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Double Skin Facade and Opening Configurations Effect on Indoor Air Distribution

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Abstract: Double Skin Facade (DSF) is a popular architectural feature created by adding a fully glazed surface to the conventional facade. Different parameters, such as climatic conditions influence DSF performance with significant impact on its efficiency. DSF construction provides an appropriate platform to apply natural ventilation within the building and DSF cavity. But, air cavity overheating is one of the prominent disadvantages on the warmer days due in most partto high solar radiation absorption. In this case, the airflow direction is important not only to prevent hot air entry but also to improve indoor ventilation which provides higher thermal comfort. The lack of precedent research on DSF performance in hot and humid climates compels these researchers to study DSF performance in the indicated conditions. The study aims to examine various opening configurations of DSF to evaluate their effects on indoor air velocity, air direction and temperature distribution using simulations of the Malaysian climate. Simulation results indicate the influenceof opening configurations on DSF performance, especially on indoor airflow directions.

Key words: Simulation, computational fluid dynamic, design builder, double skin facade, natural ventilation

INTRODUCTION

Double Skin Facade (DSF) is an architectural phenomenon that appeared with the growth in technology and is studied by architects and engineers for providing various advantages for buildings. DSF construction includes 3 sections: The external glazing, intermediate space or cavity and internal facade. The external glazing protects building against outdoor conditions and provides acoustical insulation against external noise (Ding *et al*., 2005). The intermediate cavity provides an appropriate air gap for stack effect, insulation and providesa space for installing shading devices. In some cases, it is used as a circulation path located around the building. Although, the idea of double facade is not new, the desire to utilize DSF has expanded. Architects utilize DSF for different purposes, such as thermal, ventilation and acoustic insulation and lighting aims (Gavan *et al*., 2010).

Researches have demonstrated the advantages of DSF and its impact on occupants' thermal comfort, as well as building efficiency. DSF with thermal mass has a unique energy saving advantage (El-Sadi *et al*., 2010). Saelens *et al*. (2003) in energy performance assessment of Multiple-Skin Facades has proven the feasibility of enhancing the building energy efficiency in some way using DSF. The share of the buildings in energy consumption which is one third of the total energy usage in developed countries and expanding energy consumption for mechanical ventilation systems and air-conditioning devices reveal the importance of energy reduction methods in buildings (Allocca *et al*., 2003).

Also, DSF is capable of impacting occupants' thermal comfort level (Hien *et al*., 2005; Huckemann *et al*., 2010; Zhou and Chen, 2010) which isa vital criterion for occupied spaces. Fanger (1970) defined thermal comfort, as that condition of mind which expresses satisfaction with the thermal environment. Based on the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standard 6 main parameters influence the thermal comfort including metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity and humidity (ASHRAE, 2004). This classification indicates natural ventilation with direct effect on internal air velocity is one of the most influencing parameters in the occupants' thermal satisfaction. Although, ASHRAE is the global standard, prior researches indicate it should be adapted in different climates (Al-Tamimi and Fadzil, 2011; Szokolay, 2008). Thus, numerous studies have been carried out in hot and

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humid climates to figure out the range of thermal comfort particularly under natural ventilation conditions (Busch, 1992; Webb, 1959). Al-Tamimi and Fadzil (2011) achieved 25.5-28°C, as an acceptable internal temperature of naturally ventilated space in hot and humid climate while the humidity was between 40-60% and internal air velocity was 0.3-0.5 m sec^{-1}. Also, the thermal comfort temperature range of 24.2-29.2°C has been mentioned by Abdul Rahman (1999) for naturally ventilated buildings in the hot and humid climate of Malaysia. Indeed, these researches reveal the importance of the ventilation rate and internal air velocity to define and achieve thermal comfort range. In this way, examining the ventilation performance of DSF will be significant to find out its effects on internal thermal conditions.

The ventilation performanceof DSF depends on numerous parameters, such as ventilation strategy (Gratia and de Herde, 2007a; Shameri *et al*., 2011), awning position and size, operable schedule (Gratia and de Herde, 2004a) and climatic parameters (Chan *et al*., 2009; Gratia and de Herde, 2004b). Also, concentration on simulation results shows that the combination of DSF and proper natural ventilation strategy can minimize energy consumption while improving thermal comfort (Hien *et al*., 2005).

