A Study of Thermal Environment in the Semi-open Prayer Pavilion in the Gulf Region

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ABSTRACT
Affected by local climate in the Gulf, the thermal environment in the semi-open prayer pavilion differs widely from those in conventional buildings. In this paper, the thermal environment in the outdoor prayer pavilion under three different flow patterns which are sidewall air supply and sidewall return(SSSR), sidewall air supply and opposite return(SSOR) and floor air supply and around sidewalls return(FSASR) are simulated under local weather conditions. Followed by discussions and comparisons are made through various cases and based on the thermal sensation index (TSI) which is suitable for the environment in Gulf. The FSASR flow pattern is found to be the suitable airflow organization for the thermal environment in the prayer pavilion. This paper also provides reference for the design of outdoor environment in tropical regions.

KEYWORDS
Prayer pavilion, Thermal environment, Flow pattern, Thermal sensation index

INTRODUCTION

In the Gulf, there are lots of outdoor pavilions for Muslims to pray. The architectural structure of the prayer pavilion is illustrated in Fig. 1, the inner space is 5*5 m^2(Width * Length), the bottom of the membrane heights 2.7m, clearance height is 0.8m from the roof pinnacle. The daily average temperature is very high there (Alajmi and Hanby 2008). In Doha, the highest temperature reaches 51℃ in the summer of 2010, highest soil temperature 32.2℃, average wind speed 6m/s and average relative humidity 49%(Anon.). As the prayer pavilion is semi-open, the cooling capacity can easily be carried away by the outdoor wind due to the high temperature difference, common air conditioning system is not sufficient to sustain a stable and comfortable thermal environment there. Increasing adoptions of outdoor partial enclosing measurements such as membrane roof and semi-opened glass makes it more possible to create a comfortable outdoor environment in a mild climate (Pagliarini and Rainieri 2011). However, few reports are available concerning the outdoor air-conditioning system in such

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regions as the Gulf characterized by its high temperature and windy desert area. Hence, it’s necessary to initiate the research with a focus on this space.

RESEARCH METHODS

One of the advantages of CFD technology is its capability to validate and optimize the design in advance (Q. Chen, Ph, and Srebric 2002). With CFD software, al.(Murakami 2006) discussed the key factors while designing the outdoor environment which can be affected by many factors. This paper proposes 3 different airflow patterns and studies them by comparing the cooling capacity, distribution of TSI and temperature field in various cases.

CASE-A: Sidewall air supply and sidewall return (SSSR) is the air flow pattern that is most commonly used. The outlet and intake of the air are both located on one side of the glass wall. The air supply outlet is 5m long and 200mm wide and the return air intake is also 5m long but 400mm wide, as in Fig. 2. The supply and return air have the same volume.

CASE-B: Comparing with SSSR, sidewall air supply and opposite return (SSOR)facilitates the cooling capacity to spread wider space with the momentum of supply air and the suction of the air flow intake. During the design, to limit the air speed within the pavilion the air supply outlet is expanded, which is 600mm wide, 5m long and located 900mm above the floor, as in Fig. 3.

CASE-C: Floor air supply and around sidewalls return (FSASR) flow pattern supplies the cool air directly into the occupied zone from below the floor. To avoid the intake of the hot natural wind, the air return intake is located at the downside of the glass wall which is 500mm in width. In engineering practice, the entire structure is placed at a higher level to fix condensers and heat-exchangers below and the supporting structure for the membrane roof is placed outside of the pavilion, so the roof is bigger. To place aisle, there is fewer air supply inlets on one side of glass walls, as shown in Fig. 4. The impact of air duct is ignored.

