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PERFORMANCE EVALUATION AND OPTIMIZATION OF VENTILATED DOUBLE SKIN FACADE IN CHINA

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ABSTRACT

Double-skin facades (DSF) are gaining prevalence in China. However, the benefits of DSF have not been realized due to the lack of quantitative design verification before construction, and operational challenges. Some building owners have even chosen not to turn on mechanically ventilated DSF. This paper presents a design and operation analysis of the inactive DSF in an office building in China. Its performance was carefully studied with Computational Fluid Dynamics (CFD) and Dynamic Thermal Simulation (DTS). An optimized ventilation rate and annual operation schedule are proposed and the investigation approach is introduced.

INTRODUCTION

DSF is an envelope system with two skins of glazing and an air cavity in between. The ventilation of the cavity can be driven by either buoyancy caused by temperature difference or installed mechanical fans. Being part of a building system, a DSF can contribute positively to indoor thermal comfort and mitigate HVAC loads. However it needs to be well designed and operated to achieve such targets.

We have studied 28 projects using DSF in China. 54% of them are box window DSF. (Gao et al. 2007, Lan et al. 2010, Li et al. 2004, Li 2010, Tun 2011) Typically, a box window DSF has the benefits below:

- manufactured via modular production system, eliminating site waste and assembly error; (Tanzhe 2005)
- shorter construction period; (Tanzhe 2005)
- meets fire code requirement in China. (National Building Standard Design Gallery 07J103-8-Double Skin Facade 2007)

Our observation on the existing buildings in China shows most of the box window DSFs have operation issues due to the lack of performance verification in design and poor maintenance at operation. Some systems even have undesirable impacts to the building life cycle, therefore are abandoned by the facility teams.

PROJECT DESCRIPTION

The building being investigated in this study locates in Beijing with a box window DSF. The DSF exhaust fan has been kept inactive by the building facility. This leads to poor indoor thermal comfort and excessive HVAC energy consumption. This study is to analyze the DSF thermal performance and optimize the fan operation toward solving the comfort and energy issues.

The box window DSF studied here has internal adjustable shading blinds. The cavity is ventilated mechanically with the outlet connected to the outside. The design details are shown in Table 1 and Table 2.

Table 1 DSF details

DSF	Size	See Figure 1
	Outer glazing	See Table 3
	Inner glazing	See Table 3
	Airflow rate of exhaust fan	350 m^3/h (87.5 m^3/h per subdivision of DSF)
	Inlet size	25mm*1000mm
	Outlet size	100mm*100mm
Blinds	Materials	Aluminum blinds, grey
	Porosity	8%
	Solar absorptivity	0.35
	Emissivity	0.9
	Location	See Figure 1

Table 2 Design parameters summary

U Value	Wall	0.64 $W/m^2.k$
	Roof	0.46 $W/m^2.k$
Occupants density	10 m^2/person	
Outdoor air	50 m^3/h	
Equipment power density	11 W/m^2	
Lighting power density	13.5 W/m^2	
HVAC	Cooling: Centrifugal Chillers, COP=5.6 Heating: District Heat AHU:VAVs	
Indoor temperature	Summer	25℃
	Winter	20℃
Relative humidity	Summer	55%
	Winter	45%
Clothing index	Summer	Clo 0.5
	Winter	Clo 1.0

Metabolic rate	MET 1.1
Thermal comfort range	-1.0<PMV<1.0

Table 3 Glass specifications

Location		Inner glazing	Outer glazing
Structure		12C	8C+16A+6C
Visible (%)	Transmissivity	85	75
	Outdoor reflectivity	9	11
	Indoor reflectivity	9	12
Solar （%）	Transmissivity	69	51
	Outdoor reflectivity	7	16
	Indoor reflectivity	7	20
U Value（W/m^2.k）		5.20	1.83
SC		0.88	0.66

