A PARAMETRIC STUDY OF THE THERMAL PERFORMANCE OF DOUBLE SKIN FAÇADES AT DIFFERENT CLIMATES USING ANNUAL ENERGY SIMULATION

Emir Aykut Pekdemir[1], Ralph T. Muehleisen[2]
[1]M.S., Illinois Institute of Technology, Chicago, IL
[2]Ph.D., P.E., LEED AP, FASA, Argonne National Laboratory, IL
Corresponding author e-mail: aykutpekdemir@gmail.com

ABSTRACT

This research analyzes the thermal performance of several types of Double Skin Façades [DSF] to determine which are best suited for each climate zone. The purpose of the research is to help guide project owners and unspecialized architects during their decision making process, when they choose to design a DSF. Using Building Energy Modeling [BEM] software, various types of naturally ventilated DSFs are analyzed in all seventeen ASHRAE climate zones. The thermal performance of the DSF is determined by comparing the building energy use data of a generic office building. The different types of DSFs are created following a set of parameters such as stratification type, permissibility of airflow, and width of interstitial space.

INTRODUCTION

The commercial buildings industry, especially office buildings worldwide, persistently demand aesthetically pleasing all-glass structures that indicate and emphasize transparency (Hendriksen et al., 2000). In this context, DSF is a valuable solution to mitigate the undesired thermal properties of glass while achieving the aesthetic transparent look that the building owner desires.

DSFs have a good reputation not only for their thermal performance, but also for allowing natural ventilation, increasing the natural daylight in the space, improving acoustic comfort in noisy sites and thus improving indoor environment (Poirazis, 2006). Some researchers and designers criticize the usage of DSFs, claiming the cost associated with them does not necessarily make up for their benefits (Roth et al, 2007).

Moreover, the thermal performance of a DSF is not guaranteed because they must be uniquely configured for each building and they are not standardized. The complicated physics involved in the thermo-dynamics and heat transfer in a DSF make it vulnerable to error in calculation and design. Due to the possible complications, almost always, there is a specialist involved in the construction of a DSF.

This research aims to demystify the thermal performance of different types of DSFs in varying climates.

METHODOLOGY

Baseline Building Model

Since most of the DSFs are incorporated in large office buildings, the energy model is also modeled with office thermal templates and schedules. The size of the building is based on a typical office building in the city of Chicago, 120' x 160' and 10 storeys tall with no basement, total of 192,000 ft². Floor height is chosen to be 12 ft, and the building is north-south oriented. In order to mimic the prescriptive building, the baseline model has 40% window to wall ratio and the specified construction materials in table 5.5 of ASHRAE 90.1 for each climate. The floor plate of the building has a center core that usually houses vertical circulation and shafts. This zone is modeled to be 34'0" x 20'6". The perimeter zones are offset 15' as a rule of thumb. This is the approximate distance that solar radiation directly affects. Then the zones are divided according to orientation. In the end, the floor plate is divided into 9 zones, as seen in Figure 1. The center core is modeled to be vertically continuous and there are no internal heat gains assigned to this single zone. Since, there are not many partitions in a typical open office plan; the diagonal inner walls separating the zones are modeled as 100% holes.

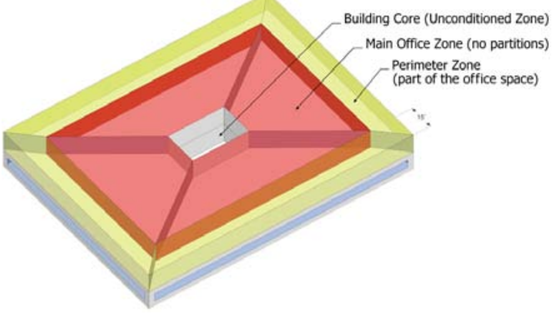

Figure 1 Zoning of the Baseline Building

Building Energy Modeling Software

IESVE 6.4 was chosen as the BEM software for parametric analysis of DSF configurations due to its capabilities in modeling airflow by natural convection. Although IESVE has a robust modeling component called ModelIT, using the Google SketchUp plug-in was preferred for flexibility in modeling. Additionally, default values were selected for HVAC equipment.

Parameters

Based on the categorization by Belgian Building Research Institute (Lancour et al., 2004), DSFs can be classified by three main criteria:

- Ventilation type
- Stratification
- Airflow path

Several parameters can be analyzed within each of these criteria. For instance, a DSF can be ventilated naturally, mechanically or using a hybrid system. This study focuses only on the naturally ventilated DSFs.