As to comfort evaluation, PMV can well predict the indoor thermal comfort and is widely used. However, al. (Ho 2002) discovered that PMV is not suitable to evaluate dynamic thermal environment. Al. (Cheng et al. 2012) confirmed that PMV may cause big deviation at points far from neutral point. Al. (Jing-feng 2005) found PMV could get error conclusion under high temperature. The climate in the Gulf area is much far from comfort; therefore PMV cannot be used as an evaluation criterion there. Thermal sensation index is a new evaluation criterion based on field study under various conditions of a certain climate (Cheng et al. 2012) and the results differ between regions for different climate. This paper chooses the formulation employed in the field study in Israel (Givoni et al. 2003) where the climate has the same characters thus it can better illustrate the thermal comfort in the Gulf region.

$$TSI=0.033\times SR+0.22\times DBT-0.05\times WS-2.3 \quad (1)$$

In the formulation, TSI ranges from 1 to 7 and the neutral point is 4, SR refers to the solar radiation to people, W/m2； WS is wind speed, m/s； DBT is air temperature, ℃.

The outer flow field is set to be 35m*35m*15m, according to al. (Can et al. 2007). Octree method is used to build tetrahedral mesh and prism mesh is adopted on the surface of air outlet and intake. In addition, partial refinement technology is used in some critical locations like roof and glass walls. The number of cells in each case is shown in table 1.Turbulence is described with RNG κ—ε model, and boussinesq hypothesis is adopted. The equation is solved using SIMPLE scheme, and then calculated with equation 1 to get TSI distribution.

