FULL SCALE TESTING AND COMPUTER SIMULATION OF A DOUBLE SKIN FAÇADE BUILDING

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ABSTRACT

This paper deals specifically with analysis of the thermal, airflow and daylighting performance of the façade elements and in particular with the Double Skin Façade (DSF) applied to the south and southeast facing office spine of a laboratory building. DSF have been applied successfully in Europe for a number of years with the desire to create a more natural internal climate, good daylight quality and access to outdoor air. The focus of this new study is not just on energy reduction and a design of a better work environment but also show building performance simulations support the design process directly.

INTRODUCTION

The Medical School's Biomedical Science Research Building (BSRB) is a major new laboratory building with up-to-date flexible, generic biomedical research space that will serve the needs of the Medical School. The 43,850 gross square meter building is intended to contain 240 laboratory modules that will house as many as four researchers in each module. The need for office space to accommodate interaction between students and faculty and to allow spontaneous small group meetings was an important goal of the design. One very visible aspect of this building will be the DSF in front of the building. The Biomedical Science Research building is located on a full-block site within the main campus.

Figure 1 BSRB building south elevation with DSF.

Environmental design goals

Environmental conditions within the laboratories and their support spaces demand high volumes of treated air to maintain safe and comfortable working conditions for research staff and their students. The overall design team environmental conditions objectives were to design a building with a DSF to the offices, which reduces the annual energy consumption. The design goals are to significantly improve the total building environmental performance in terms of energy reduction. This new design responds to individual office occupancy's demands including the ability to naturally ventilate, and the building environmental systems for the outdoors that can be tuned to suit occupancy, and the external climate including the option of natural ventilation of the space during the spring and autumn seasons.

This paper will present a specific examination of this concept and will show findings in response to analysis of the many components of the DSF which have been questioned by many other researchers [Arons, et al, 2003]. A methodology for examination of the architectural, mechanical and environmental variables affecting the final design is introduced. The paper describes the findings as they relate to the design of the building, and the potential for transfer to other future buildings with the understanding of the building control logic for proper system performance and limitations within the original design concept.

BUILDING SIMULATIONS

The evaluation of the external and internal shades and energy saving concepts associated with the design for BSRB buildings direct the building design toward the DSF concept and the utilization of the air within the cavity void for natural ventilation system. Two types of double façades were evaluated for this building at the early stage of the design. The first choice was based on the way that air moves through the cavity between the skins. The second choice was based on the way air within the cavity is utilized by the users. This distinction was based on the operability of windows in the presence of wind pressure, if any, and the associated external elements (e.g., sound and dust) entering the building. This would allow an occupant to open the inlets (windows) to obtain preheated fresh air for building system control during the heating season. Fig. 2 shows the original design concept.

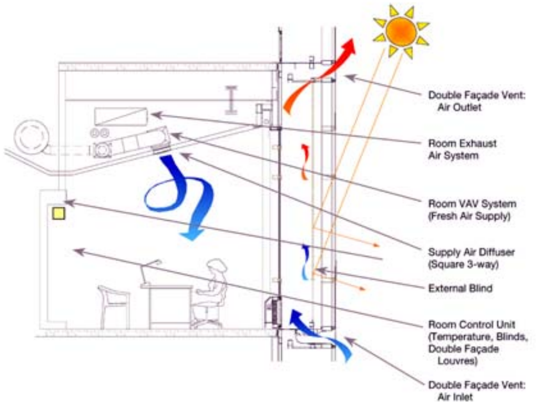

Figure 2 DSF design concept

Full-scale simulation To establish relationships between the reduced scale and the full-scale prototype when considering the free convection, the Reynolds or Grashof numbers are used, which is the ratio of the buoyancy to viscous force. It is possible to preserve the ratios in the reduced scale and the full-scale building for the free convection, as long as the turbulent intensity of the flow is over some value of the Reynolds (10,000) number [Wenting, Edwards]. We used the full-scale prototype to reduce some of the prediction or modeling problems inherent with simulation using scale models. The full-scale simulation cycle requires at least a full day as a start-up day in order to account for thermal storage effects of the material and the air within the cavity. Based on preliminary results one day testing was the appropriate temporal resolution. The two identical models side by side provided the opportunity to test different variables such as closed and open blinds or vents simultaneously. Due to computational limits (speed and memory) and the lack of sufficient data (local condition or the assumed ambient condition) more emphasis has been put on airflow simulation.