Generally, natural ventilation in buildings occurs due to two phenomena wind force or aero-motion caused by air pressure difference and buoyancy driving force or stack effect caused by temperature differences between the inside and outside of the building (Bassiouny and Koura, 2008). Solar chimney strategy is based on the pressure and temperature difference between the top and bottom of vertical spaces which force the air to rise. Indeed, it is a thermo-syphoning air channel that creates airflow due to thermal buoyancy (Zhai *et al*., 2011). Solar radiation absorption through external facade leads to expansion ofair temperature and reduction of density. It causes air within the vertical channel to rise and exit through the top of the chimney (Lee and Strand, 2009). Utilizing solar chimney strategy strongly exhibits significant enhancement on indoor natural ventilation (Afonso and Oliveira, 2000).

Special assembly is needed to provide the natural ventilation with the solar chimney strategy. The construction and elements of DSF produce a proper potential for integration with solar chimney strategy and improvement of indoor air velocity. The external glazed facade is able to absorb high amounts of solar radiation and vertical intermediate cavity provides an appropriate space to implement solar chimney strategy. Ding *et al*. (2005), examined the combination of DSF and solar chimney to improve natural indoor ventilation by small-scale experimental test and numerical methods. He studied different settings for windows and solar chimney and proved this strategy is able to enhance indoor air ventilation. Gratia and de Herde (2007b) provided a guideline for natural ventilation performance of DSF based on different wind velocities and directions. Her guideline indicates the importance of internal and external opening position, as well as outside wind direction on indoor airflow pattern provided by DSF. Additionally, concentration on simulation results reveals that the combination of DSF and an appropriate natural ventilation strategy lead to minimizing energy usage while improving thermal comfort (Hien *et al*., 2005).

Although, researchers have examined the DSF performance in different ways, a deficiency of research prevails on DSF performance integrated with a solar chimney for enhancing natural ventilation, especially in hot and humid climates. Natural ventilation efficiency deeply depends on the design and performance of the facade awnings playing major role on airflow in and out (Moghaddam *et al*., 2011). The accurate ventilation design and strategy is vital for buildings using natural ventilation systems or for buildings based on the hybrid ventilation. Cavity overheating provides excessive hot air which can enter the building spaces, if appropriate strategy and optimization are neglected during the design process. Poor design in this section leads to uncomfortable spaces, low indoor life quality and reduction inoccupants' productivity (Stavrakakis *et al*., 2009). In this study, therefore various opening configurations of DSF are examined to evaluate their effects on indoor airflow patterns and to find outopening configurations which protect indoor conditions against cavity overheating, particularly in the hot and humid climate of Malaysia.

MATERIALS AND METHODS

Building simulation: The study impact of DSF opening configurations on indoor airflow and temperature in natural ventilation conditions utilizing simulation with Computational Fluid Dynamic (CFD). Different methods have been proposed to study natural ventilation and air movement, such as empirical, small-scale experimental, full-scale experimental, multi-zone, zonal and CFD models (Chen, 2009). Although, CFD was introduced for industrials proposes, it has now become a common method to evaluate ventilation inbuildings (Asfour and Gadi, 2007).

Researchers have employed simulation with CFD to predict airflow pattern, air velocity and air direction inside and outside of the buildings (Cheung and Liu, 2011;