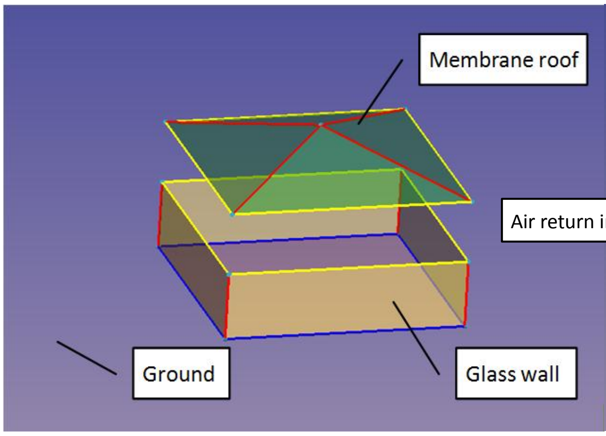


Figure 1. *Structure of prayer pavilion*

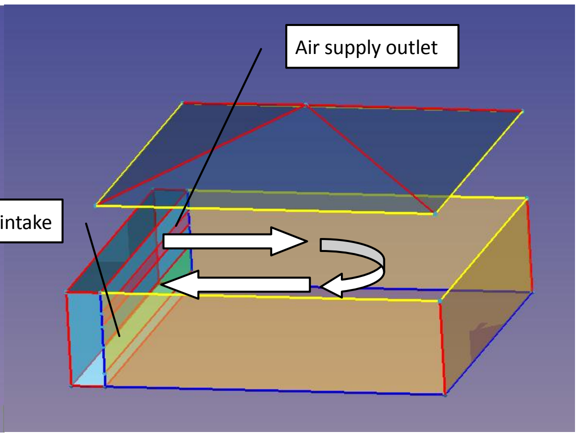


Figure 2. *Structure of CASE-A (SSSR)*

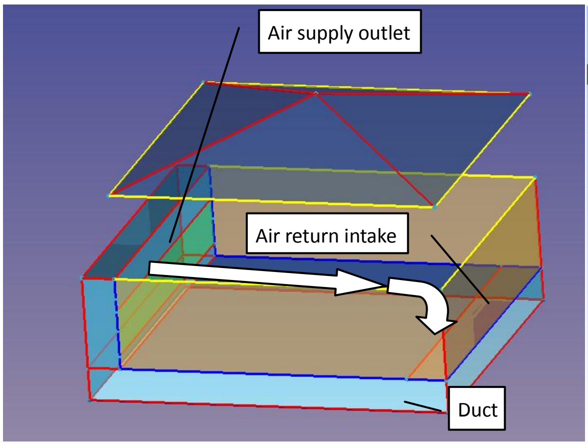


Figure 3. *Structure of CASE-B (SSOR)*

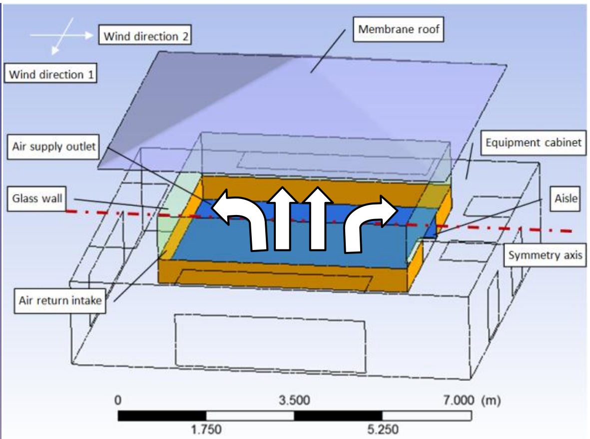


Figure 4. *Structure of CASE-C (FSASR)*

Table1. *The number of cells in each case*

	CASE-A	CASE-B	CASE-C
Cells	2 million	2.6million	3.5million

For better understanding of the characteristics of different air flow patterns, each of them is studied though at least 2 cases, as shown in table 2. To evaluate thermal comfort in the worse weather condition, the natural wind direction in CASE-A and CASE-B is just opposite to the air supply flow, while in CASE-C one vertical to and the other parallel to the symmetry axis are used with the natural wind speed 6m/s, temperature 51℃. The solar radiation, for the worse weather condition, is calculated at summer solstice, and the direct radiation is 146.5W/m^2, horizontal scattering radiation is 117.8W/m^2， and ground reflection radiation is 94.5W/m^2.The transmission coefficient of the roof is set to 20%, the solar radiation received in the pavilion is 204.2 W/m2, and 80% of the total is placed on the roof. The ground sol-air temperature is calculated to 61.8℃. Since the pavilion is not big for many people, compared with total cooling capacity, the cooling load due to occupants is rather small and negligible. As the volume of hot wind entering the pavilion varies with different air flow patterns, the cooling capacity is calculated with the result of CFD simulation for further comparison.

Table2. *Cases and boundary conditions*

Cases	Supply air speed (m/s)	Supply air flow rate (m^3/s)	Supply air temperature (℃)	Wind direction	Return air tempera ture(℃)	Cooling capacity (kW)
CASE-A-1	4	4	20	Reverse to supply air	29.7	50
CASE-A-2	6	6	20	Reverse to supply air	27.3	57
CASE-B-1	2	6	20	Reverse to supply air	33.6	106
CASE-B-2	4	12	20	Reverse to supply air	29.3	145
CASE-C-1	2	50	28	Wind direction 1	30.0	129
CASE-C-2	2	50	28	Wind direction 2	30.4	157
CASE-C-3	2	50	25	Wind direction 2	28.4	221

RESULTS AND DISCUSSION

Cases with SSSR flow pattern: CASE-A-1 is simulated under supply air speed 4m/s. Fig. 5 shows the distribution of TSI on the intermediate section of the equipment cabinet. When the cold supply air flows against the outer wind, its direction is very likely to be reversed within short distance. The average temperature in the inner space is still very high, while the zones close to the return air intake is too cold which illustrate an uneven distribution of temperature and comfort, as Fig.7. In order to verify the effect of increasing supply air velocity, CASE-A-2 is simulated with supply air (SA) speed 6m/s. As in Fig. 6, higher speed can help distribute the cooling capacity in a wider coverage, but most zones are still at uncomfortable level, as shown in Fig. 8. Concluded from above, the sidewall air supply and sidewall return air flow pattern is not suitable for the outdoor air-conditioning system in the Gulf area.