Computational fluid dynamics (CFD) simulation

The numerical simulations for this research are done using a general three-dimensional computational fluid dynamics model using the CFX Program [Ansys- CFX]. For the natural ventilation prediction, the flow is considered a low level of turbulence. The k-Epsilon model has been used in the calculations in which the conservation equations for mass, momentum and thermal energy are solved for nodes of a two or three-dimensional grid inside or around the space under study. [Hensen et al., Chen, Wenting Dinga et al.]. Fig. 3 shows CFD models of selected spaces within the BSRB building using CFX program.

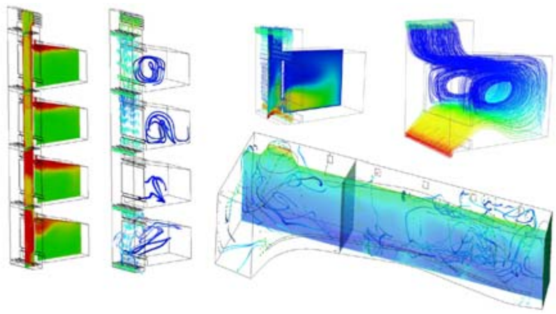

Figure 3 CFD models of DSF, Atrium and Offices

Energy simulation - This method is done using the eQUEST Program, in which a building and the relevant (HVAC) are treated as a cluster of zones representing rooms, parts of rooms and system components representing the distributed thermal zones associated with building system [DOE2.com]. Fig. 4 shows the architectural model of these spaces. The energy modeling method provides information about total consumption and or hourly building loads. CFD will provide details about the airflow field. In this study, the thermal load is very important. Given the extent of the model and the issues involved, the building energy performance can only be predicted with building energy simulation. CFD can be integrated with building energy simulation. To tune the CFD and energy model, the full-scale measured data were used as an input to the CFD and the energy models.

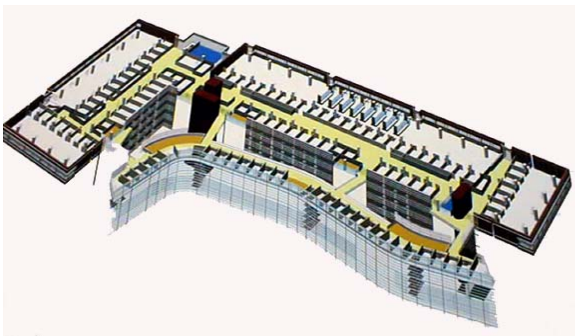

Figure 4 Atrium and Laboratory thermal zones

As shown in Fig. 5, the eQUEST model comprises a typical full 3D model of the building with the related thermal zones. The DSF is on the South and East sides of the building, and other zones representing the labs, offices, atrium and vivarium zones. The laboratory zones representing 65% and offices, atrium and the vivariam representing, 17%, 5% and 17% of the total building floor area respectively. It was assumed that the office windows and the shading devices are closed, and that effectively there would be no air exchange between the atrium and the cavity of the double-skin façade. Solar radiation passes through the double skin depending on the angle of incidence and the optical properties of the transparent systems. The outer layer of the double-skin façade is single pane clear glass 6 mm thick. The office windows have double-glazing with blinds located in the cavity of the double-skin façade. Further details of the model can be found in Figures. 6 and 7.

The interior surfaces' temperatures of the outer double skin façade and the thermal storage wall are taken as "boundary conditions" set the same as those in the experiments. All the other surfaces are set as adiabatic. Opening conditions are also set the same as those in the full-scale experiments.

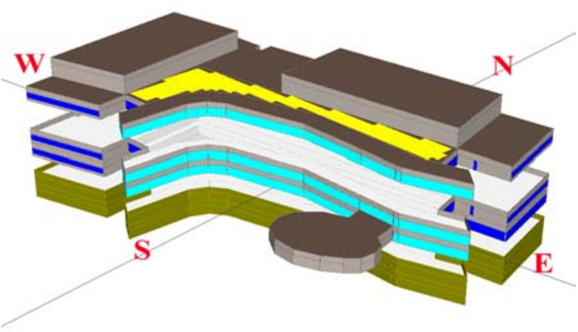

Figure 5 BSRB Energy Model by eQUEST Program

<u>SIMULATION AND EXPERIMENTAL SET UP</u>

Based on the current knowledge on DSF building design, it is clear that the computer modeling and simulation are required to predict the building performance. It is possible to provide a general design concept of the system at an early stage of the design, but in this study, simulations are used to support the design process directly. This process involves the following steps.