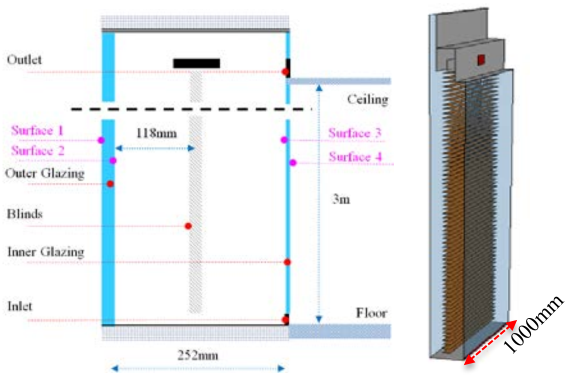


Figure 1 Structure of DSF

METHODOLOGY

An effective DSF design would need to take into account various factors including local climate conditions, building orientations, space functions and HVAC systems. In this case, as the building is in operation, the study primarily focuses on performance verification and ventilation optimization of ventilated DSF.

Thermal safety

Running airflow into the cavity can remove undesirable heat contained between the two layers of glazing. For non-airflow DSF, the cavity air will be heated up by solar radiation. Temperature gradient could increase the risk of glass breaking caused by thermal stress. (Shameri et al. 2011) Ventilation can effectively reduce the temperature of glazing, increasing the structural stability by avoiding heat accumulation. However, in winter, ventilation may bring risks of condensation.

In this study, the impacts of external environment, ventilation flow rate and ventilation schedule to the ventilated DSF performance should be considered.

Energy performance

As a thermal buffer, DSF is able to reduce heat transfer through building facade, therefore the building cooling load can be significantly reduced. This is achieved by removing accumulated heat in the cavity via ventilation. The challenge is that the additional power consumption from fans may offset energy savings brought by the DSF. This study uses dynamic thermal modeling to analyze the overall energy performance.

Thermal comfort

The direct impact of DSF on indoor thermal comfort is the radiation from the most inner surface (surface 4). In warm seasons, the surface temperature can be reduced via ventilation therefore it minimizes the radiant heat to occupants. The variation of indoor thermal comfort can be obtained through evaluating the average surface temperature of glazing over time. The comfort variation near the facade can be inferred by the mean radiant temperature calculated as follow. See Figure 2 for the schematic.

$$MRT = T_g + \left[tan^{-1}\left(\frac{L}{H-h}\right) + tan^{-1}\left(\frac{L}{h}\right)\right] \times \frac{T_w - T_g}{\pi} \qquad (1)$$

where MRT is the mean radiant temperature, T_g is the average temperature of the inner glazing of DSF, T_w is the average temperature of interior walls, L is the distance from the calculation spot to the facade, h is the height of the calculation spot, H is the overall height of the glazing.

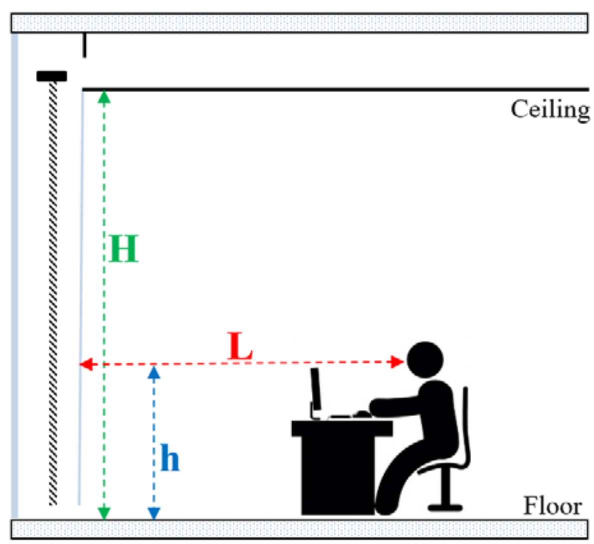


Figure 2 Schematic drawing

Simulation method

There are two simulation tools used for the complete modeling scope of this study. CFD (ANSYS Fluent) is used to study the airflow and thermal conditions inside the DSF cavity for both ventilated and non-ventilated scenarios. It provides a fine resolution on the spatial distribution of air temperature which helps with understanding the thermal stratification of the cavity air. Dynamic Thermal Simulation (EnergyPlus) is the other simulation tool used for modeling the whole year energy and comfort performance of the DSF, see Figure 4 for the whole building energy model rendering. Table 4 shows the conditions in summer and winter which are used for the CFD simulation. For clear sky scenarios, solar radiation is derived based on the given time, orientation and location.