Stratification parameters modeled in this study are:

- Multi Storey [MS]
- Corridor Façade [CF]
- Juxtaposed Modules [JM]
- Shaft Box [SB]

MS is the configuration in which the DSF is an uninterrupted continuous cavity without any partitions. In BEM, the DSF is a single unconditioned zone.

CF is the configuration in which the DSF is partitioned horizontally. In BEM, the DSF is comprised of ten unconditioned zones.

JM is the configuration in which the DSF is partitioned both horizontally and vertically. In BEM, the DSF is comprised of 80 unconditioned zones which would prevent interaction from module to module.

SB is the configuration in which the individual modules of DSF are connected by a vertical shaft. In BEM, the holes for airflow are 2’x2’ and the DSF is comprised of 44 unconditioned zones.

In terms of airflow path, a DSF can be either open or closed to environment. The closed configurations are:

- Static Air Buffer [SAB]
- External Air Curtain [EAC]
- Internal Air Curtian [IAC]

SAB is the configuration in which the DSF does not have any openings and is air sealed. This configuration is expected to trap air inside and allow it to reach very high temperatures with solar radiation, and also it is expected to act as a thermal buffer.

EAC is the configuration in which the outside air penetrates into the cavity from the lower opening, sweeps the internal skin and exits the cavity from upper opening. This configuration is expected to ventilate the cavity fastest.

IAC is the configuration in which the inside air penetrates into the cavity from the lower opening, sweeps the external skin and re-enters the building from upper opening. This configuration is expected to increase heat transfer through convection, and may reduce the overall U-value of the façade

Open DSF configurations can be broken down into:

- Supply Air [SA]
- Exhaust Air [EA]

SA is the configuration in which the outside air penetrates into the cavity from the lower opening, heats up and enters the building from the upper opening to allow heat transfer through mass flow and convection.

EA is the configuration in which the inside air enters the cavity from the lower opening, heats up and leaves the building from the upper opening to allow heat transfer through mass flow and convection.

The overall categorization of DSFs is shown in Figure 2.

