Article

Acoustical Evaluations of a Double Skin Façade as a Noise Barrier of a Naturally-Ventilated Facade

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ABSTRACT

Urban traffic noise deters building occupants from utilizing window ventilation that helps lower the concentrations of indoor air pollutants. Traffic noise transmission via operable windows has become an environmental hazard, degrading the indoor acoustic quality of built environments. The objective of this study is to investigate the acoustical performance of shading louvers and air vents in a double skin façade (DSF) along with natural ventilation performance. A DSF mock-up was tested for noise reduction at the reverberation chamber depending on the percentage of air vent open surface area (e.g., 100% versus 40%), type of shading louvers (e.g., vertical versus horizontal), orientation of shading louvers (e.g., closed versus open position), and surface material of shading louvers (e.g., wood versus acoustic fabric-wrapped). In addition, a preliminary simulation study using computational fluid dynamics (CFD) software was performed to predict air velocity and air temperature distributions inside the DSF air cavity. The results showed that a DSF mock-up achieved noise reduction by approximately 33 to 36 dB(A). Vertical shading louvers tilted at a 90-degree angle, which is a closed position, was effective in noise reduction by 3 to 6 dB(A) at a lower mid- (500 Hz), a mid- (1000 Hz), a higher mid-frequency (2000 Hz and 4000 Hz) when compared to shading louvers tilted at a 0-degree angle (open position). However, the percentage of air vent open surface area, acoustic fabric of shading louvers, and type of shading louvers were not significant contributors to noise reduction. The outcomes of a preliminary CFD simulation study also showed that air vent configurations can improve the inflow of outdoor air volume with a comfort air velocity of 1.5 m/s.

KEYWORDS: noise reduction; natural ventilation; double skin façade; naturally-ventilated building

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INTRODUCTION

According to the World Health Organization (WHO), the concentration of indoor pollutants is two to five times higher than outdoor pollutants, and lack of ventilation in developed countries results in poor indoor air quality [1]. Even though naturally-ventilated buildings enable reducing the concentrations of indoor air pollutants through improving ventilation rate, indoor acoustic quality can decline by traffic noise transmission via operable windows in high noise areas [2].

Noise is generally defined as an unwanted effect of sound which can register physiologically and psychologically [3,4]. Transportation noise is a primary outdoor noise source that has caused adverse health effects such as hearing impairment, annoyance, and sleep disturbance. The WHO reports that traffic-related noise has become the most health-threatening environmental stressor in Europe. These adverse health effects can also lead to social handicaps, reduced productivity, decreased performance in learning, absenteeism in the workplace and schools [5–7]. The impacts of transportation noise exposure are related to specific non-auditory stress consequences, such as changes in physiological systems (e.g., high blood pressure), cognitive memory degradation, sleep disturbances, modifications of social behavior, psychosocial stress-related symptoms and emotional effects, such as annoyance [3–8].

For these reasons, there are several studies on the acoustical performance of building façade components such as lintels and louvers. Lintels and louvers seldom achieve acoustical performance, but significant acoustical improvement occurs with an absorbent surface. Louvers with ventilation openings are proven to reduce noise transmission by blocking the direct sound propagation. Particularly, absorptive materials applied to the underside of louver slats can attenuate the indirect reflected path. Noise reduction of louvers is valid at the higher frequencies of sound rather than at lower sound frequencies due to sound diffraction [9]. Thin and rigid screens placed on the walls of a tall building were simulated to predict noise attenuation from the direct sound incidence [10]. Sound absorbing shading systems applied to building façades reduce the average sound pressure level (SPL) of 5 or 6 dB when sound absorbing louvers are used compared to the standard shading system [11]. An extruding building balcony was tested for acoustical insertion loss using a multi-story scale model depending on geometrical variables such as a floor width-to-depth ratio and canopy ceiling angles [12,13]. A wide range of noise control devices in naturally-ventilated buildings was investigated with fins, lintels, screens, protrusions, resonant devices, balconies, plenum windows, and double-wall plenum structures with air vents [14].

However, it is crucial to understand the coinciding environmental conflicts between outdoor air inflow and noise transmission via ventilation openings. To achieve the environmental requirements of ventilation performance and noise reduction in naturally-ventilated buildings, this study is intended to employ the environmental benefits of double skin façades including (1) air cavity and air vents between two layers of glass that create micro-climate conditions depending on outdoor climate conditions; (2) adjustable shading louvers that avoid direct solar radiation as thermal barriers; (3) air cavity volume that acts as noise barriers against outdoor noise transmission; and (4) curtain wall glazing systems that offer full visual accessibility to outdoor environments [15–24].