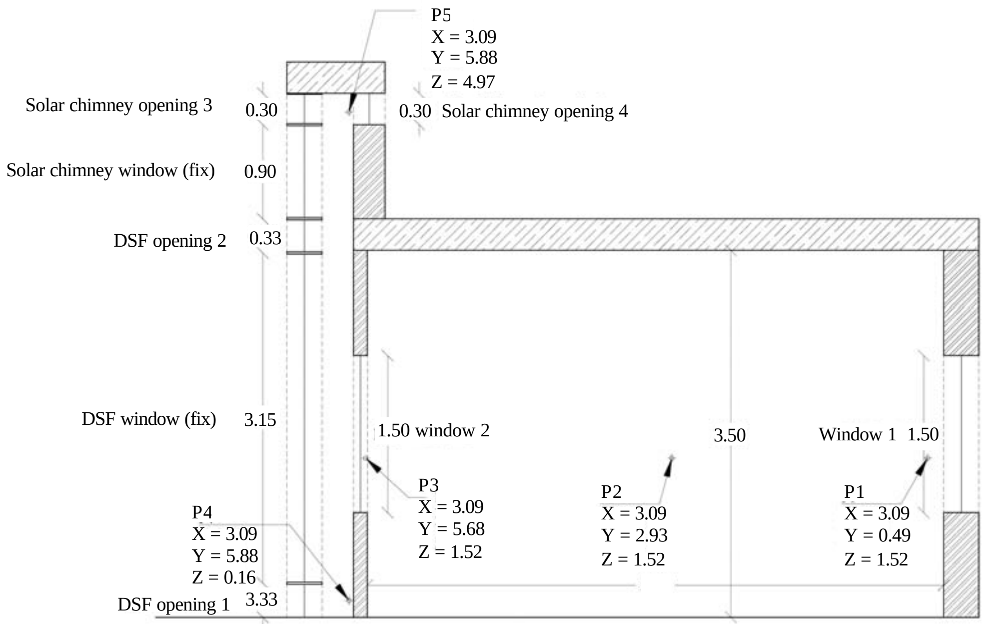

Fig. 1: Model geometry, openings location and monitoring points coordination

Table 1: The 1st phase configurations, air gap width (cm) and opening area (%)

Simulation No.	Window 1 (%)	Window 2 (%)	Air gap width (cm)	DSF opening 1	DSF opening 2	Solar chimney opening 3 (%)	Solar chimney opening 4
1	50	50	-	-	-	-	-
2	100	100	-	-	-	-	-
3	50	50	30	-	-	90	-
4	100	100	30	-	-	90	-

Larsen *et al*., 2011; Nahor *et al*., 2005; Ramponi and Blocken, 2012; Susin *et al*., 2009). Also, simulation with CFD has been usedtopredict the performance of DSF (El-Sadi *et al*., 2010; Mingotti *et al*., 2011; Pasut and de Carli, 2012; Takemasa *et al*., 2009) and solar chimney (Amori and Mohammed, 2012; Bassiouny and Korah, 2009; Hami *et al*., 2012).

In this research, Design Builder Software version 3.2.0.067 has been employed using energy plus and standard k-ε turbulent model for calculations. Ventilation verification and validation of the software in natural ventilation conditions have been reported by the researchers (Baharvand *et al*., 2013). To achieve accurate results in design builder, simulations are run for each configuration and the results of simulations are used, as an input data for CFD calculations. The weather data of Kuala Lumpur, Malaysia is used for this study and all simulations are run on the 21st of March suggested and applied, as a design day in Kuala Lumpur (Abdullah and Wang, 2011).

Model geometry and table of simulations: To obtain the aim of the research, a single room with DSF on the North elevation is modeled. The room dimensions are 6.5×5.5×3.5 m and windows are located on the North and South elevations with 2.45 m length and 1.5 m height (window 1 and 2). DSF is modeled on the North orientation of the room with fixed 30 cm air cavity in all simulations. About 4 openings are assumed between vertical cavity and outside which are located at the bottom of the DSF, at the room ceiling level, at the top North and top South face of the solar chimney. Also, 5 monitoring points (P1-5) are defined inside the model in order to obtain accurate CFD results. Figure 1 shows the room, DSF, solar chimney and window dimensions, as well as coordinates of monitoring points.

The simulationsare divided into 2 phases. In the 1st phase, the airflow pattern of the room integrated with DSF is compared with a simple room without DSF (CFD1-4). The 2nd phase examines the impacts of different opening configurations on internal air pattern and temperature (CFD5-15). Total 4 simulations are run in the 1st step based on Table 1 and 10 simulations are run based on the different configurations during 2nd step (Table 2). In all configurations, the open areas are assumed in the top part of the openings.