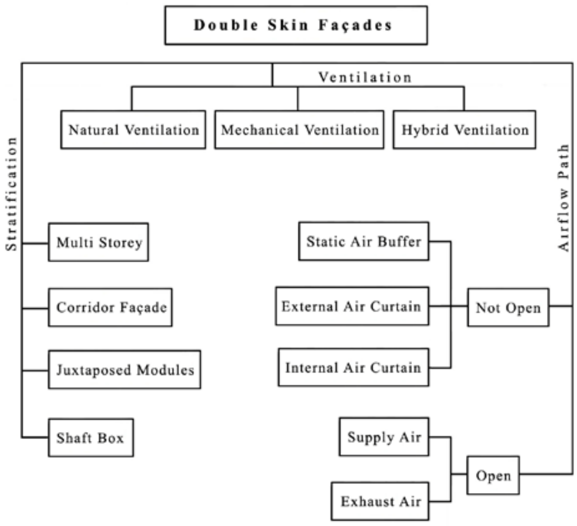

Figure 2 Categorization of Double Skin Façades

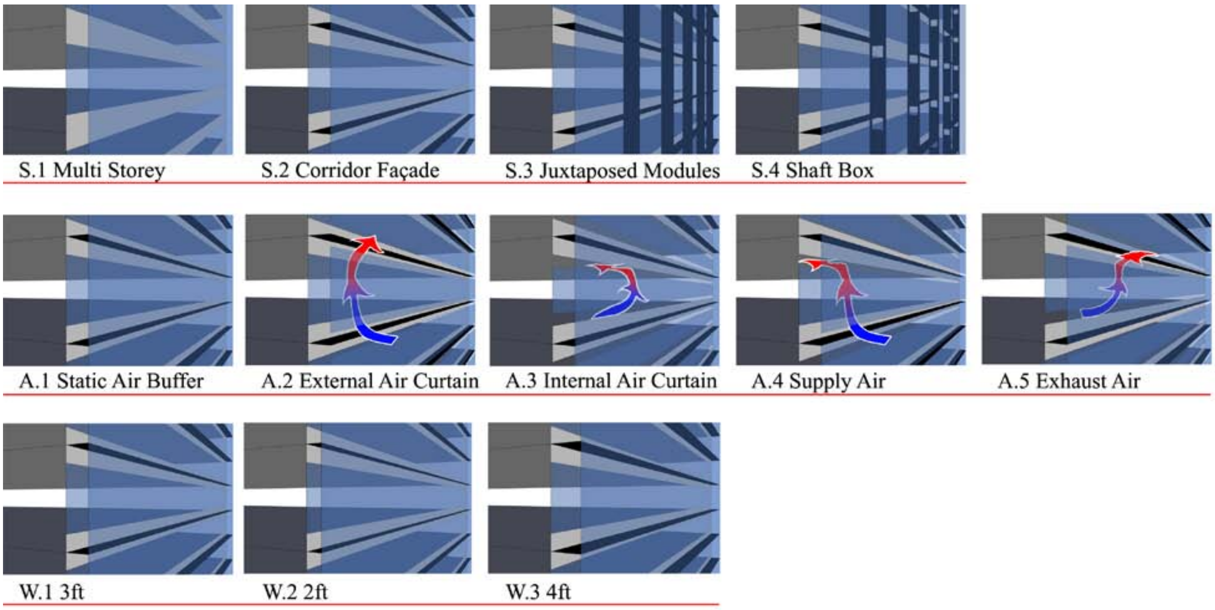

Figure 3 Modeled Double Skin Façades

In addition to the stratification and airflow parameters, width of the interstitial space is also taken into consideration by modeling the cavities:

- 3ft
- 2ft
- 4ft

The graphic representations of the modeled DSFs are shown in Figure 3. To compare the impact on the thermal performance of each of the three parameters, the remaining two parameters were fixed. For the stratification analysis a 3ft wide SAB, for the airflow path analysis a 3ft wide CF, and for the cavity width analysis a SAB CF was chosen to be the fixed parameters.

Finally, annual energy simulations are run for the baseline models and the 10 DSF configurations located in selected cities (Briggs et al., 2002) representing 17 ASHRAE climates, shown in Table 1.

SIMULATION RESULTS

The result files from the simulation of 187 models were bundled in three ways to extract analyses:

- Results for each climate zone
- Results for each DSF configuration
- Overall ranking of DSF configurations
- Performance of combined DSF configurations

Table 1 Climate Classifications

ZONE	DESCRIPTION	CITY
1A	Very Hot – Humid	Miami, FL
1B	Very Hot – Dry	Riyadh, Saudi Arabia
2A	Hot – Humid	Houston, TX
2B	Hot – Dry	Phoenix, AZ
3A	Warm – Humid	Memphis, TN
3B	Warm – Dry	El Paso, TX
3C	Warm – Marine	San Francisco, CA
4A	Mixed – Humid	Baltimore, MD
4B	Mixed – Dry	Albuquerque, NM
4C	Mixed – Marine	Salem, OR
5A	Cool – Humid	Chicago, IL
5B	Cool – Dry	Boise, ID
5C	Cool – Marine	Vancouver, BC
6A	Cold – Humid	Burlington, VT
6B	Cold – Dry	Helena, MT
7	Very Cold	Duluth, MN
8	Subarctic	Fairbanks, AK

Results for Each Climate Zone

The data are grouped together to compare the impact of stratification, airflow path, and cavity width parameters individually for each climate zone. Due to length restrictions of this publication, only the results for 5C Cool-Marine climate Vancouver, BC, Canada are presented here. Also note that, the schedules for the equipment and lights do not vary with climates; therefore their annual energy consumption [AEC] is calculated to be the same throughout the simulations and thus not included after Table 2 to avoid repetition.

Table 2 Annual Energy Consumption of the Baseline Model in Climate 5C

	HEATING [MBTU]	COOLING [MBTU]	FANS & PUMPS [MBTU]	LIGHTS [MBTU]	EQUIPMENT [MBTU]	TOTAL [MBTU]
Baseline	1675.6	1662.7	2678.6	2304.4	2304.4	10625.8

Table 3 Stratification Analysis in Climate 5C

3FT - SAB	HEATING [MBTU]	COOLING [MBTU]	FANS & PUMPS [MBTU]	TOTAL [MBTU]
MS	1681.4	1994.5	2815.5	11100.2
	0.34%	19.96%	5.11%	4.47%
CF	1673.3	1990.0	2813.6	11085.7
	-0.14%	19.68%	5.04%	4.33%
JM	1668.1	1944.7	2794.9	11015.6
	-0.45%	15.96%	4.34%	3.68%
SB	1668.2	1981.2	2810.0	11068.2
	-0.44%	19.15%	4.90%	4.16%

The results in Table 3 reveal that significant decrease in heating energy cannot be achieved by any configuration but they all increase the cooling energy. All of the configurations with SAB give us unpleasant results annually due to their high cooling penalties. However, the JM would be the preferred choice among them.