RESEARCH DESIGN AND TEST

In general, Figure 1 shows hypothetical airflow patterns inside DSF air cavities. Depending on air vent configurations, the air coming in via air inlets is intended to travel to other air vents vertically through the air cavity, that generally allows three modes of airflow patterns such as outside-ventilated (airflow pattern 1), inside-ventilated (airflow pattern 2), and hybrid-ventilated (airflow patterns 3 through 5) [24]. Through vertical air movement by the stack effect, the air cavity is expected to dissipate excessive heat as well as to dilute concentrated indoor air pollutants. In this study, a DSF mock-up set-up and a preliminary CFD simulation study are designed based on schemes of hybrid ventilated ones (airflow patterns 4 and 5) as available configurations of air vents.

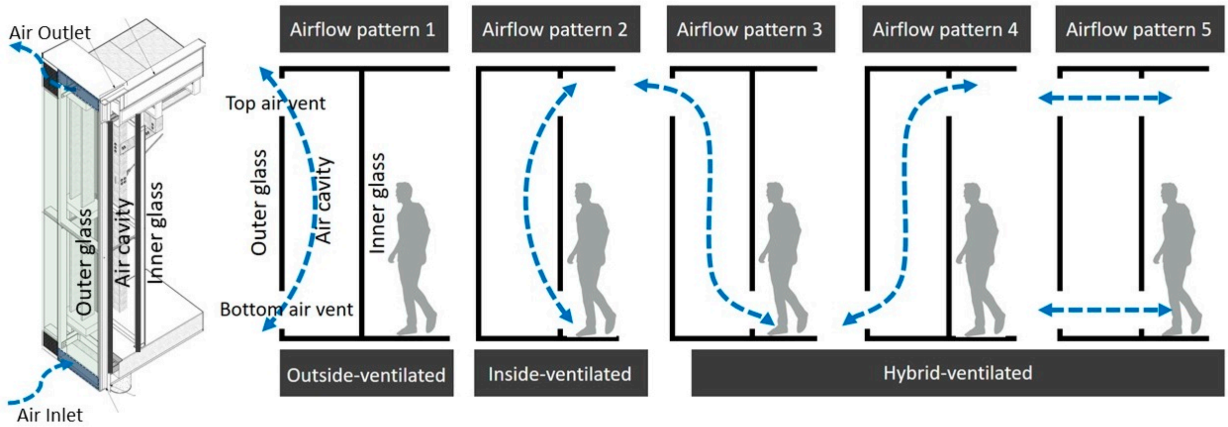


Figure 1. Sectional drawings of hypothetical airflow patterns inside DSF air cavity.

Figure 2 shows an actual DSF building façade, which is comprised of the air cavity, vertical shading louvers, and air vents. Under the assumption that transmitted noise travels through DSF air vents and air cavity during the intermediate seasons suitable for natural ventilation, this mock-up study is designed with several control variables: (1) the percentage of air vent open surface area (e.g., 100% versus 40%); (2) type of shading louvers (e.g., vertical versus horizontal); (3) orientation of shading louvers (e.g., closed versus open position); and (4) surface material of shading louvers (e.g., wood versus acoustic fabric-wrapped).

Figure 2. Double skin façade building at the University of Kansas (source: https://studio804.com/).

A hypothetical design of a DSF mock-up is a box-window DSF air cavity, which is commonly used in situations where there are high external noise levels [15]. Due to the limitations of acoustic simulation software to test noise reduction based on control variables, a DSF mock-up was built inside a reverberation chamber to measure the difference of sound pressure levels (SPLs) for 36 test cases between a sound sending room and a sound receiving room. In this mock-up test, sound pressure levels (SPLs) in dB(A) were measured between two rooms separated by a DSF mock-up specimen because the primary descriptor for noise annoyance correlates to its physical characteristics such as SPLs, spectral characteristics, and variations of properties with time [6].

Test Standard

The basic requirements for the measurement standard of DSF mock-up test regarding test room, specimens, sound source, equipment, and test equation follow the American Society for Testing and Materials (ASTM) E90-02. As for acoustical instrumentation for the airborne sound insulation measurement at the reverberation chamber, there was an opening of 1.22 m (4 feet) wide by 2.44 m (8 feet) high between two adjacent rooms as shown in Figure 3. The test specimen is installed in the opening to measure the noise reduction (NR) of a DSF mock-up comprised of two layers of glass, shading louvers, and air vents.