Table 2: The 2nd phase configurations, air gap width (cm) and opening area (%)

Simulation No.	Window 1 (%)	Window 2 (%)	Air gap width (cm)	DSF opening 1	DSF opening 2	Solar chimney opening 3 (%)	Solar chimney opening 4
5	30	30	30	-	-	-	-
6	30	30	30	50	-	-	-
7	30	30	30	-	50	-	-
8	30	30	30	-	-	50	-
9	30	30	30	-	-	-	50
10	30	30	30	50	50	-	-
11	30	30	30	50	-	50	-
12	30	30	30	50	-	-	50
13	30	30	30	-	50	50	-
14	30	30	30	-	50	-	50
15	30	30	30	-	-	50	50

RESULTS AND DISCUSSION

The 1st step is to find out the DSF and solar chimney effects on internal air velocity and temperature. To achieve this aim, four simulations are run with two different opening areas in the simple room and room integrated with DSF. CFD1 and 2 are examined, the internal air velocity of the simple room (without DSF) with 50 and 100% openings, respectively (Table 1). The results are compared with the room integrated with DSF through CFD3 and 4. As Fig. 2 indicates the air patterns of these cases are dissimilar and although, both cases show very low air velocity, CFD1 is able to provide a better airflow pattern in the lower half of the room. The existing ventilation and air velocity rate cannot be felt by occupants due to the very low speed. Thus, it cannot affect occupants' thermal comfort.

CFD3 and 4 are run for the room with DSF and solar chimney strategy in no-wind condition with 50 and 100% open space, respectively (Table 1). The DSF opening 1 and 2 are closed and only solar chimney opening number 3 is open. Both CFD3 and 4 show higher air velocity in comparison with CFD1 and 2 and 0.3 m sec^{-1}, air velocity is observed around window 1 in CFD4 and both window 1 and 2 in CFD3 (Fig. 3). Although, CFD3 and 4 show different temperature distributions within the room, the temperatures at 1.5 m altitudeare similar and slightly lower than those of the simple room. The results indicate that DSF and solar chimney strategy are able to improve indoor air velocity and reduce temperature in comparison with simple room in the no-wind condition. Also, better air pattern and velocity are achieved with half-open windows in comparison with entirely open windows.

As mentioned, external wind direction has a significant effect on DSF performance and indoor airflow direction. So in the 2nd part, different opening configurations are examined in the room with DSF with external wind to findout their effects on indoor air velocity, airflow direction and room temperature. Table 2 shows the CFD5-15 with different DSF and solar chimney opening configurations. The external wind velocity and direction in these simulations are 1.43 m sec^{-1} and North to South, respectively based on Kuala Lumpur weather data with room windows fixed on 30% opening to provide equal conditions in all configurations.

CFD5 without any opening in DSF and solar chimney is run to have an index for comparison (Fig. 4a). In this configuration, maximum air velocity is observed near window 1 with 0.25 m sec^{-1} which is limited to the small area while the air velocity at window 2 is inconsiderable. Due to the low airflow, there is not a clear wind direction between room and DSF. The center of the room and top of the solar chimney do not show remarkable air movement and temperature distribution is approximately uniform in all parts of DSF and solar chimney. This conditions lead to the absence of vertical air movement within the air cavity (Fig. 4b). Also, temperature distribution in the room does not show remarkable changes in 1.5 m height except near window 1 due to higher air velocity of the area (Fig. 4b).

CFD6 is based on the lower opening of DSF and closing other DSF and solar chimney openings (Table 2). In this configuration, air enters the DSF cavity from the bottom and moves into the room through window 2 (Fig. 5a). So, the air velocity shows remarkable improvement in this configuration and is around 0.3 m sec^{-1} in window 2. The highest airflow is in the upper half of the room with no significant airflow in the lower part while the upper part of the solar chimney does not show remarkable air movement. This opening configuration provides the airflow direction from DSF to the room, unpleasant for the occupants, since it makes the room warmer than the air cavity.

In CFD7, the top awning of DSF (DSF opening 2) is open, causing a similar scenario, as the previous configuration within the room (Fig. 5b). The air pattern in DSF is different due to higher opening level. Although, highest air velocity is observed near window 2 in the air cavity which is around 0.52 m sec^{-1}, the effect of this air velocity on the internal air pattern is lower than CFD6. The wind direction is still unpleasant and raises the temperature of the room in comparison with DSF cavity.