1). Use of an appropriate simulation model at a given stage of design. 2). Validation of the models for a given cycle of time. 3). Simulations of the final design given the boundary and unique design conditions. 4). Analyzing and reporting of results based on the simulation or the computer models, to support the design concepts under consideration.

Full-scale simulation set up

The full mock up or Full Scale Model (FSM) testing is designed and built to examine the performance of the DSF with respect to the BSRB total building energy performance under all weather conditions in Michigan, USA. The performance evaluation criteria for this FSM testing are defined by the architects' design team, medical school and campus architects, engineers, plant operation, utility and building automation system groups within the university. The building performance is addressed along with the comfort of the users and ease of operation within interior and exterior of the building. The full-scale testing facility is located within the North Campus, at the Architecture Building Technology Laboratory.

The objective of the study was to generate building performance data in support of the design team by predicting the environmental conditions within the DSF and the resulting cooling and heating loads, if any, for the perimeter offices during extreme winter and summer conditions. The temperatures in the cavity/void are of interest for the building automated control system. In this case, the maintenance team has actually very little interest in the DSF itself. Since the layout of the building is very regular, there is no need to include the whole width or depth of the building. However, the FSM needs to include at least two of the offices adjacent to the façade plus the stack effect within the full height of one floor within the DSF itself. Figures 6 and 7 show the exterior and interior views of the full mock up and the size and geometry of the design intents.

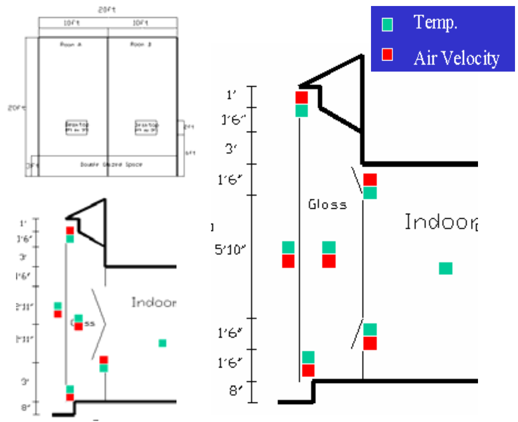

Figure 6 Plan and Section of the Full scale mock up

Figure 7 interior and exterior views of the FSM

The FSM of these two identical offices with DSF faces directly south, and is free of shading from other building structures. All architectural details are constructed very close to the final design dimensions and spatial geometry. The interior windows are made to be operable, the interior of the void is shaded with operable blinds, and the interior office space is shaded with operable fabric shades. The inlets and outlets are closely modeled after the proposed final design. The opening of the inlets are covered by screens or adjustable openings to model the various design options for physical performance alteration and operating strategies of building operations. The glazing system is a single pane clear glass for outside of the DSF and the inner façade is made of double clear glass using untreated glass for heat stress, to examine its' performance under the extreme winter season conditions. Simply closing and opening the inlets manually could easily control the airflow through the FSM. The above stated conditions are used to establish the base case. The fully automated data collection system measures the various thermal, lighting variables and airflow velocities [Raouf,2001]. The six second reported data are tabulated for five-minute averages, and reported and or saved on a hard disk. The facility provides full access to a research weather station operating in accordance to the CIE and WMO standards [Navvab,1995].

Assumed ambient conditions for simulations

The air through the void space is heated due to solar radiation. The airflow through the inlet openings within the void space is ventilated by stack effect. The high summer air temperature in the void is exhausted with this stack effect, which in return contributes to the reduction of the cooling load. In winter, the inlets are closed to protect the heat loss from occupied spaces, and in mid seasons, the stack effect is to be used to encourage natural ventilation. Many studies show the natural ventilation within the DSF is effective. The natural ventilation is impacted by air buoyancy and wind velocity. It is not easy to assess its efficiency given the complexity of the design and the number of variables for a given exterior condition. In our case, probability of a windless condition is very high within this local climatic condition, and the situation does not provide assurance of full stack effect. The design of the intermediate openings was provided to strengthen the stack effect. [Elisabeth2004, Gonchar2003, Hensen,2002].