The Larson 831 sound level meter, a dodecahedron loudspeaker, a mixing console, and a pink noise generator were used to measure more accurate SPLs in each room as shown in Table 1. The Larson 831 sound level meter features various measurement parameters such as multiple time weightings (e.g., slow, fast & impulsive) and frequency weightings (A, C, and Z). A condenser microphone can measure SPL ranging from 16 to 140 dB. The dodecahedron loudspeaker has a full-range speaker mounted in each of the 12 sides, providing uniform sound radiation. A mixing console and a pink noise generator produce pink noise, of which each octave carries an equal amount of noise energy.

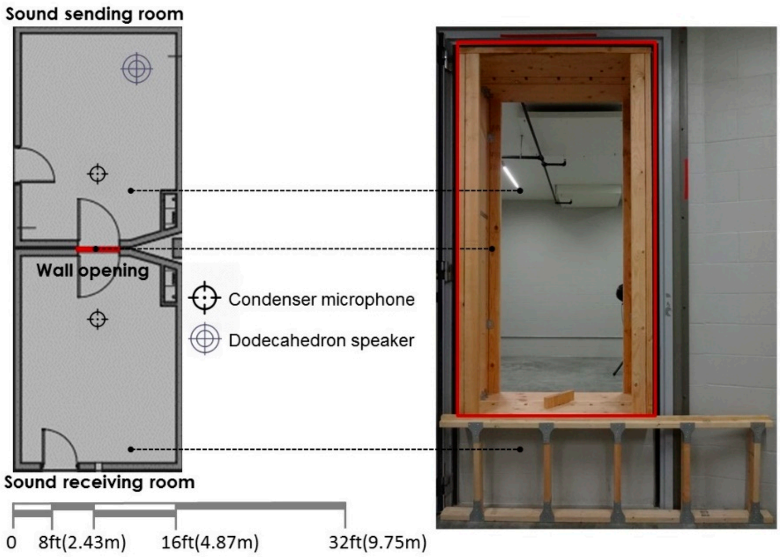


Figure 3. Reverberation chamber plan drawing.

Table 1. Instrumentation for the airborne sound insulation measurements.

Item	Sound sending room	Sound receiving room	Control room
Microphones	Larson 831	Larson 831	N/A
Sound source	NTi dodecahedron	N/A	N/A
Analyzer	Larson 831	Larson 831	N/A
Amplifier	N/A	N/A	QSC RMS5050a
Mixer	N/A	N/A	Podium Pro MS1204
Calibrator	N/A	N/A	Extech 407744

DSF Mock-up Construction

Figure 4 shows the construction procedure of a DSF mock-up made of wooden structural frames, two layers of glass, and shading louvers. Two layers of 0.635 cm (0.25 inches) thick glass were installed as the inner and outer layers of glass, which form the air cavity of a DSF mock-up. A piece of outer glass is designed to be operable to orient various shading louver angles. Duct sealant and glass fiber filled joint gaps of the wooden frame to minimize sound leakage through structural frames and pieces of glass.

The size of shading louvers is heat-treated pine fir with 22.86 cm (9 inches) wide and 6.35 cm (2.5 inches) thick (see Figure 4c,d). The type of shading louvers was intended to compare the differences in the NR values between vertical and horizontal shading louvers. Test cases of vertical and horizontal shading louvers were designed to orient at a 90-degree angle, which is in a fully closed position. Depending on test cases, they are also designed to be tilted at 0, 30, 60, and 90-degree angles.

Applied acoustic fabric to solid wooden shading louvers is a control variable related to noise attenuation. Acoustical surface material and its noise reduction coefficient (NRC), an index of the amount of sound energy absorbed upon striking a particular surface, is 0.005 (see Figure

4a,b,f). The width of the DSF air cavity is designed to be 61 cm (2 feet) between the inner and outer layers of glass (see Figure 4e).