Table 4 CFD simulation conditions

SEASON	ORIENTATION	OUTDOOR TEMP.	TIME
Clear Summer	North	33.5℃	12:00
	East		09:00
	South		12:00
	West		16:00
Overcast Winter	-	-9.9℃	daytime

The CFD model of DSF is shown in Figure 3, there are 1,212,218 hexahedron cells in the model.

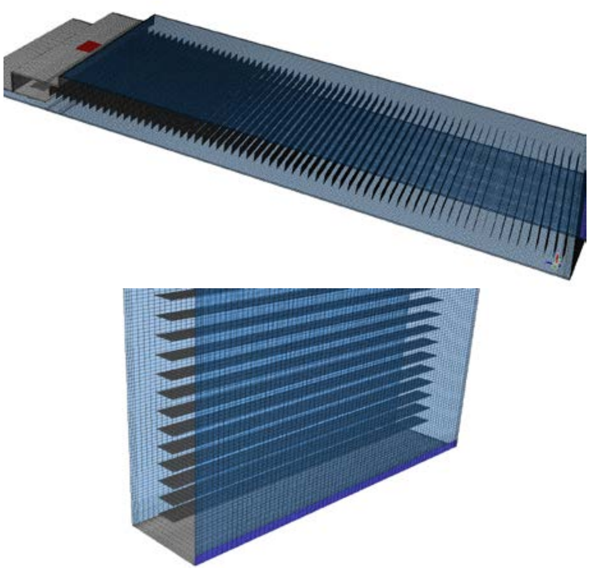


Figure 3 CFD model of the DSF

The CFD physics models are shown in Table 5.

Table 5 CFD physics models

VISCOUS MODEL	Realizable k-e
SOLAR LOAD	Solar Ray Tracing
RADIATION MODEL	Surface to Surface
BUOYANCY	Boussinesq

A comparison study between ventilated DSF and non-ventilated DSF was performed to understand the energy and comfort benefit to the building.

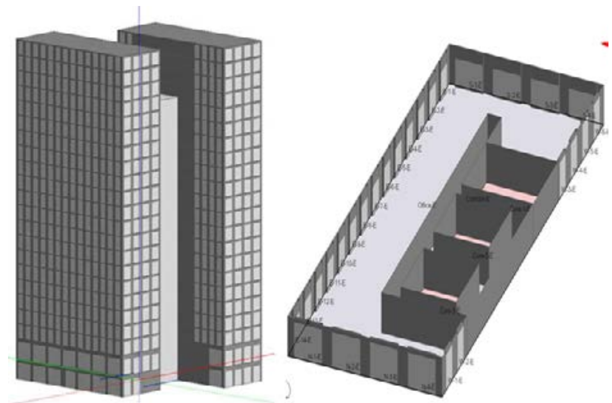


Figure 4 EnergyPlus Model of the DSF

RESULTS AND DISCUSSION

The following discussion is based on the ventilation mode illustrated in Figure 5.

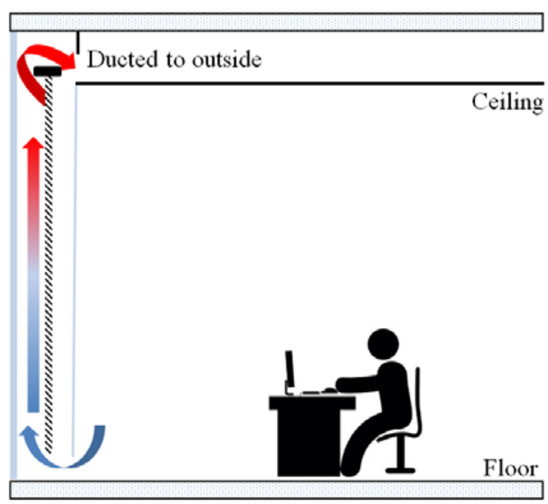


Figure 5 Mode of ventilation

Ventilation performance

1. Air temperature in cavity

In summer, when the DSF is not ventilated, the air temperature inside the cavity is highly stratified as shown in Figure 6. For the west facing facade, ventilating the cavity could cool down the hottest air by 20 ºC. This reduces the cooling load imposed by the facade and improves the facade's structural safety.