The temperature fluctuations and the dynamics of the airflow are the results of simultaneous optical, thermal and fluid flow processes. These processes depend on material, geometric, thermo-physical and aerodynamic properties of the components used within the DSF. The ambient temperature, wind speed and direction, spectral characteristics of the glazing system and the solar and daylight availability for the outdoors as well as indoors are the key variables. The interactions among these variables result in transient conditions, and make it difficult to predict the building performance and evaluate the design components of the DSF accurately. There are some major issues with respect to building performance simulation using full-scale modeling and computer computational accuracy. One is with scale of the mock up and the times and duration of the full scale testing. A second is the numerical modeling and the boundary conditions specified for to CFD and selected thermal zones for energy simulation methods.

Physical performance and operating strategies

The following sections describe the physical performance and scenarios for operating strategies used in this simulation and testing. The objective is to see whether the airflow control logic shown in Fig. 8 would provide any advantageous control of the building given the stated setting with respect to local weather data and the results of the testing within this facility. The intent is to see the needs for actuators for automatic inlets operations.

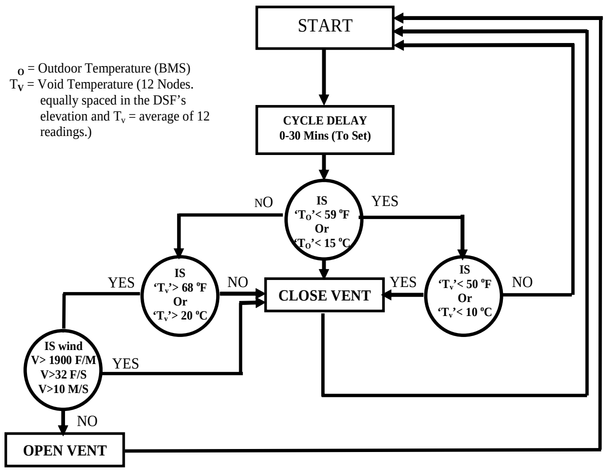

Figure 8 Airflow logic control for inlets operation

Typical Day operation mode The inlets are fully open venting out the heat gain from the void. The horizontal or closed to 45° - 90° blinds in the void giving full solar protection. The solar heat gains striking the blinds are removed by the airflow in the void. The inner double-glazed window (the thermal wall) is closed and the room cooling system is on. Most likely, the room occupant may have closed the internal fabric shade or blinds for glare control. This mode of operation is not taken into account in this analysis, since it is occupant dependent. Closing the glare control blind within the DSF will improve the solar performance of the façade. Little if any direct solar heat, gain enters the conditioned space. The result is a very efficient solar protection screen, which has the ability to be altered / tuned by the room users.

The full specification and design of the room HVAC system is not part of the FSM scope of the study. The proposed system is a ceiling mounted four-pipe fan coil system. The room(s) is supplied with a treated fresh air system, the air being introduced to the room via a "displacement" type air grille located in the base of the office furniture on the back wall. The intention being that the fresh air supply system can be used for night cooling when external conditions permit. Should the users not wish to have the fan coil system operating then the fresh air system can continue to provide air change to the space albeit with minimal cooling / heating capacity. Its supply temperature will be in the order of 20°C (68°F).

Table 1 shows summary of seasonal operation mode for the building.

Table 1 Seasonal Operation Mode for the Building

Season	Inlets	Blinds	window	HVAC	Office Fab.Shade
Summer Day	Open	45/90	Close	On	Close
Summer Night	Open	0/0	Close	Off	Open
Fall/Spring Day	Open	0/45	Open	Off	Open
Winter Day Clear	Close	0/45	Open	1/2 on	Open
Winter Day Cloudy	Close	0/0	Close	1/2 on	Open
Winter Night	Close	90	Close	1/2 on	Close

Application of the control logic and a micro switch on the inner façade opening automatically switches off the room's fan coil units to prevent the units being used with the window open. It is during fall and spring seasons that the room occupants can open their windows to naturally ventilate the room. Using direct outdoor air for ventilating and cooling can yield significant energy savings (45% of the office zone in F/S season). The outer rain screen of the double façade reduces incoming air velocities.

RESULTS

Given the above operating strategies of operations scenarios, various summer and winter day FSM results were used to examine the performance of the DSF. The total building energy consumption is estimated using the eQUEST energy modeling. Table 2 shows the results based on the stated operation modes in Table 1.