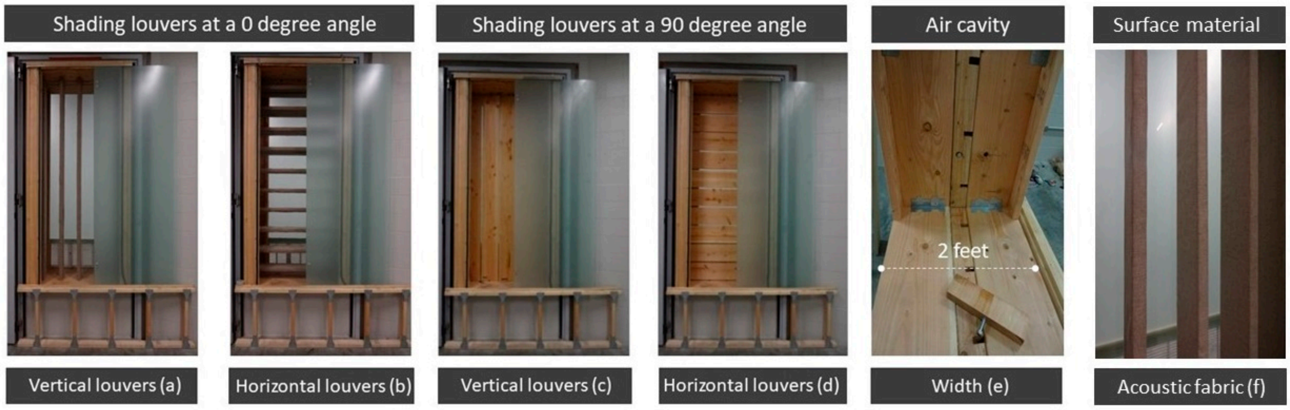


Figure 4. Shading louvers tilted at 0-degree angles (**a**,**b**), 90-degree angles (**c**,**d**) air cavity width (**e**), and acoustic fabric (**f**).

DSF Mock-up Set-up

Figure 5 shows DSF mock-up set-ups at the reverberation chamber. A dodecahedron loudspeaker and condenser microphones were situated at 1.5 m from the ground in a sound sending and a sound receiving room. The average of A-weighted continuous sound levels (L_{Aeq}), which is a single number of constant sound pressure levels responding to human hearing, was measured from four different locations every 30 s. The hypothesis for a mock-up set-up includes: (1) transmitted noise via air inlets of a DSF travels along with DSF air cavities horizontally and vertically, (2) a higher percentage of air vent open surface area is proportional to an increase in noise transmission, (3) shading louvers tilted at 90-degree angles help reduce noise transmission, (4) horizontal shading louvers are more effective in blocking noise propagation than vertical shading louvers, and (5) shading louvers with a layer of acoustic fabric are more effective in noise reduction than reference cases.

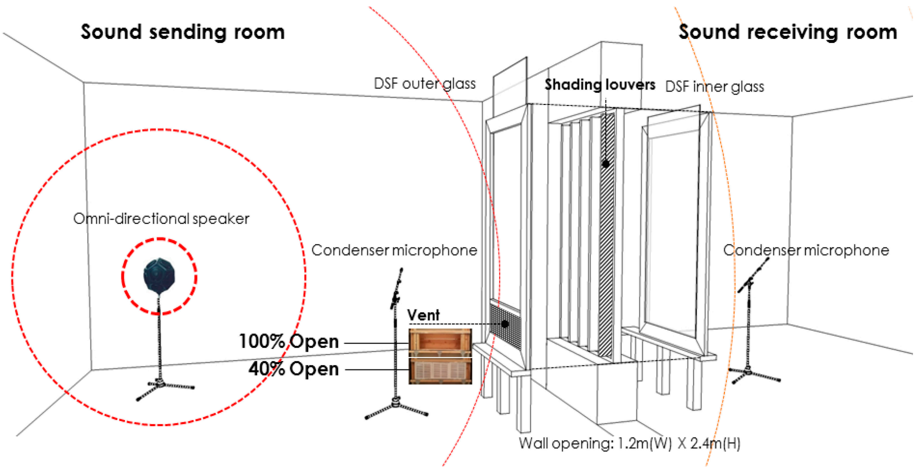


Figure 5. DSF mock-up set-up with shading louvers and air vents as noise barriers.

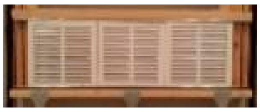
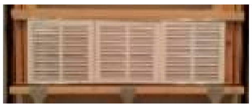
Three perforated sheet aluminum air vents with 40% of air vent open surface area were used as air vents in a DSF mock-up in Figure 6. Each rectangular size is 25 cm (10 inches) high and 25 cm (10 inches) wide. In this mock-up test, two different percentages of air vent open surface areas were applied to the bottom of the outer glass to compare the acoustical difference in noise reduction (see Figure 6a,b).

Figure 6. DSF mock-up set-up of a sound sending (**a**,**b**) and receiving room (**c**).

DSF Test Cases

Table 2 shows that the number of test cases is comprised of 36 cases based on the following control variables depending on (1) a percentage of air vent open surface area; (2) vertical versus horizontal shading louvers; (3) orientation of shading louvers; and (4) surface material of shading louvers. The objective of several test cases is not only to compare the NR values with and without air vents but also to evaluate the acoustic performance of shading louvers of a DSF mock-up as noise barriers. For instance, the test scenario of Case 2 is for 40% of air vent open surface area and 0-degree angled vertical shading louvers wrapped with 1.6 mm thick acoustic fabric.