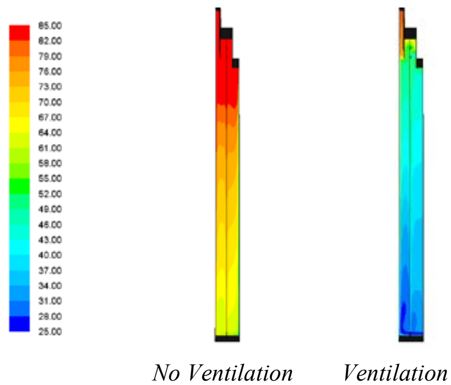


Figure 6 Air temperature of cavity on clear summer day at 16:00 (ºC)

2. Surface temperature of glazing

In summer, the cavity ventilation cools down the glazing, thus increase the comfort for spaces adjacent to the facade. Shown in Figure 7, the surface 4 temperatures are reduced on all orientations. Based on the PMV calculation (PMV no higher than 1.0), the maximum allowed MRT is 35 ºC. For south and north, the ventilated DSF is already able to maintain comfort (with surface 4 temperature lower than 35 ºC). For east and west, the surface 4 temperatures are largely reduced to be close to the maximum allowed MRT.

In winter, bringing indoor airflow into the cavity warms up the internal glazing for comfort benefit. However, our study shows that the surface 4 temperature rises by 2.6 ºC, see Figure 8. This contributes to the thermal comfort positively but is not effective enough to justify its associated additional fan energy. Condensation will not occur on surface 4 under the ventilation mode. However, the bottom part of surface 2 may have the risk of condensation due to the warm moisture air entered from indoor, see Figure 9.