Table 2 Energy use of the BSRB Building

Function	%Area	%Energy	KWhr/ft^2/yr	KBTU/ft^2/yr	KBTU/m^2/yr
Lab	56	60	18	61	192
Offices	17	12	24	82	259
Atrium	5	8	52	177	558
Vivarium	17	15	39	133	419
Total	95	95	133	453	1428

After basic calibration and fine-tuning the various FSM components for their ability to be used for operating strategies of desirable operations a base case was established. The results show that the laboratory is a major user of the energy due to the needs for continuous supply of fresh air to the labs with animals. The 6-air change or 20 CFM is the minimum requirement for a healthy environment for the people and the animals within this building. The temperature difference between the inside and the outside is measured as a function of the void air space and the position of the inlets. The uses of inlets were tested under all weather conditions using the FSM [ASHRAE,1972 Awbi, 1991]. The Fig. 9 shows the monthly outdoor and indoor thermal conditions within the Full Mock-up of the DSF. The difference in the Maximum, Average and Minimum temperatures is due to the closed or opened inlet positions within the DSF. The outdoors air temperature (max., avg. and min.) are also shown in Figure 9. The results show the max. Temp. Difference of 11°C (20°F) could occurred when the vents are closed during the summer season.

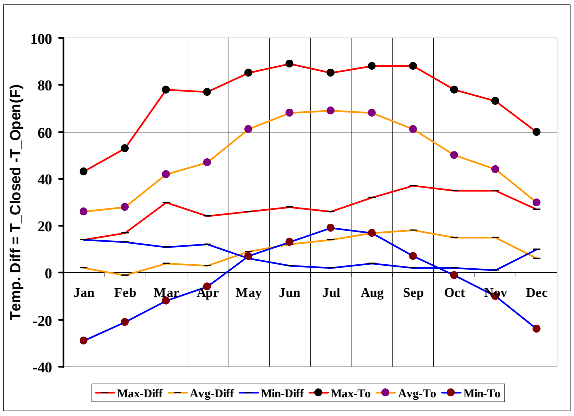

Figure 9 Outdoors temperature and difference in T within the DSF as a function of inlets' position.

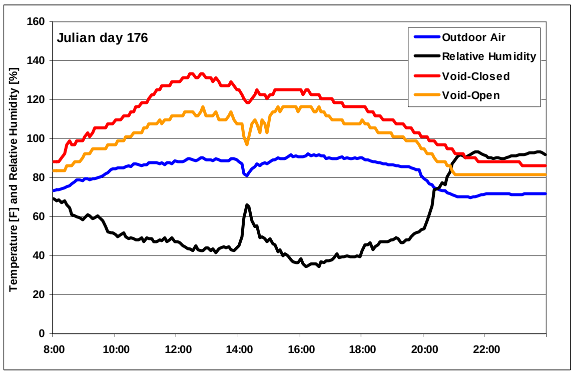

Figure 10 Temperature and humidity outside and within DSF void as a function of time (J- day 176)

This DSF design was very sensitive to the outdoor climatic changes. The results on a summer stormy day show the variability of the illuminance, irradiance, humidity and temperature within the DSF. See Figures 10 and 11. The increase in humidity and the drop in temperature show the sensitivity and the dynamics of the variables within the DSF cavity.

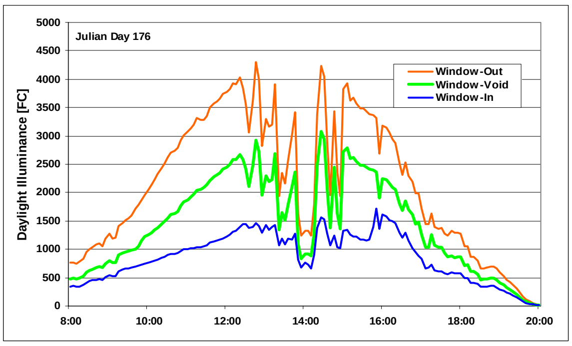

Figure 11 Illuminance outside, within DSF and inside the office as a function of time (J- day 176)

DISCUSSION AND ANALYSIS

The following are representative of the major findings based on the various parametric studies using FSM and using the results as an input to CFD simulation.