Table 2. DSF mock-up test cases.

Louver	Test case	% of air vent open surface area	Orientation	Surface material
Vertical Shading Louver	Case 1		No shading louvers	
	Case 2		0° angle	without 1.6 mm (0.0625") thick acoustic fabric
	Case 3		30° angle	
	Case 4		60° angle	
	Case 5	40% of open surface area	90° angle	
	Case 6		0° angle	with 1.6 mm (0.0625") thick acoustic fabric
	Case 7		30° angle	
	Case 8		60° angle	
	Case 9		90° angle	
	Case 10		No shading louvers	
	Case 11		0° angle	without 1.6 mm (0.0625") thick acoustic fabric
	Case 12		30° angle	
	Case 13		60° angle	
	Case 14	100% of open surface area	90° angle	
	Case 15		0° angle	with 1.6 mm (0.0625") thick acoustic fabric
	Case 16		30° angle	
	Case 17		60° angle	
	Case 18		90° angle	
Horizontal Shading Louver	Case 19		No shading louvers	
	Case 20		0° angle	without 1.6 mm (0.0625") thick acoustic fabric
	Case 21		30° angle	
	Case 22		60° angle	
	Case 23	40% of open surface area	90° angle	
	Case 24		0° angle	with 1.6 mm (0.0625") thick acoustic fabric
	Case 25		30° angle	
	Case 26		60° angle	
	Case 27		90° angle	
	Case 28		No shading louvers	
	Case 29		0° angle	without 1.6 mm (0.0625") thick acoustic fabric
	Case 30		30° angle	
	Case 31		60° angle	
	Case 32	100% of open surface area	90° angle	
	Case 33		0° angle	with 1.6 mm (0.0625") thick acoustic fabric
	Case 34		30° angle	
	Case 35		60° angle	
	Case 36		90° angle	

RESULTS AND DISCUSSIONS

Noise Reduction

Table 3 shows the test results of 18 cases for 40% of air vent open surface area (Cases 1 through 9, and Cases 19 through 27) and Table 4 shows test results of the other 18 cases for 100% of air vent open surface area (Cases 10 through 18, and Cases 28 through 36). The overall NR values were calculated as the acoustical difference of SPLs between each sound sending and sound receiving room. From the experimental data, a DSF mock-up itself achieved the overall NR by 33 to 37 dB(A) across the entire octave band center frequency when the sending sound source with a pink noise spectrum was 89 dB(A). When shading louvers were oriented at a 90-degree angle, such as Cases 5, 9, 14, 18, 23, 27, 32 and 36, the overall NR values across 1/1 octave band center frequency were higher by approximately 3 to 4 dB(A) than cases at a 0-degree angle such as Cases 2, 6, 11, 15, 20, 24, 29, and 33.

Between vertical and horizontal shading louvers, there was a slight difference in NR values by about 1 dB(A). There was also a slight acoustical difference by 1 dB(A) in cases for shading louvers covered with 1 millimeter (0.0625 inches) thick acoustic fabric such as Cases 5 versus 9, Cases 14 versus 18, and Cases 23 versus 17. As for the percentage of air vent open surface area in relation to NR values, there was no significant acoustical difference between 40% of air vent open surface area (Cases 1 through 9, and Cases 19 through 27) and 100% of air vent open surface area (Cases 10 through 18, and Cases 28 through 36).

Table 3. NR values based on 40% air vent open surface area and shading louver orientation.

40% of air vent open surface area on outer glass					[unit: dB(A)]
Sound sending room (A)					89
Sound receiving room (B)					**Noise Reduction (A) − (B)**
Cases 1 and 19 (reference cases): No shading louvers				56	33
Vertical Shading Louver (Cases 2–9)	Solid wood surface	**Case 2.**	**0° angle**	**56**	**33**
		Case 3.	30° angle	56	33
		Case 4.	60° angle	55	34
		Case 5.	**90° angle**	**53**	**36**
	Acoustic fabric	**Case 6.**	**0° angle**	**56**	**33**
		Case 7.	30° angle	55	34
		Case 8.	60° angle	54	35
		Case 9.	**90° angle**	**52**	**37**
Horizontal Shading Louver (Cases 20–27)	Solid wood surface	**Case 20.**	**0° angle**	**55**	**34**
		Case 21.	30° angle	55	34
		Case 22.	60° angle	55	34
		Case 23.	**90° angle**	**53**	**36**
	Acoustic fabric	**Case 24.**	**0° angle**	**55**	**34**
		Case 25.	30° angle	54	35
		Case 26.	60° angle	55	34
		Case 27.	**90° angle**	**52**	**37**

Table 4. NR values based on 100% air vent open surface area and shading louver orientation.