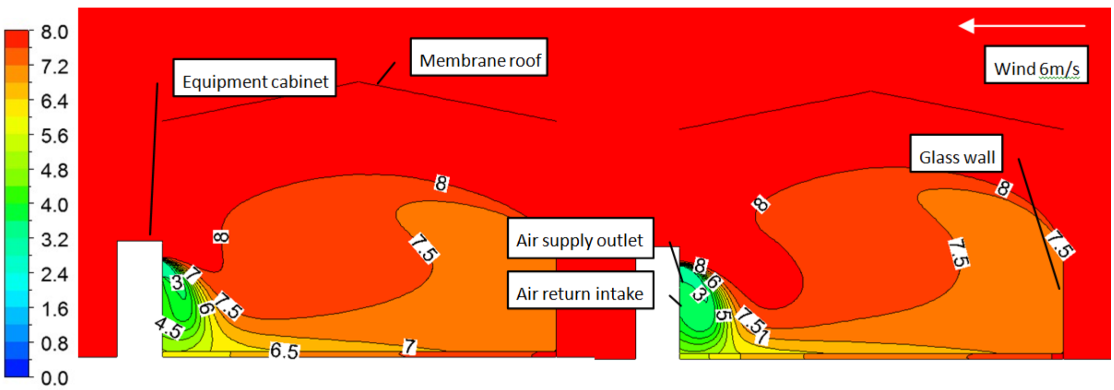


Figure 5. *TSI distribution SA speed 4m/s, CASE-A-1*

Figure 6. *TSI distribution SA speed 6m/s,CASE-A-2*

Cases with SSOR flow pattern: In CASE-B-1 the supply air temperature is 20℃, speed is

2m/s. Comparing Fig.6 with Fig.9, SSOR performs better than SSSR and CASE-B-1 nearly provides twice as much as the cooling capacity than CASE-A-1. The comfort of the entire space in the pavilion is improved, but the uneven distribution of temperature and comfort still exists, as in Fig.11. To verify the improvement of higher supply air speed, CASE-B-2 is simulated under 4m/s of supply air speed. However, some zones adjacent to the supply air outlet gets too cold and the uneven distribution becomes even worse, as in Fig. 12. Even though SSOR is better than SSSR, it is still not able to ensure a comfortable environment in the pavilion. Because the impact of hot natural wind on the temperature increase is amplified along its path, it also prevents the cooling capacity from further increasing.