Table 4 Airflow Path Analysis in Climate 5C

3FT - CF	HEATING [MBTU]	COOLING [MBTU]	FANS & PUMPS [MBTU]	TOTAL [MBTU]
SAB	1673.3	1990.0	2813.6	11085.7
	-0.14%	19.68%	5.04%	4.33%
EAC	1914.7	1690.2	2689.9	10903.7
	14.27%	1.65%	0.42%	2.62%
IAC	1900.2	2153.0	2880.9	11542.8
	13.40%	29.49%	7.55%	8.63%
SA	3641.0	597.5	2239.2	11085.6
	117.29%	-64.06%	-15.40%	4.34%
EA	3089.6	1544.8	2630.0	11873.2
	84.38%	-7.09%	-1.82%	11.74%

Table 4 indicates that only the SAB configuration is beneficial during the heating season, but it would have a severe penalty for cooling. On the other hand, SA provides immense energy savings in cooling; therefore two different operation modes of airflow are required in this climate.

Table 5 Cavity Width Analysis in Climate 5C

SAB - CF	HEATING [MBTU]	COOLING [MBTU]	FANS & PUMPS [MBTU]	TOTAL [MBTU]
3 ft	1673.3	1990.0	2813.6	11085.7
	-0.14%	19.68%	5.04%	4.33%
2 ft	1668.5	2031.3	2830.6	11139.2
	-0.43%	22.17%	5.68%	4.83%
4 ft	1675.9	1945.4	2795.6	11027.7
	0.07%	17.06%	4.37%	3.78%

Looking at the width of interstitial spaces in Table 5, it can be determined that a 4 ft gap has the least annual penalty and would, therefore, be the preferred choice.

The results suggest that if implemented, an overall correct DSF design choice in this climate would be a JM of 4 ft or wider gap, which has two airflow modes, SAB in winter and SA in summer.

Table 6 Combined DSF Analysis in Climate 5C

JM - SA	HEATING [MBTU]	COOLING [MBTU]	FANS & PUMPS [MBTU]	TOTAL [MBTU]
	1668.1	597.5	2239.2	9113.7
	-0.45%	-64.06%	-15.40%	-14.23%

In an attempt to generate the best hypothetical performance of a naturally ventilated DSF in this cool and marine climate, the heating energy from the JM, and cooling + fans & pumps energy from the SA configuration are combined in Table 6.

This table shows that in climate 5C, with the combination of the best values from previous tables, immense thermal energy savings can be achieved by a naturally ventilated DSF. These savings are mostly due to reduction in cooling energy.

This analysis theoretically defines the thermal benefit limits of a non-mechanically ventilated DSF with no HVAC link. The hypothetical combined DSF is then compared to the baseline by its AEC, and hourly energy use during heating and cooling peak days in Figures 4 and 5. This method of combining the best values of different configurations for heating, cooling, fans & pumps, lacks accuracy and does not necessarily show the performance of an optimum DSF in operation. This research refrains from designing optimum DSFs mostly because of the fact that they are supposed to be uniquely crafted for different needs of each building. However, the percentage savings will still serve as a good guide for decision making based on the hypothetical performance of a natural ventilated DSF in each climate zone.

The hourly sensible energy use, outside dry bulb temperature and inside air temperature of the south perimeter zone on peak energy days are plotted in Figures 4 and 5. Analyses of these peak day graphs reveal that the combined DSF provides zero savings in the heating peak day but considerable reduction in energy in the cooling peak day.