100% of air vent open surface area on outer glass					[unit: dB(A)]
Sound sending room (A)					89
Sound receiving room (B)					**Noise Reduction (A) − (B)**
Cases 10 and 28 (reference cases): No shading louvers				56	33
Vertical Shading Louvers (Cases 11–18)	Solid wood surface	**Case 11.**	**0° angle**	**56**	**33**
		Case 12.	30° angle	56	33
		Case 13.	60° angle	55	34
		Case 14.	**90° angle**	**53**	**36**
	Acoustic fabric	**Case 15.**	**0° angle**	**56**	**33**
		Case 16.	30° angle	55	33
		Case 17.	60° angle	54	34
		Case 18.	**90° angle**	**52**	**37**
Horizontal Shading Louvers (Cases 29–36)	Solid wood surface	**Case 29.**	**0° angle**	**55**	**34**
		Case 30.	30° angle	55	34
		Case 31.	60° angle	56	33
		Case 32.	**90° angle**	**53**	**36**
	Acoustic fabric	**Case 33.**	**0° angle**	**55**	**34**
		Case 34.	30° angle	55	34
		Case 35.	60° angle	55	34
		Case 36.	**90° angle**	**53**	**36**

Table 5 shows NR values across 1/1 octave band center frequency. Shading louvers oriented at a 90-degree angle such as Cases 5, 9, 14, 18, 23, 27, 32, and 36 achieved higher NR values by about 3 to 6 dB(A) at a lower mid- (500 Hz), a mid- (1000 Hz), a higher mid- (2000 Hz and 4000 Hz), compared to reference cases such as Cases 1, 10, 19, and 28. The NR values were highest by 6 dB(A) at a higher mid-frequency (2000 Hz).

Table 5. NR values across 1/1 octave band center frequency.

Case	**Test variable**	**NR**	**NR values (1/1 octave band center frequency (Hz))**								**NR Index**
		dB(A)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	0
Case 1	No shading louvers	0	0	0	0	0	0	0	0	0	1
Case 2	w/ air vents, V-solid, 0°	0	−1	−2	−1	1	0	1	1	0	2
Case 3	w/ air vents, V-solid, 30°	0	−1	0	−1	1	0	1	2	0	3
Case 4	w/ air vents, V-solid, 60°	1	−1	1	−2	1	0	2	2	0	4
Case 5	w/ air vents, V-solid, 90°	3	−1	−2	0	4	3	5	3	0	5
Case 6	w/ air vents, V-fabric, 0°	0	0	−1	−1	0	0	1	2	0	6
Case 7	w/ air vents, V-fabric, 30°	1	0	0	0	1	1	2	2	0	
Case 8	w/ air vents, V-fabric, 60°	1	0	0	−1	2	1	2	3	0	
Case 9	w/air vents, V-fabric, 90°	4	−1	0	1	5	4	6	4	0	