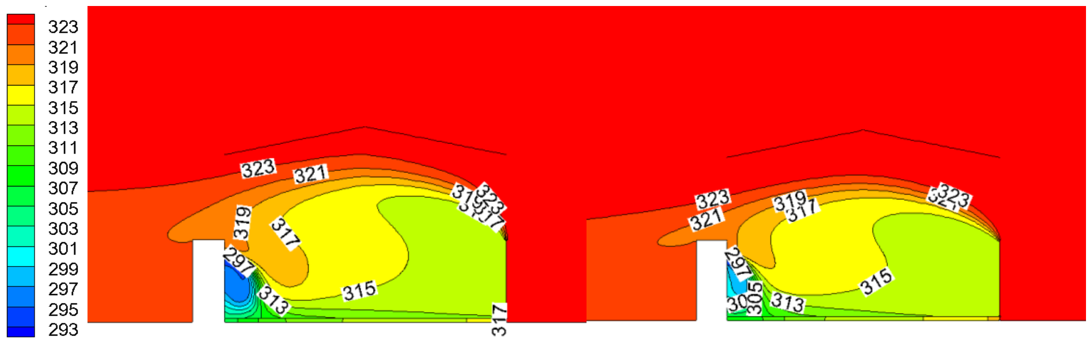


Figure 7. *Temperature distribution SA speed 4m/s, CASE-A-1*

Figure 8. *Temperature distribution SA speed 6m/s,CASE-A-2*

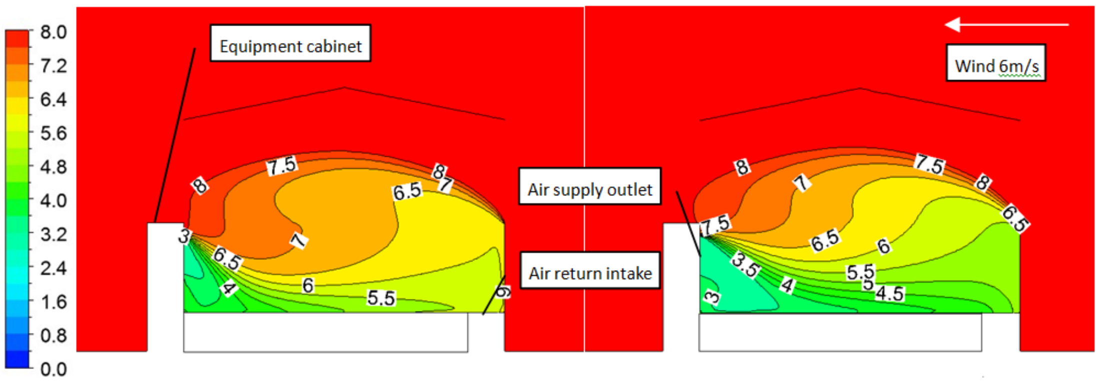


Figure 9. *TSI distribution SA speed 2m/s CASE-B-1*

Figure 10. *TSI distribution SA speed 4m/s CASE-B-2*

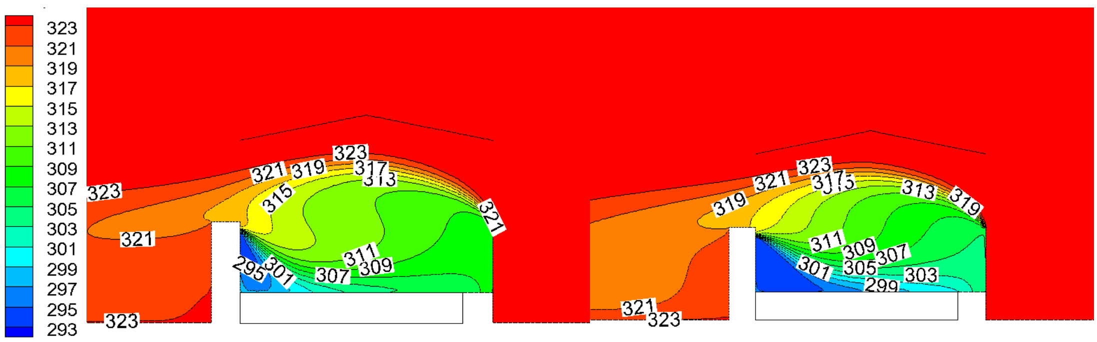
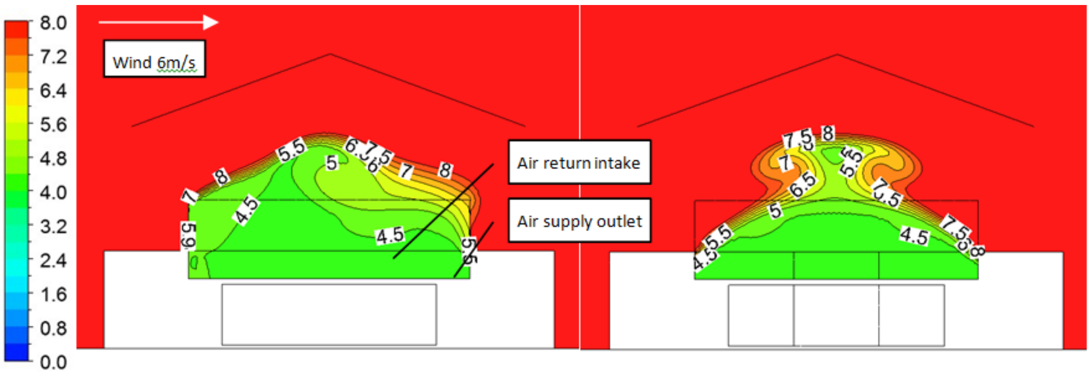