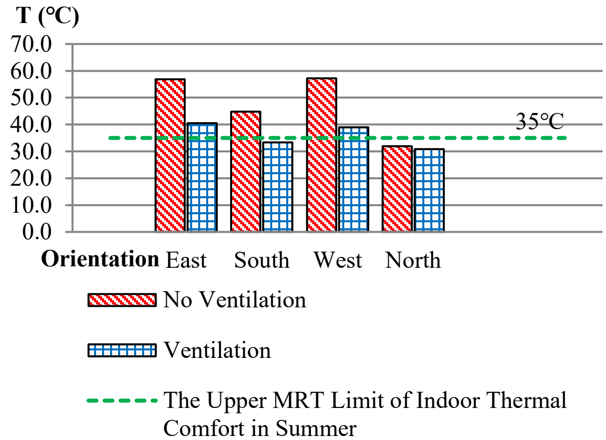


Figure 7 Average temperature of surface 4 in summer

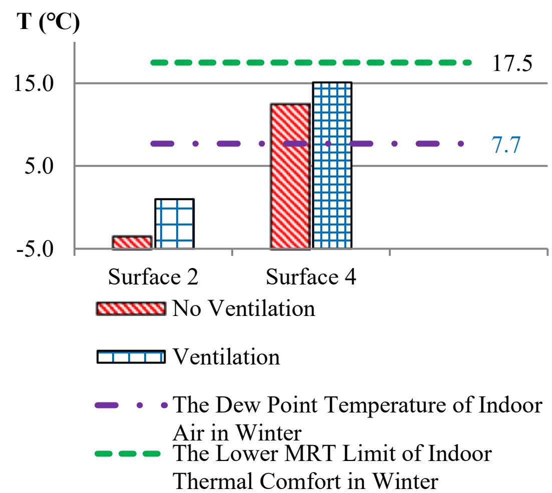


Figure 8 Average temperature of surface 2 & 4 temperature of glazing in winter

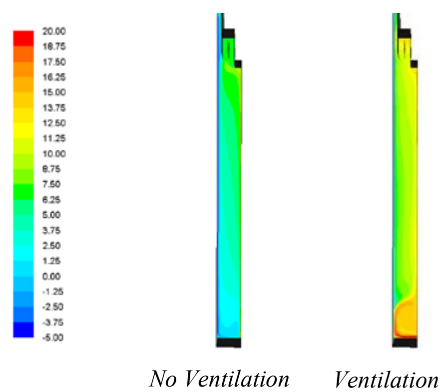
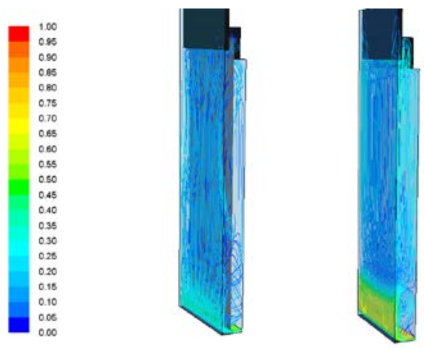


Figure 9 Air temperature of cavity on overcast winter day (℃)

3. Impact of blinds to cavity flow

When blinds are deployed inside the cavity, they create resistance to the flow into the cavity. The impact of it is studied by the CFD analysis. When the blinds are fully deployed, there is a multi-centimeter gap between the lowest slat and the bottom of the DSF structure where local flow resistance is introduced. Overall the ventilation flow rate is reduced by about 3% when blinds are fully deployed in the cavity. This is acceptable in this particular project, see Figure 10.



Blinds deployed *Blinds retracted*

Figure 10 *Streamline visualization in the cavity*

4. Thermal comfort

The thermal comfort was studied using the west facing facade, which is typically the worst orientation for solar radiation control. There are two instances: 4pm in a summer clear day and daytime in a winter overcast day. The zone which is immediately adjacent to the DSF typically has poor comfort performance due to the negative impact from the glazing temperature, see Figure 11 for the PMV value transition along the depth of the space. In summer, occupants (1.2m above floor) may feel uncomfortable within 3m from the DSF under the non-ventilated mode. This could be reduced to 0.6m with ventilation. Compared with the summer scenario, the comfort benefit of DSF in winter is less, as seen from Figure 9, the discomfort depth is reduced from 1.0m to 0.5m when ventilation is available.

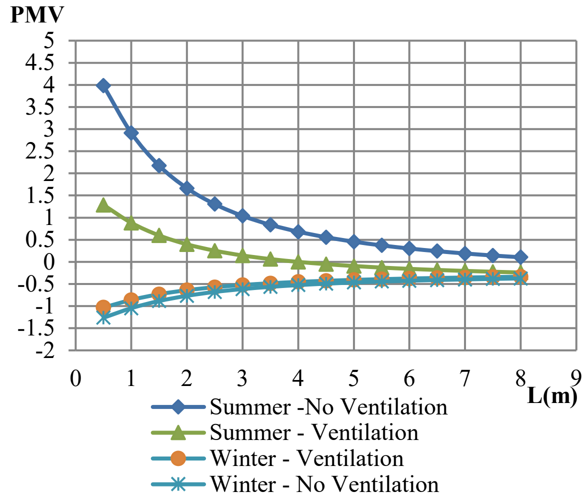


Figure 11 Thermal comfort transition regarding to the distance off the DSF

5. Energy

The intent of the energy study is to evaluate DSF's thermal insulation under various seasonal conditions with and without cavity ventilation. The transmitted solar radiation is not considered as part of this calculation as it is not affected by the ventilation status inside the cavity.