Table 5. *Cont.*

Case	Test variable	NR dB(A)	NR values (1/1 octave band center frequency (Hz))								NR Index
			63	125	250	500	1000	2000	4000	8000	0
Case 10	No shading louvers	0	0	0	0	0	0	0	0	0	
Case 11	w/o air vents, V-solid, 0°	0	−7	−4	−1	1	0	0	2	0	
Case 12	w/o air vents, V-solid, 30°	0	−7	−2	−1	1	0	1	2	0	
Case 13	w/o air vents, V-solid, 60°	1	−7	−2	−2	1	0	1	3	0	
Case 14	w/o air vents, V-solid, 90°	3	−7	−4	−1	3	3	5	4	0	
Case 15	w/o air vents, V-fabric, 0°	0	−6	−5	−1	0	0	1	3	0	
Case 16	w/o air vents, V-fabric, 30°	0	−6	−4	−1	0	0	1	3	0	
Case 17	w/o air vents, V-fabric, 60°	1	−6	−2	−1	2	0	2	3	0	
Case 18	w/o grilles, V-fabric, 90°	4	−7	−3	0	5	4	6	5	0	
Case 19	No shading louvers	0	0	0	0	0	0	0	0	0	
Case 20	w/ air vents, H-solid, 0°	1	−3	−1	−1	0	1	3	3	0	
Case 21	w/ air vents, H-solid, 30°	1	−11	−1	−1	1	1	3	3	0	
Case 22	w/ air vents, H-solid, 60°	1	−13	−3	−2	1	0	2	3	0	
Case 23	w/ air vents, H-solid, 90°	3	−14	−2	−2	3	3	6	4	0	
Case 24	w/ air vents, H-fabric, 0°	1	−1	1	0	1	1	2	3	0	
Case 25	w/ air vents, H-fabric, 30°	2	−1	1	0	2	1	2	3	0	
Case 26	w/ air vents, H-fabric, 60°	1	−2	0	−1	3	1	2	3	0	
Case 27	w/ air vents, H-fabric, 90°	4	0	0	0	4	3	5	4	0	
Case 28	No shading louvers	0	0	0	0	0	0	0	0	0	
Case 29	w/o air vents, H-solid, 0°	1	−5	-1	−1	0	0	2	3	0	
Case 30	w/o air vents, H-solid, 30°	1	−13	-2	−1	1	1	2	3	0	
Case 31	w/o air vents, H-solid, 60°	0	−14	-3	−2	0	0	2	3	0	
Case 32	w/o air vents, H-solid, 90°	2	−14	-3	−2	3	3	6	4	0	
Case 33	w/o air vents, H-fabric, 0°	1	−1	0	0	1	1	2	2	0	
Case 34	w/o air vents, H-fabric, 30°	1	−1	1	0	2	1	1	3	0	
Case 35	w/o air vents, H-fabric, 60°	1	−1	0	−1	2	1	2	3	0	
Case 36	w/o air vents, H-fabric, 90°	3	−1	0	0	4	3	5	4	0	

Table 6 and Figure 7 show the measured NR values (L_{Aeq}) across the entire octave band center frequency based on the percentage of air vent open surface area, shading louvers covered with acoustic fabrics, and shading louver orientation. The overall NR values across the entire 1/1 octave band center frequency range from 33 to 37 dB(A). The highest NR values are found by 38 dB(A) at a higher mid-frequency (2000 Hz). This data also shows that there were no significant differences in NR values on the percentage of air vent open surface area, in contrast, the orientation of shading louvers is an influential contributor to noise reduction in Cases 5, 9, 14, 18, 23, 27, 32, and 36.

Table 6. NR across 1/1 octave band center frequency.

Test Case	NR dB(A)	NR values (1/1 octave band center frequency [Hz])							
		63	125	250	500	1000	2000	4000	8000
Case 1	33	27	30	33	33	33	33	34	31
Case 2	33	26	28	32	34	33	34	35	31
Case 3	33	26	30	32	34	33	34	36	31
Case 4	34	26	31	31	34	33	35	36	31
Case 5	**36**	**26**	**28**	**33**	**37**	**36**	**38**	**37**	**31**
Case 6	33	27	29	32	33	33	34	36	31
Case 7	34	27	30	33	34	34	35	36	31
Case 8	34	27	30	32	35	34	35	37	31
Case 9	**37**	**26**	**30**	**34**	**38**	**37**	**39**	**38**	**31**
Case 10	33	27	30	33	33	33	33	34	31
Case 11	33	26	29	32	34	33	33	35	31
Case 12	33	26	31	32	34	33	34	35	31
Case 13	34	26	31	31	34	33	34	36	31
Case 14	**36**	**26**	**29**	**32**	**36**	**36**	**38**	**37**	**31**
Case 15	33	27	28	32	33	33	34	36	31
Case 16	33	27	29	32	33	33	34	36	31
Case 17	34	27	31	32	35	33	35	36	31
Case 18	**37**	**26**	**30**	**33**	**38**	**37**	**39**	**38**	**31**
Case 19	33	27	30	33	33	33	33	34	31
Case 20	34	24	29	32	33	34	36	37	31
Case 21	34	16	29	32	34	34	36	37	31
Case 22	34	14	27	31	34	33	35	37	31
Case 23	**36**	**13**	**28**	**31**	**36**	**36**	**39**	**38**	**31**
Case 24	34	26	31	33	34	34	35	37	31
Case 25	35	26	31	33	35	34	35	37	31
Case 26	34	25	30	32	36	34	35	37	31
Case 27	**37**	**27**	**30**	**33**	**37**	**36**	**38**	**38**	**31**
Case 28	33	27	30	33	33	33	33	34	31
Case 29	34	22	29	32	33	33	35	37	31
Case 30	34	14	28	32	34	34	35	37	31
Case 31	33	13	27	31	33	33	35	37	31
Case 32	**35**	**13**	**27**	**31**	**36**	**36**	**39**	**38**	**31**
Case 33	34	26	30	33	34	34	35	36	31
Case 34	34	26	31	33	35	34	34	37	31
Case 35	34	26	30	32	35	34	35	37	31
Case 36	**36**	**26**	**30**	**33**	**37**	**36**	**38**	**38**	**31**