Figure 11. *Temperature distribution SA speed 2m/s, CASE-B-1*

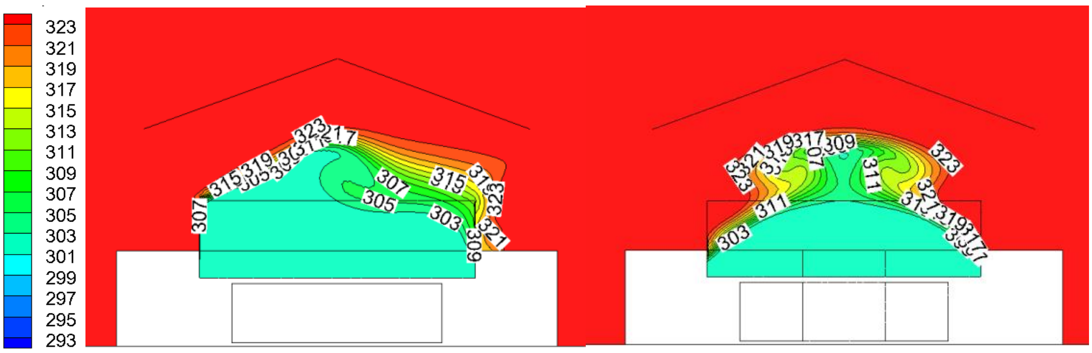
Figure 12. *Temperature distribution SA speed 4m/s, CASE-B-2*

Cases with FSASR flow pattern: FSASR is simulated in CASE-C under the condition of supply air speed 2m/s, temperature 28℃ and the volume of supply air and return air is the same. Fig. 13 shows the distribution of TSI on the sections vertical and parallel to the wind direction. As the neutral point is 4, most inner zones has index ranging from 4 to5, which means most zones is quite comfortable. On the section vertical to the wind direction, due to the disturbance of external wind, it may feel hot in the zones near the glass wall, but overall, the environment in most zones is already as satisfactory as expected. From table 2, the cooling capacity in CASE-C-1 is even less than that in CASE-B-2, which means FSASR can provide better thermal environment by better use of the cooling capacity.