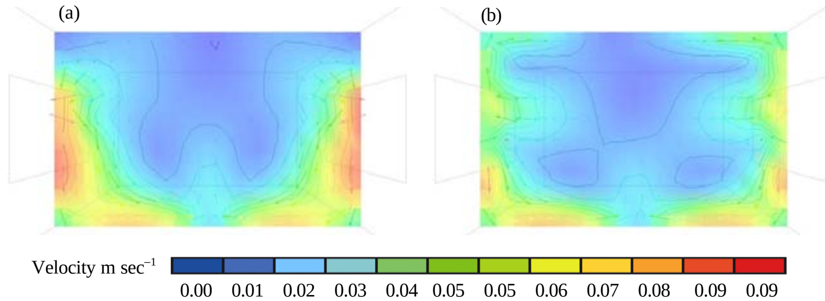

Fig. 2: a) CFD1 air velocity; b) CFD2 air velocity

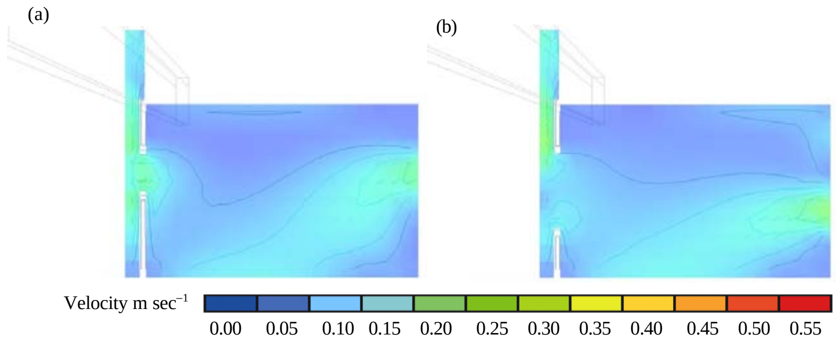

Fig. 3: a) CFD3 air velocity; b) CFD4 air velocity

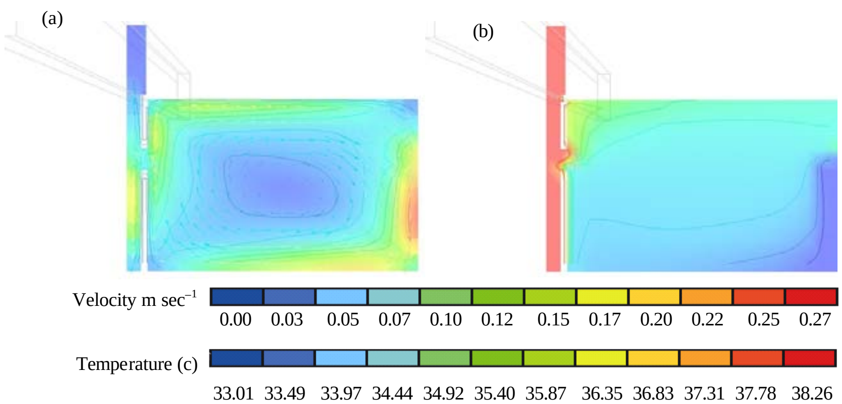

Fig. 4: a) CFD5 air velocity; b) CFD5 temperature distribution

CFD8 is based on the airflow of solar chimney opening 4 which is located on the windward side of the chimney. Although in this condition, airflow direction is again from DSF to the room, the indoor air pattern is changed and the lower half of the room has been affected more than the upper part (Fig. 6a). The air velocity at window 2 is approximately 0.32 m sec^{-1} and the maximum rate in this configuration is observed in the DSF air cavity, at around 0.7 m sec^{-1}. The average room temperature in the center is around 35°C which is 2°C higher than DSF.

In the next configuration (CFD9), the solar chimney opening 4 is open on the leeward side of the chimney. The significant change in this opening configuration is the airflow direction from room to the DSF and against the previous configuration (Fig. 6b). As Fig. 6b indicates fresh air flows into the room from window 1, passes through and enters the cavity through window 2. The used air rises up in DSF and exits through solar chimney opening 4 and the majority of the airflow is in the lower half of the room, felt by the occupants. The room temperature is 32.12°C and this airflow direction makes the room cooler than the DSF, since it prevents the warm air of the DSF from entering the room.