Figure 12 shows in summer, the ventilation air in the cavity could carry the absorbed heat inside the cavity to outdoor. This considerably reduces the heat flux entering the building. Similar to the summer performance, the cavity ventilation decreases DSF's thermal interaction between indoor and outdoor during swing seasons, see Figure 13. In winter, it is desirable to increase the heat flux coming into the building for heating purpose, therefore the reduced heat flux brought by the cavity ventilation would negatively affect the energy performance, shown in Figure 14.

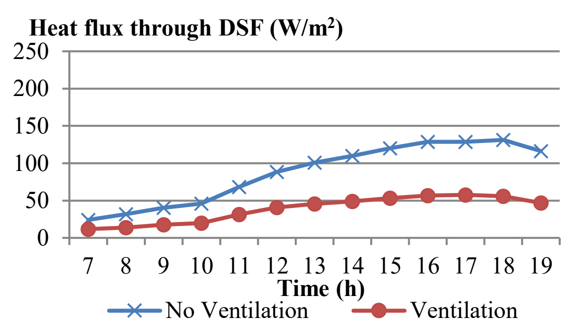


Figure 12 Heat flux through DSF facing south in summer

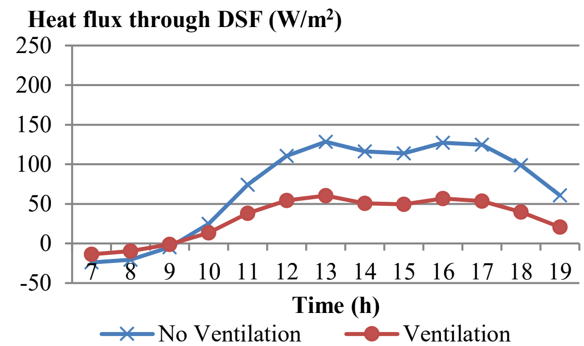


Figure 13 Heat flux through DSF facing south in swing seasons

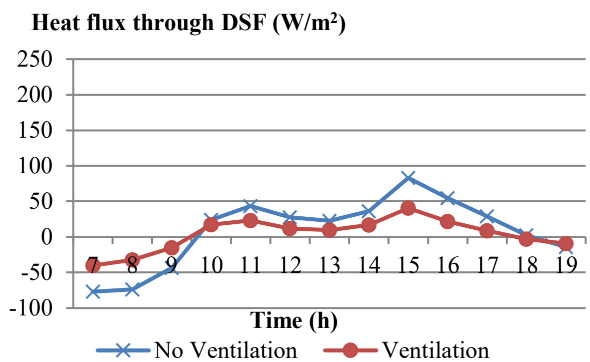


Figure 14 Heat flux through DSF facing south in winter

Ventilation optimization

1. Ventilation rate

The ventilation rate of the cavity is optimized based on two factors: temperature of the cavity and overall energy consumption.

Increasing the ventilation rate would promote the heat transfer between the air of the cavity and glazing surfaces. A diminishing return point can be seen in Figure 15, in the range between 300 and 400m3/h, which is where the design value falls into.

The other factor is the overall energy consumption, including the building HVAC and the DSF cavity exhaust fans. The optimum can be found in the range of 350 to 400m3/h, shown in Figure 16.

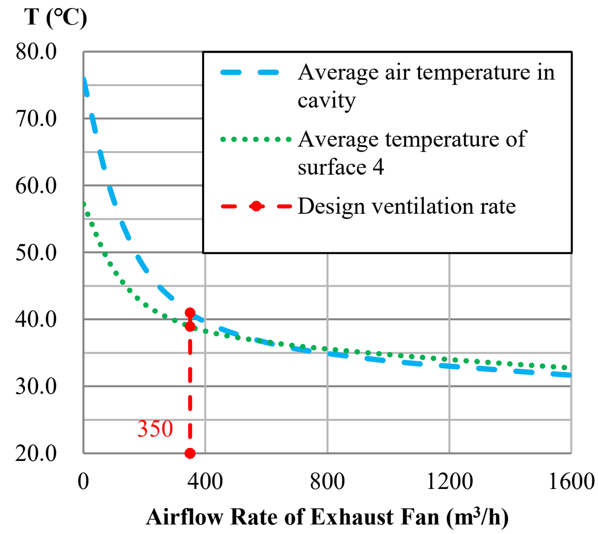


Figure 15 Diminishing return curves for the ventilation rate optimization, summer, west oriented facade, 4pm