a) Section parallel to wind *b) Section vertical to wind*

Figure 13. *TSI distribution, wind direction 1, CASE-C-1*

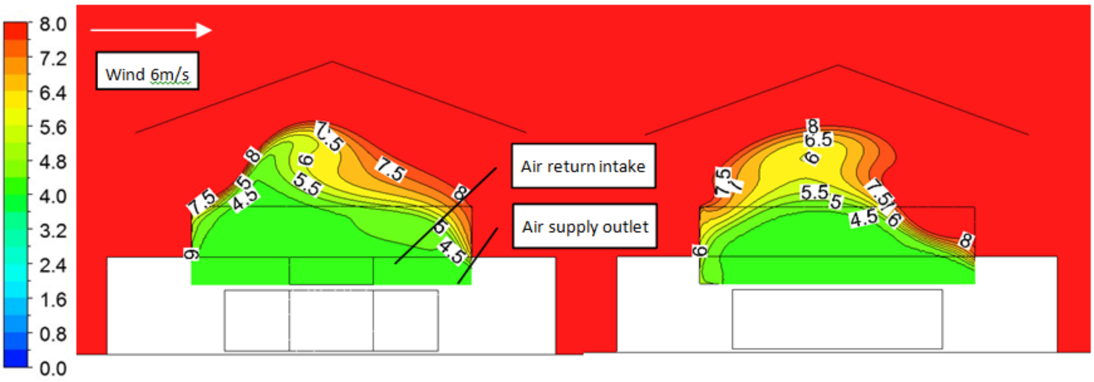


a) Section parallel to wind *b) Section vertical to wind*

Figure 14. *temperature distribution, wind direction 1, CASE-C-1*

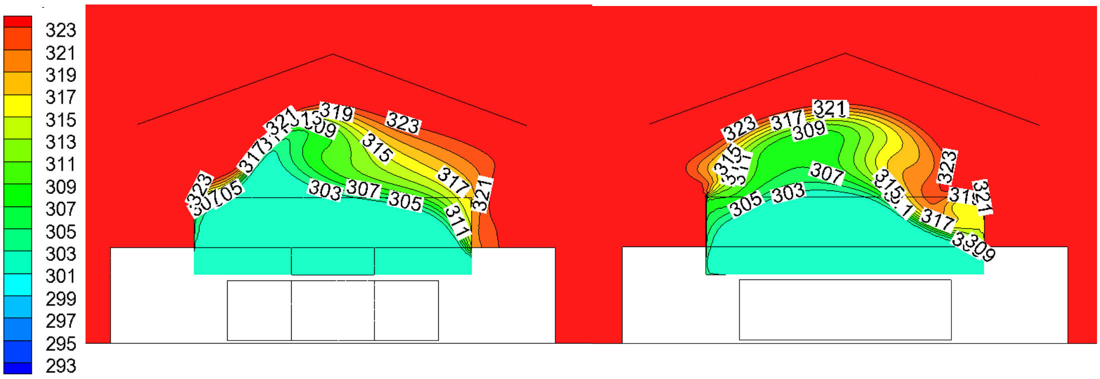
In order to further test and verify this kind of air flow organization, the simulation is also conducted under wind direction 2. The result is shown in Fig. 15-16, since at this direction air supply inlet area is reduced, the entire thermal environment is a bit worse, but the temperature in most of the area is still under 30℃ and it feels comfortable as a whole.

The effectiveness of FSASR has been confirmed by CASE-C-1 and CASE-C-2. However, the TSI in most prayer pavilion area is 4.5 indicating a hot feeling to some degree. In CASE-C-3 the supply air temperature is reduced to 25℃ for more comfortable environment, leading to an increase of cooling capacity, from table 2. Fig. 17 shows the most part of inner space has reached a comfortable environment, and the temperature field in Fig. 18 illustrates that the temperature inmost areas is also well controlled under 26℃. Therefore, the inner thermal environment of prayer pavilion has successfully fulfilled the requirement of comfort.



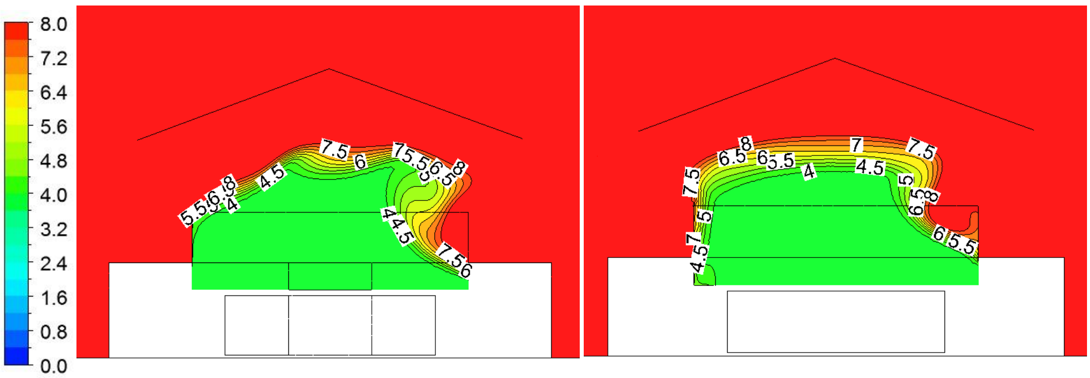
a) Section parallel to wind *b) Section vertical to wind*