CFDs 10-15 show airflow patterns and temperatures of configurations based on the combination of two

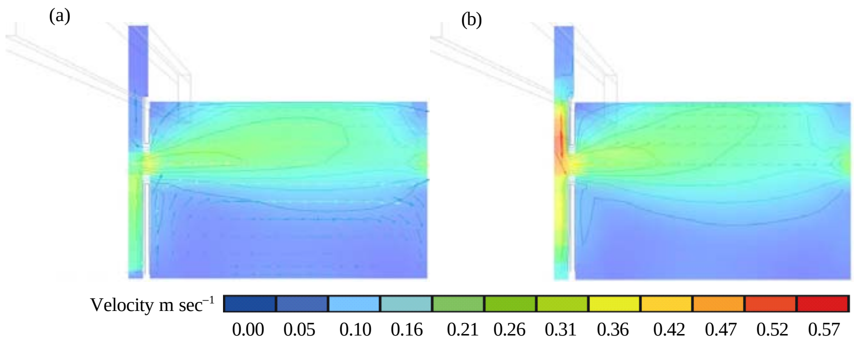

Fig. 5: a) CFD6 air velocity; b) CFD7 air velocity

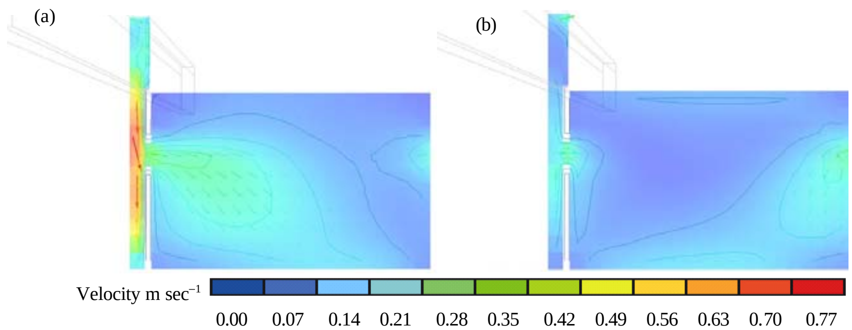

Fig. 6: a) CFD8 air velocity; b) CFD9 air velocity

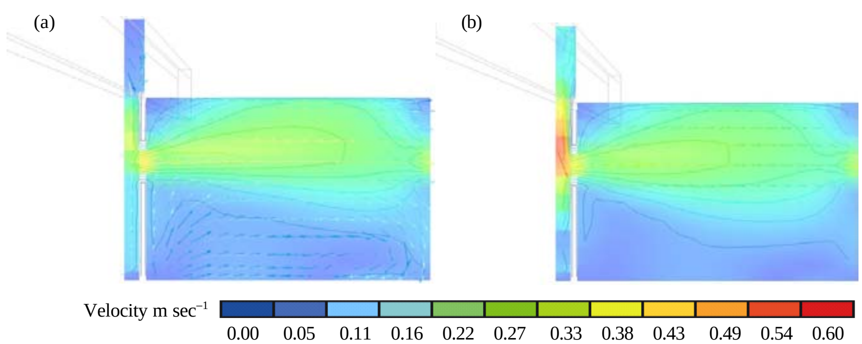

Fig. 7: a) CFD10 air velocity; b) CFD12 air velocity

openings in DSF and solar chimney (Table 2). DSF openings 1 and 2 are open in CFD10 which cause wide air movement patterns within the room (Fig. 7a) while the higher air velocity is limited to the upper half the room and the maximum air velocity is around 0.3 m sec^{-1}. Similar to the previous configurations except CFD9, the airflow direction is from DSF to the room and causes excessive heating in the room. CFD11 is very similar to CFD10 and does not provide a better condition for occupants. CFD12 is based on the low DSF opening (DSF opening 1) and solar chimney opening 4, on the leeward side of the chimney. Airflow direction does not change under this condition and it’s from DSF to the upper half of the room (Fig. 7b). This pattern cannot provide an effective airflow to achieve thermal comfort for occupants. Also, higher room temperature is observed in comparison with DSF air cavity.