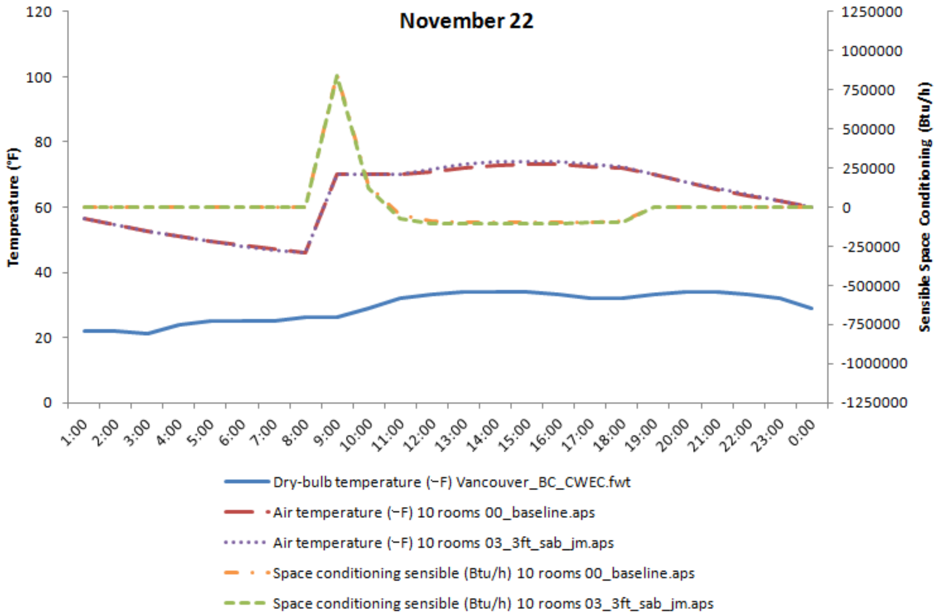

Figure 4 Peak Heating Day Hourly Analysis in Climate 5C

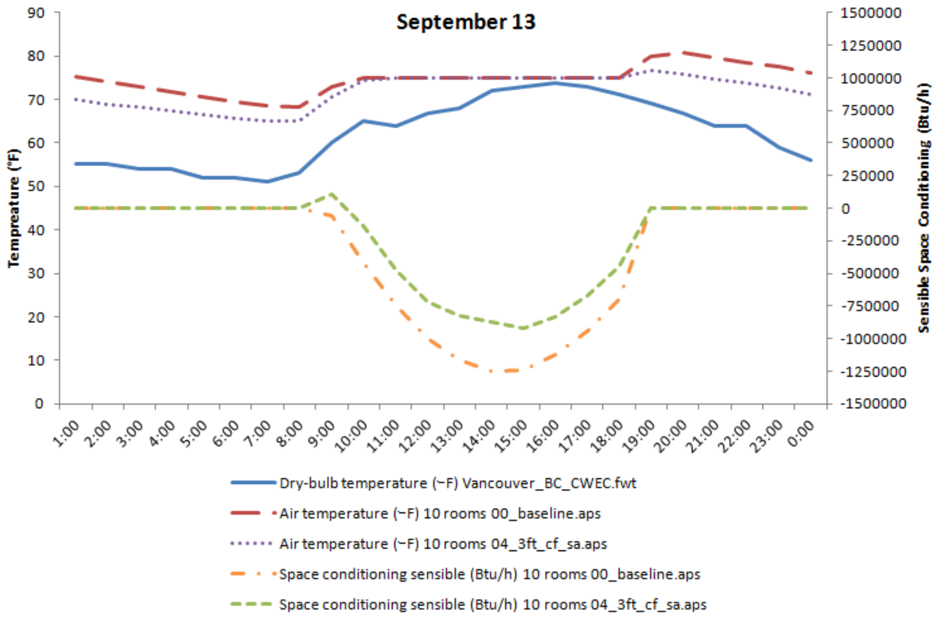

Figure 5 Peak Cooling Day Hourly Analysis in Climate 5C

Results for Each DSF Configuration

In this section, the same data are bundled for each DSF configuration to focus in their performance at different climates. Due to length restrictions of this publication, only the results for 3ft-JM-SAB and 3ft-CF-SA are presented here, since they performed best in Vancouver.

