of all computed variables. The target for all residuals was to drop for less than $1 \times 10^{-3}$ for all solved equations except energy and radiation to $1 \times 10^{-6}$. The number of iterations was doubled to be sure of the stability of the results. Thermal boundary conditions for the exterior and interior layers were imposed as convective and radiative heat fluxes and convective heat flux respectively. Convection coefficient was set to 12 W/m$^2$K for outdoors glazing surfaces. This value was taken in reference of reported external convection coefficients for similar weather conditions of Barcelona, Spain on warm, sunny summer day (Parra et al., 2015; Velasco et al., 2017). Regarding the indoor heat exchange, it was assumed that the indoor desired temperature is 24°C, while the internal convection coefficient is considered to be 8 W/m$^2$K for the inner glazing surface.

Numerical model validation
A well-documented experimental database for a south oriented DSF from (Baldinelli, 2009) was selected to validate the CFD code for a kinetic shading system on a single storey building. When the shading system closes, it performs as a DSF. The location is in central Italy as indicated by the original study. The dimensions and boundary conditions of Baldinelli model DSF were exactly reproduced to allow accurate results. Visible solar radiation absorbed by the DSF elements in summer configuration as well as Mid cavity temperature profile are measured, compared and matched data documented in the original research as shown in figure 6.
Results and discussions

Temperature profiles inside the DSF cavity are obtained to qualitatively assess the DSF thermal performance. The first set of simulations tested the cavity width parameter for unventilated and naturally ventilated cavities. Figures 7 and 8 shows the mid cavity temperature evolution comparing the three cavity widths (0.6 m, 0.8 m & 1.0 m) for both unventilated and naturally ventilated cavities at 12:00 pm 15th of July, around peak solar radiation is expected. The results obtained from the preliminary analysis of the cavities without solar-shadings showed significant difference between the unventilated and naturally ventilated DSF. The unventilated cavities resulted in extremely higher cavity and surface temperatures as shown in figure 7 & 8. Figure 9 provides a summary statistic for the external and internal surface temperatures for the three cavity widths in unventilated and naturally ventilated cavities.

The results show that the 1 m width naturally ventilated cavity without shading resulted in a drop of 7.5 °C between external and internal surface temperatures. While the 0.8 cavity resulted in a drop of 7°C and the 0.6 cavity resulted in a drop of 6.5 °C. It was found that increasing the cavity width can improve the thermal performance of the DSF, and internal surface temperatures.

Figure 6: (a) Visible solar radiation absorbed by the DSF results by (Baldinelli, 2009) (b) Visible solar radiation absorbed by the DSF elements reproduced by the researcher.

Figure 7: Mid cavity temperature contours for the studied unventilated cavities with (0.6 m, 0.8 m & 1.0 m) widths.

Figure 8: Mid cavity temperature contours for the studied naturally ventilated cavities with (0.6 m, 0.8 m & 1.0 m) widths.

Figure 9: Comparison of inner surface temperature for the studied three cavity widths for the ventilated & unventilated cavities.
Figure 10: Mid cavity temperature and air velocity contours for the 1.00m cavity with shading screen (simplified and detailed).
According to the previous results, the 1 m cavity is chosen for installing the solar-shading screen and assessing the thermal performance of three solar-shading opening percentages; 30%, 50% & 70%; to detect the optimal setting that prevent interior over-heating measured as reduction of the solar load entering the building. The shading screen is installed at the highest temperature profile to activate the smart system thermally. The highest temperature profile is found to be in the range between 0.1m and 0.2m away from the outer glass. After installing the screen, the cavity temperature decreases as shown in figure 10 due to lower solar radiation and the heat absorbed by the solar-shading. The results obtained from the simulation runs for the shaded cavities are summarized in figure 11. The results of average surface and cavity temperatures for the shaded DSF in all cases are lower than the values reported for the DSF cavity without a shading system. The detailed 3D model of the solar shading resulted in more accurate results compared to the simplified/abstracted model. The 3D model with the double curved surfaces influenced the flow inside the cavity, and resulted in a different thermal performance. A difference in the results has recorded around 8 °C between simplified and detailed 3D model.

In the detailed model, the 30% aperture resulted in a drop of 9.5 degrees in the surface temperature of inner surface more than the cavity without shading case, the 50% aperture resulted in a drop of 8.5 degrees and the 70% aperture resulted in a drop of 4 degrees. As shown in figure 10 and 11, the 30 % aperture recorded lower surface temperature than the 50% and 30% aperture. These lower surface and cavity temperatures may improve the DSF thermal performance by reducing the conductive/convective heat transfer towards the building interior.

The analysis of the thermal conditions along the shading device read a difference of 3 degrees in temperatures as shown in figure 10 which might affect each smart material sensor differently resulting in slightly different aperture size for each module.

Comparing the performance of the ventilated DSF with and without shading devices, the detailed model of shading devices of 30% aperture size is predicted to decrease the internal surface temperature by approximately 25% reductions in temperature.

**Conclusion**

This paper tested the DSF cavity conditions and measured the surface and cavity temperatures, to detect the activation temperatures required to activate the responsive solar shading system. It is recommended to use the Embedded Shape Memory Alloys (SMAs) with actuation temperature 35-40 degrees Celsius. The SMAs are activated at this temperature and start to change its form resulting in a closing configuration that affords more shade. Then it gets back to its original form when the temperature goes below the activation temperature.

This range of temperature is achieved inside the DSF cavity in a hot arid climate at peak daily temperatures and solar radiation times.

The effects of several DSF parameters as cavity’s width, screen position and aperture size showed a significant role in controlling DSF’s performance. It was found that increasing the cavity width can improve the thermal performance of the DSF. The location of the solar-screen can also affect the thermal performance of the façade. The closer the solar-shading screen to the outer glazing, the lower the solar heat gains. The paper recommended an integrated responsive solar-shading system within 1.00m wide DSF cavity where the screen is located in the range between 10 and 20 cms away from the outer glass to be activated. Apertures of 30% resulted in good thermal performance in the cavity. A balance between the energy model and daylighting requirement need to be further studied to optimize the aperture size.

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**Figure 11: Inner and outer surface temperatures for the shaded 1m naturally ventilated cavity (simplified vs detailed).**

<table>
<thead>
<tr>
<th></th>
<th>Ventilated cavity without shading (Basecase)</th>
<th>Abstracted-30</th>
<th>Detailed-30</th>
<th>Abstracted-50</th>
<th>Detailed-50</th>
<th>Abstracted-70</th>
<th>Detailed-70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer surface</td>
<td>46.1</td>
<td>42.0</td>
<td>36.5</td>
<td>42.9</td>
<td>36.7</td>
<td>43.9</td>
<td>36.6</td>
</tr>
<tr>
<td>Inner surface</td>
<td>38.6</td>
<td>38.2</td>
<td>29.1</td>
<td>38.3</td>
<td>30.1</td>
<td>38.5</td>
<td>34.4</td>
</tr>
</tbody>
</table>
More simulations have still to be done on annual basis to study the range of deformation needed for the kinetic modules and the overall benefits of the solution. Further experimental investigations are needed to validate the numerical results.

Acknowledgment
I would like to thank Dr. Dominic Flynn, for his guidance and advice regarding Ansys software simulations.

References