CFD13 and 14 are run by configuring DSF opening 2 with the solar chimney opening 3 and 4. In both cases, the airflow direction is from DSF to the room which causes higher temperature in the room than the DSF air cavity. Two windward openings in CFD13 lead to straight indoor air movement in the upper half of the room while in CFD14 the circular pattern is observed due to two different opening sides (Fig. 8). The maximum air velocity within the room in CFD13 is around 0.4 m sec^{-1} and in

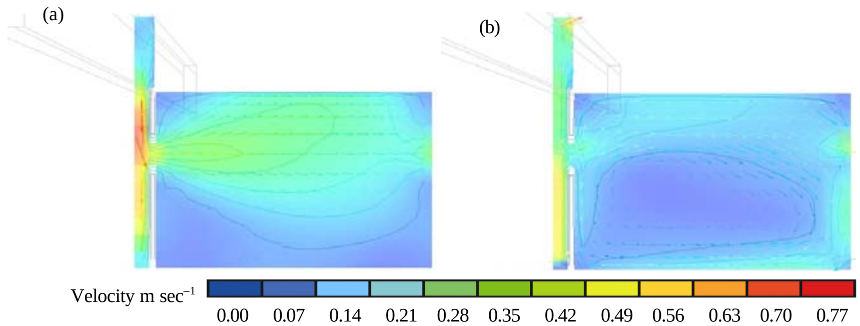

Fig. 8: a) CFD13 air velocity; b) CFD14 air velocity

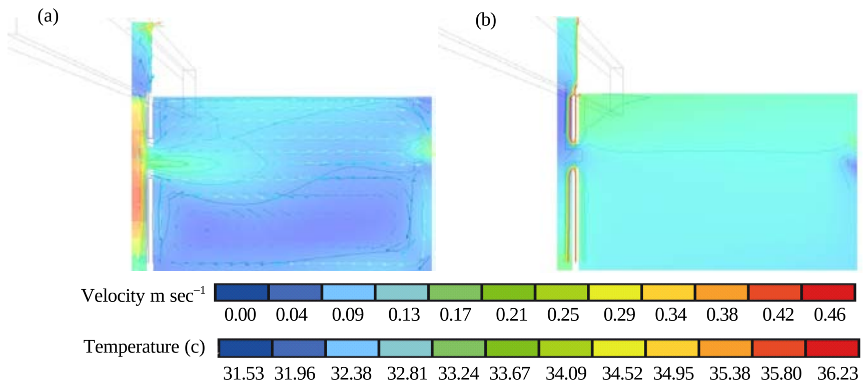

Fig. 9: a) CFD15 air velocity; b) CFD15 temperature distribution

CFD14 around 0.22 m sec^{-1}. The average temperature of 33°C is considered in both cases with slight differences.

CFD15 is the last configuration formed based on the solar chimney openings 3 and 4. In this configuration, the airflow direction does not change and air flows from the room to the air cavity. It is more effective in the upper half the room and poor circular pattern is created (Fig. 9). The room temperature is around 32.81°C and the maximum air velocity is 0.21 m sec^{-1} near window 2.

CONCLUSION

Double Skin Facade (DSF) performance strongly depends on prevailing climatic conditions. Thus, the optimization of the DSF is necessary for each climate. Overheating of DSF cavity is one of the main problems preventing the wide usage of DSF in countries with hot climates. This study aims to evaluate, various opening configurations of DSF to provide appropriate indoor natural ventilation in hot and humid climates under a stable external wind velocity and wind direction.

Along the first phase, the performance of DSF attached to a simple room is compared with a simple room without DSF and this comparison is done under no-wind conditions. The results indicate DSF and solar chimney strategy is able to improve natural ventilation and decrease the temperature within the room. In a 2nd phase, the indoor natural ventilation is examined under 10 opening configurations. Different airflow patterns are observed and except CFD9 in all other cases the airflow direction is from DSF to the room. This airflow direction creates an excessive temperature due to higher DSF cavity temperature in comparison with the room. Indeed in all cases except CFD9, overheating of DSF cavity due to high solar radiation absorption affects the indoor conditions in an unpleasant manner for occupants.

The acceptable airflow direction is onlyobserved in CFD9 which provides airflow from room to the DSF cavity. Although, it cannot provide thermal comfort conditions within the room with this configuration the temperature of the room is lower than DSF cavity and acceptable airflow is created in the lower half of the room. Thus, it can be concluded that the performance of DSF and especially, the internal airflow direction strongly depends on the opening configurations and external wind directions. Also, DSF can be an effective approach during the hot days if it is calculated and optimized accurately.

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