Table 7 Performance of 3ft-JM-SAB Configuration

3FT JM SAB	HEATING [%]	COOLING [%]	FANS & PUMPS [%]	TOTAL [%]
1A	-2.40%	1.22%	0.49%	0.35%
1B	-7.63%	-0.11%	-0.05%	-0.53%
2A	-2.30%	3.24%	1.13%	0.84%
2B	-2.48%	4.35%	1.60%	1.30%
3A	-2.18%	5.95%	1.87%	1.40%
3B	-2.38%	7.28%	2.32%	1.86%
3C	-2.13%	10.26%	2.27%	1.74%
4A	-2.18%	13.39%	4.53%	3.69%
4B	-3.59%	15.22%	5.69%	4.65%
4C	-1.18%	14.09%	4.10%	3.45%
5A	-2.97%	14.48%	4.39%	3.15%
5B	-2.12%	15.21%	5.08%	3.96%
5C	-0.45%	15.96%	4.34%	3.68%
6A	-2.78%	15.62%	4.27%	2.85%
6B	-2.87%	18.00%	4.96%	3.31%
7	-3.77%	19.94%	4.78%	2.57%
8	-1.11%	22.34%	4.27%	1.93%

Table 8 Performance of 3ft-CF-SA Configuration

3FT JM SAB	HEATING [%]	COOLING [%]	FANS & PUMPS [%]	TOTAL [%]
1A	-4.24%	8.21%	3.28%	2.95%
1B	14.88%	13.73%	5.17%	5.83%
2A	28.97%	3.32%	1.16%	3.72%
2B	5.93%	5.89%	2.16%	2.59%
3A	50.76%	-2.61%	-0.82%	5.62%
3B	17.97%	-4.59%	-1.47%	0.59%
3C	13.92%	-33.35%	-7.37%	-4.74%
4A	67.04%	-8.79%	-2.97%	5.56%
4B	88.84%	-45.57%	-17.41%	-4.66%
4C	105.21%	-55.00%	-15.30%	0.29%
5A	167.19%	-43.51%	-13.20%	19.12%
5B	128.38%	-51.79%	-15.22%	7.85%
5C	117.29%	-64.06%	-15.40%	4.34%
6A	185.11%	-52.36%	-14.31%	27.97%
6B	149.20%	-55.73%	-15.62%	20.71%
7	142.16%	-25.77%	-5.18%	33.56%
8	105.03%	-17.99%	-3.44%	45.04%

Table 7 indicates that 3ft-JM-SAB configuration cannot deliver overall annual energy savings due to the cooling penalties. However, small savings in heating energy can be achieved in some climates. In the end, this configuration performs best in climate 1B, and worst in 4B.

Table 8 indicates that 3ft-CF-SA configuration shows erratic behavior across the different seasons. SA draws air inside and outside temperatures fully influence the inside temperature. In cold climates, SA dramatically reduces the cooling energy but is twice as detrimental to the heating energy. Therefore, this airflow configuration works great only in cooling the excess summer heat gains in the cold climates. Also, it can be used to bring the heat in from outside during winters of climate 1A. In the end, this configuration performs best in climate 5C and worst in 1B.

Overall Ranking of DSF Configurations

In this section, the DSF configurations are ranked in a spectrum of all climates. A point based method is developed in which the configurations receive points for their performance in each climate. For example in climate 5C, among stratification types, JM is the best performing configuration and receives 4 points, while MS is the worst one and will receive 1 point. When two configurations are tied in scores for a climate, they share their average score. Tables 9 through 11 show overall ranking of configurations.

Table 9 Stratification Type Scores and Overall Ranking

	MS	CF	JM	SB
1A	3.5 (H)	1	3.5 (C)	2
1B	1	2	4	3
2A	1	2	3.5 (C)	3.5 (H)
2B	1	2	4	3
3A	1	2	3.5 (C)	3.5 (H)
3B	2	1	3.5 (C)	3.5 (H)
3C	1	2	3.5 (H)	3.5 (C)
4A	1	2	3.5 (C)	3.5 (H)
4B	1	2	4	3
4C	1	2	4	3
5A	1	2	3.5 (C)	3.5 (H)
5B	1	2	4	3
5C	1	2	4	3
6A	3.5 (H)	1	3.5 (C)	2
6B	1	2	3.5 (C)	3.5 (H)
7	1	2	3.5 (C)	3.5 (H)
8	1	2	3.5 (C)	3.5 (H)
Total	**23**	**31**	**62.5**	**53.5**
Rank	4	3	1	2