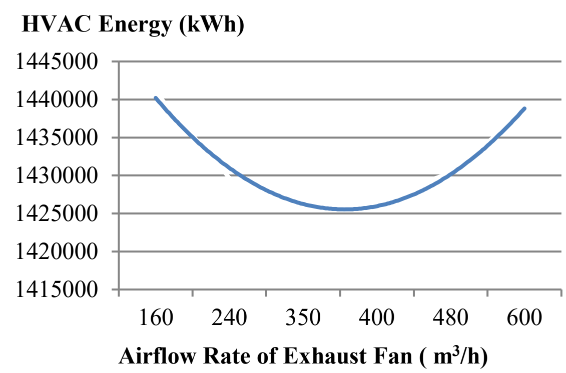


Figure 16 Variation of HVAC energy with different ventilation rate

After all, the two optimal ranges of the ventilation rate overlaps quite well. Therefore the design value (350m^3/h) is a reasonable specification and suitable to this project.

2. Annual operation

The annual operation of the cavity ventilation plays an important role on the DSF performance. There are two perspectives need to be considered when defining the operation: energy and comfort. Therefore the trade-off between the two was studied. In winter, as discussed previously, the cavity ventilation should be kept off for energy savings and preventing condensation. In summer, the DSF should be operated at occupancy hours to improve thermal comfort and mitigate undesirable heat gain. In swing seasons, a more detailed operation schedule needs to be developed by the principal of maximizing DSF's ability to reduce external thermal disruption and balancing fan energy consumptions. Table 6 shows the two annual operation modes for the comparison.

Table 6 Annual operation modes

	MODE A	MODE B
SWING SEASONS		
Month	Mar - May, Sep - Nov	May, Sep
Hour	ON: 7am – 7pm	ON: noon – 5pm
SUMMER		
Month	Jun - Aug	
Hour	ON: 7am – 7pm	
WINTER		
Month	Dec - Feb	
Hour	All OFF	

Mode A has an extended period of cavity fan operation compared with Mode B. By looking at the tradeoff between HVAC and cavity fan energy in Table 7, being energy conscious, it is preferable to shorten the ventilation operation in swing seasons, basically to avoid the hours when DSF's HVAC saving cannot justify the associated cavity fan energy expense.

Table 7 Energy saving comparison of different modes (whole year)

MODE	ORI.	ENERGY SAVINGS (KWH) HVAC (GAIN)	ENERGY SAVINGS (KWH) CAVITY FAN (LOSS)	NET SAVINGS* (KWH)
A	East	9,903	22,991	-37,865
	North	2,882	9,196	
	South	3,902	9,196	
	West	9,822	22,991	
B	East	3,913	3,564	1,351
	North	1,315	1,425	
	South	1,664	1,425	
	West	4,437	3,564	

* Negative values indicate the HVAC energy saving does not justify the additional fan energy consumption of DSF ventilation.

Another factor of consideration is comfort. It has been discussed that cavity ventilation can considerably increase hours of comfort in summer, see Figure 17. In swing seasons, cavity ventilation with Mode A is able to increase 117h comfortable hours, while in Mode B, this becomes 50h, see Figure 18 and 19.