1)- Glass spectral characteristic and daylight
2)- Open and closed inlets
3)- Open (horizontal) and closed (90 Degrees) blinds
4)- Glass surface temperature.
5)- Airflow rate within the void

1) The solar-optical properties of the glazing system were measured in the laboratory and under real sky conditions, and results were used as an input to the computer energy model. Fig. 11 shows the spectral transmittance of the office glazing system within the DSF using low-e coating.

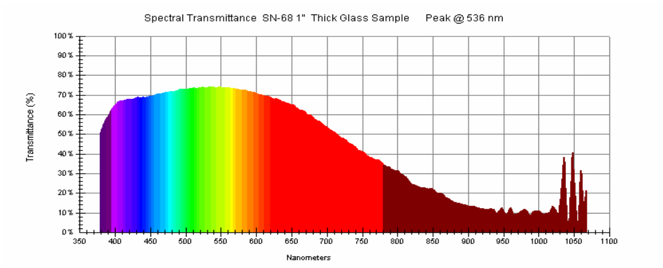

Figure11 Spectral transmittance of the glass

Figure 12 shows the impact of sunlight and daylight. The fluctuation of the daylight within the room is due to the sun light leaking through the blind slats. The interior fabric would eliminate the undesirable glare at low sun angles.

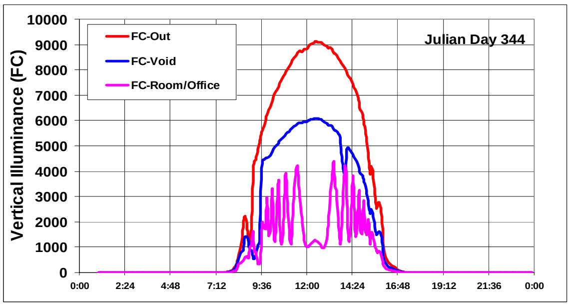

Figure 12 Daylight within the DSF & the office

2) The winter control logic does not require the inlets to open whenever the void temperature exceeds 11°C (50°F). Thus, the void may reach internal temperature in excess of 38°C (100°F). when exposed to direct sun. The inlets could be opened to ventilate the void whenever the void temperature exceeds 32°C (90°F), regardless of wind velocity. This closed condition creates temperature difference exceeding 10°C (50°F).Fig. 13 shows the temperature difference within DSF in winter condition

3) The blinds (at least at horizontal position) do continue to cover the entire façade; this would also reduce the solar gain by a noticeable amount. The high temperature in the void at night confirms this condition. The use of manual opened /closed blinds result in a very efficient solar protection screen, which has the ability to be altered / tuned by the outdoor conditions.

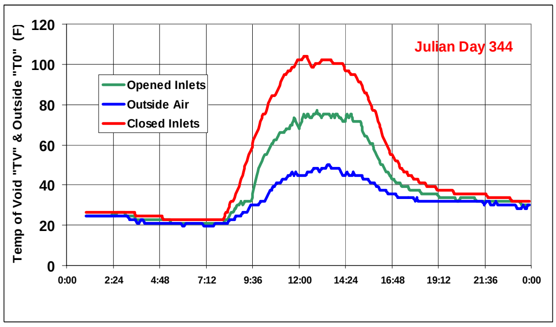

Figure 13 Temperature difference within DSF

Fig. 14 shows use of the blinds during five days in summer. This capability may also affect the perceived brightness and the glare conditions that exist outside of the building due to the large glazing surface area washed by sun light at low or high sun angles. Side by side, FSM made these results possible.

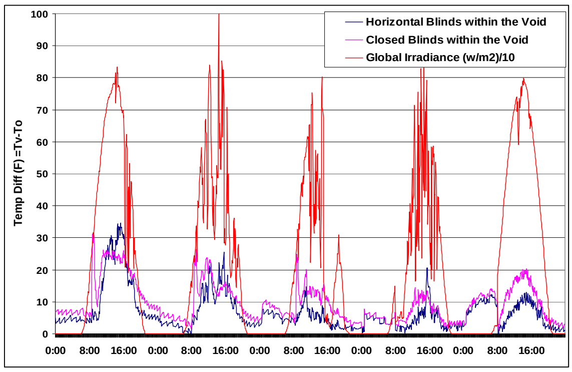

Figure14 Blinds influence DSF temperature

4) The temperature difference between the outdoors air and the glass surface number 2 for single (SG) and double-glazing (DG) systems were measured in winter conditions. The results are sown as a function of the inlets position in Fig 15.