Table 10 Airflow Type Scores and Overall Ranking

	SAB	EAC	IAC	SA	EA
1A	3	4.5 (C)	2	4.5 (H)	1
1B	4.5 (H)	4.5 (C)	3	2	1
2A	4.5 (H)	4.5 (C)	3	2	1
2B	4.5 (H)	4.5 (C)	2	3	1
3A	4.5 (H)	3	2	4.5 (C)	1
3B	4.5 (H)	3	1	4.5 (C)	2
3C	4.5 (H)	1	2	4.5 (C)	3
4A	4.5 (H)	2	1	4.5 (C)	3
4B	4.5 (H)	3	1	4.5 (C)	2
4C	4.5 (H)	2	1	4.5 (C)	3
5A	4.5 (H)	2	1	4.5 (C)	3
5B	4.5 (H)	2	1	4.5 (C)	3
5C	4.5 (H)	2	1	4.5 (C)	3
6A	4.5 (H)	2	1	4.5 (C)	3
6B	4.5 (H)	2	1	4.5 (C)	3
7	4.5 (H)	2	1	4.5 (C)	3
8	4.5 (H)	2	1	4.5 (C)	3
Total	**75**	**46**	**25**	**70**	**39**
Rank	1	3	5	2	4

Table 11 Cavity Width Scores and Overall Ranking

	3FT	2FT	4FT
1A	2	1	3
1B	2	1	3
2A	2	1	3
2B	2	1	3
3A	2	1	3
3B	2	1	3
3C	2	1	3
4A	2	1	3
4B	2	1	3
4C	2	1	3
5A	2	1	3
5B	2	1	3
5C	2	1	3
6A	2	1	3
6B	2	1	3
7	2	1	3
8	2	1	3
Total	**34**	**17**	**51**
Rank	2	3	1

Performance of Combined DSF Configurations

Figure 6 compares and the performance of combined DSFs using the hypothetical AEC data which are generated by combining benefits of the best heating and cooling configurations in each climate zone.

CONCLUSION

Based on the methodology utilized, the stratification, airflow path, and cavity width parameters were analyzed. Additionally, from the annual energy simulation data, a climatic analysis was also extracted.

As a result of the stratification analysis, juxtaposed modules [JM] and shaft box [SB] appeared to be the best configurations overall. The analysis also concluded that this was mostly due to shading provided by the horizontal and vertical partitions. Therefore this study failed to determine a recommended stratification type, but affirmed the importance of shading in order to decrease the cooling loads.

The analysis for the airflow types revealed that the preferred configurations varied by season. While in winter, static air buffer [SAB] decreased heating loads, supply air [SA] and external air curtain [EAC] helped cooling the building in summer. Additionally, the results of this analysis were found to be affected by the climate zones more than the stratification type or cavity width analyses. For cooling purposes, EAC performed best in very hot and hot climates, whereas SA was the preferred choice for every other climate. As an exception to SAB being the best passive heater in all climates, SA performed better in Miami. As a note, SA should be used carefully in cold climates because it can cause thermal discomfort in the perimeter zones, if the windows are opened before the air temperature in the cavity reaches acceptable levels.

Cavity width analysis showed indications that overheating occurs in narrower cavities. This was not advantageous even in the coldest climate; therefore, as a result of this analysis, 4ft or wider cavities are recommended, when used without additional shading.

Climatic analysis via combined DSFs showed that mild and cold climates are the most preferred locations to construct a natural ventilated DSF, followed by extreme cold climates and warm climates. In the very hot and hot climates, natural ventilation was proven to be inadequate for cooling. In case a DSF is desired at locations with such climates, mechanical ventilation of the cavity is highly recommended. Suggested way would be circulating the return air to cool the hotter air inside the cavity.

FURTHER STUDY RECOMMENDATIONS

There are a few limitations to the BEM used in this research. First of all, daylight dimmers were not included in the models to retain the limits of the analysis to thermal benefits only. If realized, daylight dimming systems would reduce the lighting energy cost