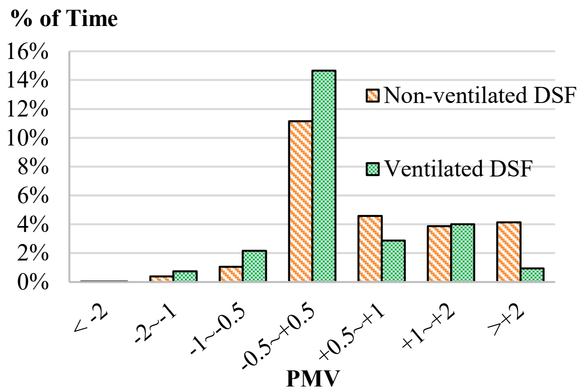


Figure 17 Thermal comfort comparison in summer

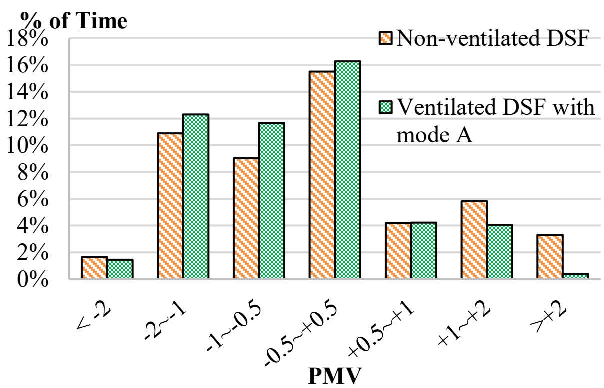


Figure 18 Thermal comfort comparison with Mode A in swing seasons

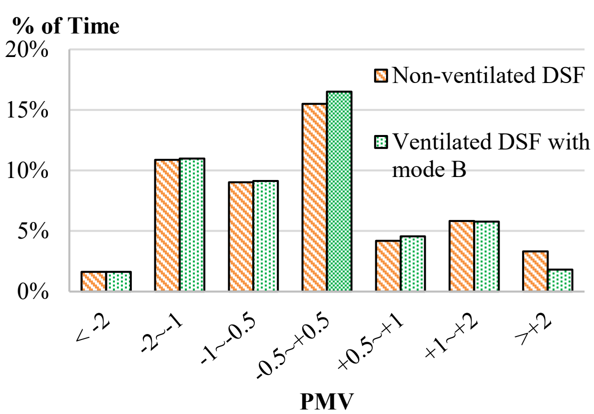


Figure 19 Thermal comfort comparison with Mode B in swing seasons

In practice, a ventilated DSF design would seek balance between energy and comfort performance. Mode B in this study is a more balanced approach. Although its comfort performance is slightly worse than Mode A, it provides overall energy savings considering the HVAC and DSF ventilation fan altogether.

CONCLUSION

Based on the above analysis, effective ventilation is essential for DSF, otherwise there may be many risks such as excessive fan energy consumption, uncomfortable MRT, condensation, and even the glass or structural adhesive damaged due to overheating. But DSF is not a rigid facility, but a complex system. Its performance is influenced and restricted by many factors. Its energy efficiency and comfort need to be refined by careful design and operation.

Compared with the traditional curtain wall, DSF brings different benefits in different seasons: reducing energy consumption of heating in winter and improving indoor thermal comfort in summer. Obviously the benefits are closely related to climate change. China has many climate zones, therefore there is no "apply-to-all" design standards for DSF in China. The design of DSF should be based on the environmental conditions and is evaluated and analyzed in different perspectives as follows:

Table 8 Design perspectives of DSF

GENERAL	
Outdoor climate conditions	Indoor noise
Outdoor air quality	Indoor daylighting
Building fire protection	Building Structure
Initial investment	Usable floor area
DETAIL	
Type of DSF	Size of DSF
Glazing material	Blinds material and Size
Ventilation rate and ventilation efficiency	Vents design
Temperature control in cavity and glazing	Condensation on glazing
Heat recovery	Ventilation strategy

The operation of DSF focuses mainly on ventilation management. As a rule of thumb, ventilation is always on in summer and off in winter. However, the winter in southern China is warmer, similar to swing season, DSF may need to be ventilated at the right time based on well-design. Generally, it is recommended that the ventilation period should be selected in afternoon of the hottest months to achieve greater returns.

Regularly check ventilation performance of DSF to ensure that the ventilation rate always meets the design requirements. In addition, it is important that periodically monitor the cavity temperature of DSFs that are facing west in the summer afternoon, so as to take remedial measures to avoid dangerous extreme temperature caused by heat accumulation.

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