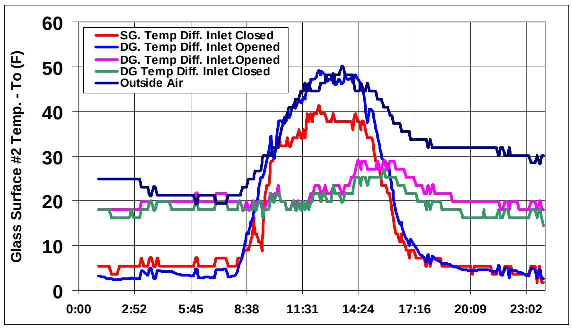

Figure 15 Glass surface temperature difference with respect to outside air in December

The glass manufacturers recommend avoiding temperature difference of 10°C (50°F) within the void as well as on large glazing system surfaces exceeding 100ft^2 (10m^2) area. We used untreated glass and tested this condition and the glass cracked under extreme winter clear day weather condition. Fig. 16 shows the real time data when the glass window broke including the IRR. Data at five minutes intervals.

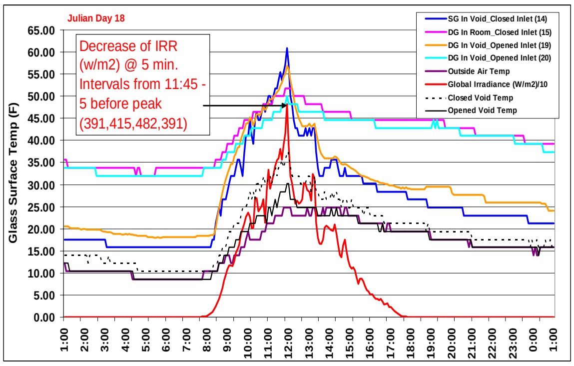

Figure 16 Glass surface temperatures at the time of its breakage due to sudden drop of ~100 W/m2

5) The parameters for the design of the double façade were set by engineers based on their CFD analysis. However, this analysis relies on the measured data from FSM. The reported CFD and temperature data analyses show that reducing the cross section would be dramatically lower the air removal time from the void. This time dependence during winter conditions for which the inlets are intended to function by closing off the air intake, may cause adverse impact. The size and the geometry of the intake and the exhaust air flow and inlets do change the average void's T to as low as 2°C (4°F) or as high as 5°C (10°F). The airflow velocity was measured at the inlets and the outlets and within the cavity using the termistors [Raouf,2001]. The negative or the downward flow 10 f/s, 3 m/s (600 f/min) from the top inlet to the bottom outlet of the DSF is due to the ground level given the local flow of wind and its direction. The condition would be very different at upper floor levels within the real building. See typical results in Fig 17.

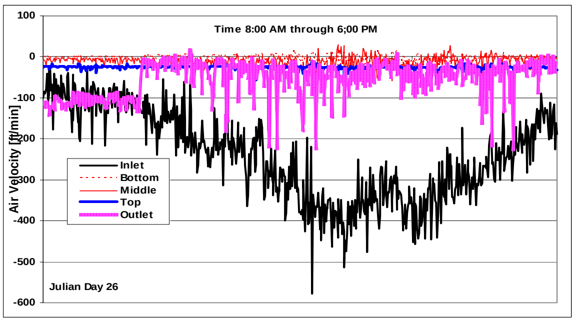

Figure17 Airflow through the FSM of the DSF

Comparison of CFD and experimental results.

Although there are some differences between the results of CFD and experiments, it can be inferred that the CFD modeling is appropriate to reproduce the phenomena occurring in the experiments. Openings on top of the DSF in the summer case are two times those of the winter case, which leads small temperature rise in the double skin and void space. Pressure difference from bottom to top of the double-skin space decreases gradually, which means driving force for ventilation in the office space. Since the atrium and the DSF are not connection, we do not have the pressure balancing problems. This means that the blinds will need to be resistant to 'flapping' due to the void ventilation air velocity created by the outdoor air wind speed.