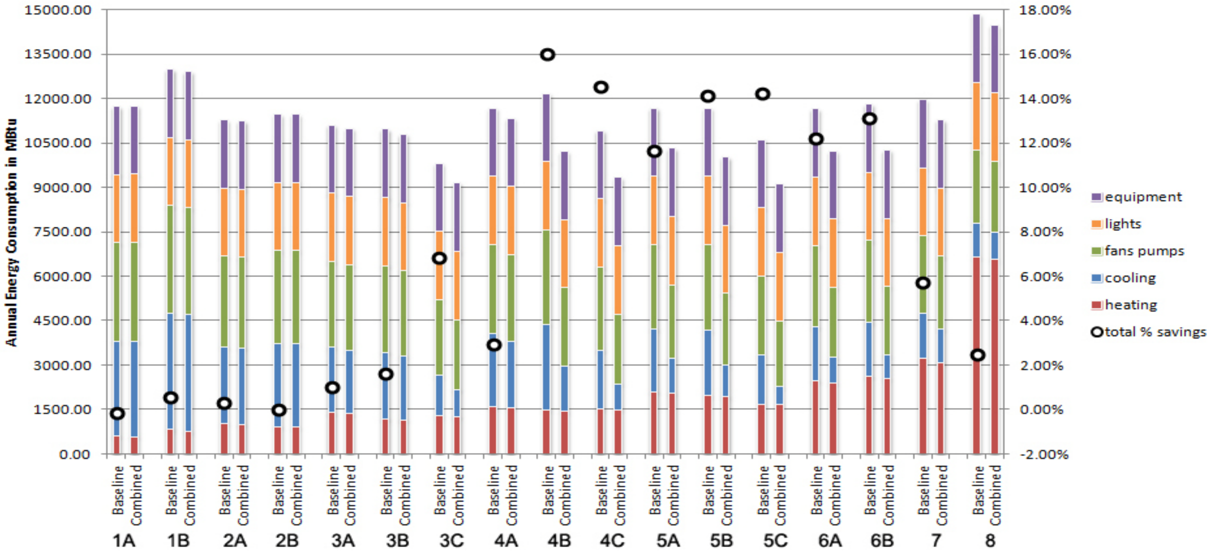

Figure 6 Performances of Combined DSF Configurations Compared to Baselines in Each Climate Zone

significantly. Another short-coming of the model is not incorporating any shading elements, which would decrease the cooling loads and improve reliability of the stratification analysis results. Thirdly, there was no control over the openings of DSF; the system was either fully open or fully closed. In a better model, they need to be formulated to follow a schedule or a logic statement to ensure acceptable temperature range for the airflow. Finally, other possible combinations of stratification-airflow-width parameters could have been modeled in junction. For example in the current study, stratification analysis is done only for 3ft-SAB, but could possibly yield better results in other combinations.

This study can be further developed by adding other analyses. Firstly, forced mechanical ventilation of the cavity could be incorporated to take this study to a next level. This may provide better results for very hot and hot climates, and possibly others. An additional analysis could be done to determine the optimum areas of opening in the DSF. Lastly, the glass surfaces of DSF can be analyzed in detail by introducing different coatings and reverse formation of double pane and single pane skins.

As a last remark, utilizing computational fluid dynamics would be beneficial to aid the findings of this study and/or other similar BEMs.

ACKNOWLEDGMENT

This paper is based upon the Master of Science thesis by Emir Aykut Pekdemir (Pekdemir, 2011).

REFERENCES

Briggs, R. S., Lucas, R. G., & Taylor, Z. T. (2002). Climate Classification for Building Energy Codes and Standards. Technical Paper Final Review Draft. Pacific Northwest National Laboratory.

Hendriksen, O. J., Sorensen, H., Svenson, A., & Aaqvist, P. (2000). Double Skin Façades – Fashion or a step towards sustainable buildings. Proceedings of ISES, Eurosun.

Integrated Environmental Solutions. (2011). IES-VE Pro, V.6.4

Lancour, X., Deneyer, A., Blasco, M., Flamant, G., & Wouters, P. (2004). Ventilated Double Facades – Classification & Illustration of Facade Concepts. Department of Building Physics, Indoor Climate and Building Services, Belgian Building Research Institute.

Pekdemir, E. A. (2011). A Parametric Study Of The Thermal Performance Of Double Skin Façades At Different Geographical Locations Using Annual Energy Simulation. Master of Science thesis. Department of Civil, Architectural and Environmental Engineering. Illinois Institute of Technology. Available at goo.gl/rFNe9

Poirazis, H. (2006). Double Skin Façades - A Literature Review. A report of International Energy Agency SHC Task 34 Energy Conservation in Buildings and Community Systems Programme Annex 43.

Roth, K., Lawrence, T., & Brodrick, J. (2007). Double-Skin Façades. ASHRAE Journal. issue 10. 70-73