Figure 15. *TSI distribution, wind direction 2, CASE-C-2*



a) Section parallel to wind *b) Section vertical to wind*

Figure 16. *TSI distribution, wind direction 2, CASE-C-2*

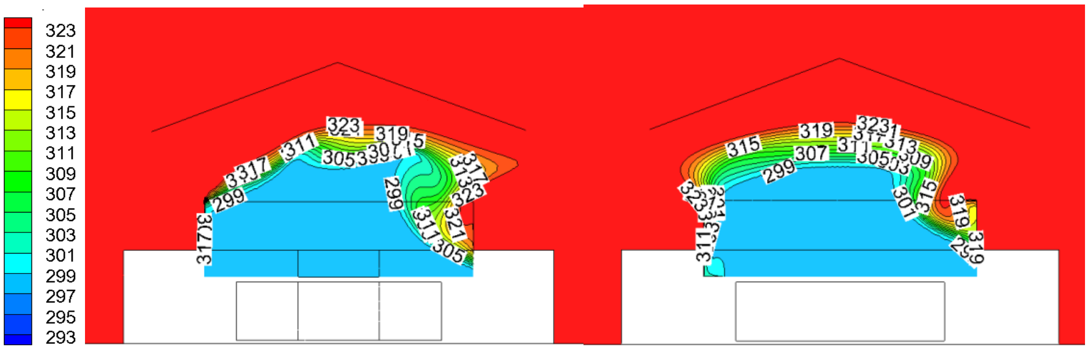


a) Section parallel to wind *b) Section vertical to wind*

Figure 17. *TSI distribution, wind direction 2, CASE-C-3*

CONCLUSION AND IMPLICATIONS

Three different air flow patterns in prayer pavilion are evaluated in this paper by using the CFD simulation tool and analyzing the result with TSI evaluation system. Finally, FSASR is found to be the most suitable air flow pattern in prayer pavilions in the Gulf area. FSASR coupled with glass wall and membrane roof can well accomplish the task of controlling the partial thermal environment, and this paper also provides reference to the design of outdoor thermal environment control system in other regions with similar conditions.



a) Section parallel to wind *b) Section vertical to wind*

Figure 18. *TSI distribution, wind direction 2, CASE-C-3*

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REFERENCES

Al-ajmi, Farraj F., and V.I. Hanby. 2008. "Simulation of energy consumption for Kuwaiti domestic buildings." Energy and Buildings 40(6):1101–1109.

Can, L I, L I Nian, G A O Feng, and L E Di. 2007. "Measurement Method for Micro Thermal Environment of Residential District." Building Science 27(8): 61-65.

Chen, Qingyan, D Ph, and J Srebric. 2002. "A Procedure for Verification , Validation , and Reporting of Indoor Environment CFD Analyses." 201–216.

Cheng, Vicky, Edward Ng, Cecilia Chan, and Baruch Givoni. 2012. "Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong." International journal of biometeorology 56(1):43–56.

Anonymityhttp://www.weatherforecastmap.com/Qatar/doha/.last accessed on 27 July 2012

Givoni, Baruch et al. 2003. "Outdoor comfort research issues." Energy and Buildings 35(1):77–86.

Ho, Peter. 2002. "Different aspects of assessing indoor and outdoor thermal comfort." Energy and buildings 34:661–665.

Jing-feng, XU. 2005. "Discussion on the Application Range of the PMV Equation." Journal of Chongqing Architecture University 27(3):13–18.

Murakami, Shuzo. 2006. "Environmental design of outdoor climate based on CFD." Fluid Dynamics Research 38(2-3):108–126.

Pagliarini, G., and S. Rainieri. 2011. "Thermal environment characterisation of a glass-covered semi-outdoor space subjected to natural climate mitigation." Energy and Buildings 43(7):1609–1617.