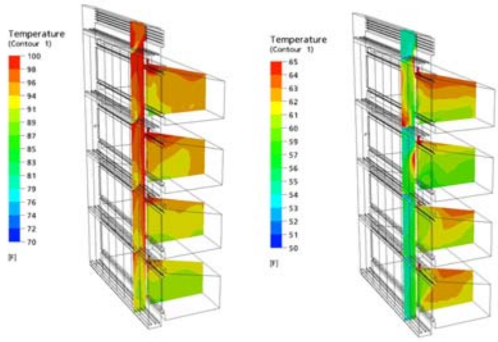

Figure 18 CFD models of DSF and office space for summer (left) and winter (right) seasons.

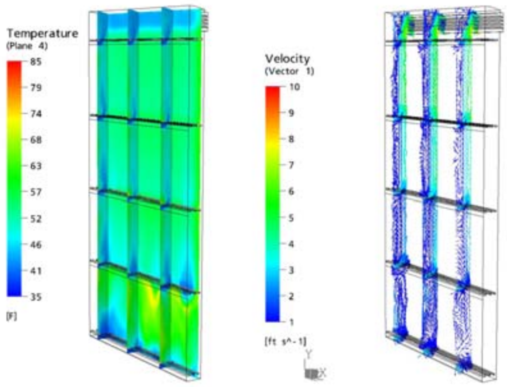

Figure 19 CFD model of DSF wall using measured winter boundary conditions for Temp and Wind.

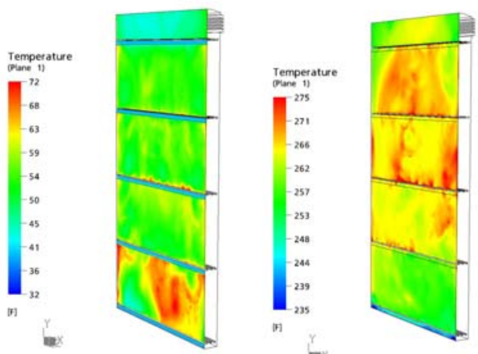

Figure 20 CFD model of DSF using measured boundary conditions for open inlets winter (left) and closed inlets summer (right) seasons.

The measured results were reproduced closely using the measured boundary conditions as an input to CFD models. The utilization of the DSF cavity air for the offices during the summer and winter (see Fig. 18) shows that fall and spring are the best times for the application of this concept. Fig 19 shows the airflow within the winter season contributes to the heated air removal and reducing the thermal storage under extra clear cold days. The extreme air and surface temperature within the cavity in summer time is due to the closing of the inlets. See Fig. 20. A double skin façade on the offices provides the ability to naturally ventilate, which reduces the annual energy consumption of the office zone by 2% for every 2°C (5°F) increase in cooling temperature or decrease of 4°C (8 °F) in heating as compared with a conventional façade. This is due to the highly insulated façades that would reduce the building energy in winter and heat gain in summer. The building environmental conditions are to be monitored through the building energy management system for the outdoors as well as indoors, and the office spine thermal conditions should be tune to suit occupancy and the external climate including the option for natural ventilation of the space during the spring and autumn seasons.

CONCLUSION

The results using various simulation models show that this new design responds to individual office occupancy's demands including natural ventilation of the space. The building environmental systems for the outdoors can be tuned to suit occupants and the external climate including the option for natural ventilation of the space during the spring and autumn seasons. The full scale mock up testing for duration of one year, energy computer simulation using hourly weather file and detail modeling of the airflow using CFD simulation within this DSF building show that this design reduces the annual energy consumption of the office zone more as compared with a conventional façade. This highly insulated façade would reduce the building energy loss in winter and heat gain in summer. The amount of energy reduction is a function of building operation and its energy management systems' capabilities and limitations. The glazing, shading, lighting control systems and the airflow circulation within the void of the DSF are major contributors to efficient and safe performance of this building environmental system. These contributions are made possible by applying advance simulation tools and their integrated use supports the design process directly.

In subsequent publications, we will explore the specific variables such as glass surface temperature, atrium airflow distribution including stack effect thermal load under skylights and upper levels offices during the daytime and nighttime respectively. They thereby accumulate very different thermal load under seasonal peak conditions, which has major consequence for optimal building energy performance. Here it suffices to emphasize that the CFD simulation model adjustment to boundary condition of real building measurement is important and insufficiently investigated. This contributes to performance assessment of various simulation models for one in which systematic comparison between measured and predicted is corrected by real time measured data [Oreskes].

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CIE = International Commission on Illumination

WMO = World Methodological Organization.