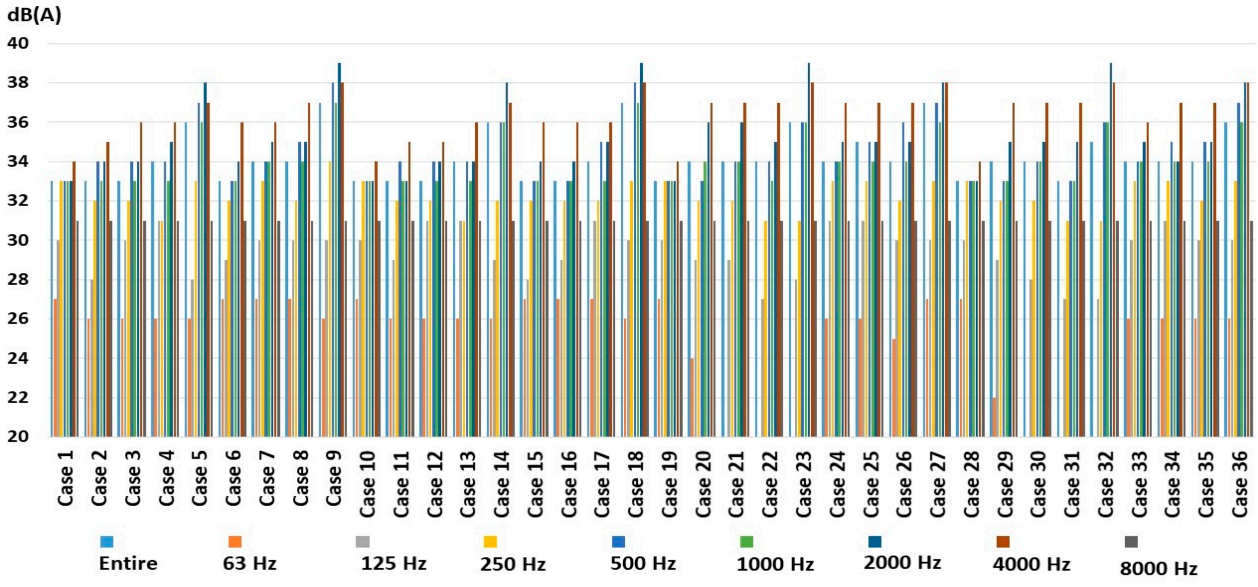


Figure 7. NR values by the frequency range (Hz) of each test case.

Air Behaviors

A preliminary CFD simulation study is designed based on schemes of hybrid ventilated ones as possible configurations of air vents based on a DSF mock-up set-up. Airflow patterns, air velocity, and air temperature distributions inside the DSF air cavity with 40% of air vent open surface area were simulated using CFD software, FloVENT, depending on the location of air vents. The preliminary CFD simulation study aimed to predict the effect of air vent locations for natural ventilation performance that not only improves indoor thermal conditions but also dilutes the concentration of indoor air pollutants.

Table 7 describes CFD boundary conditions for the same size of the air cavity, the same number of shading louvers, and the same percentage of air vent open surface area modeled based on the existing DSF mock-up test set-up. Air vents were applied with 40% of open surface area in case that the mean wind velocity was assumed to be 7 m/s during the intermediate seasons suitable for natural ventilation. For better vertical air movement inside the DSF air cavity, shading louvers were oriented at a 0-degree angle.

Table 7. CFD simulation boundary conditions.

Outdoor variables		**Model variable**	
Site location	Latitude (38°57’ N) Longitude (95°15’ W)	Air cavity size	1.22 m(W) × 2.44 m(H) × 0.61 m(D) (4 ft.(W) × 8 ft.(H) × 2 ft.(D))
Outdoor temperature	29 °C (average high in Jun: 85 °F)	Air vent open surface area (location)	40% (top) and 40% (bottom)
Outdoor wind velocity	7 m/s (11 mph: gentle breeze)	Shading louver orientation	0 degree (open mode: perpendicular to glass)

Figure 8 illustrates the CFD outcomes of airflow patterns, air velocity, and air temperature distributions inside the DSF air cavity. Two CFD scenarios were intended to have (1) one outer air vent at the bottom and one inner air vent at the top (see Figure 8a) and (2) two outer air vents at the top and bottom and one inner air vent at the top. (see Figure 8b). From CFD findings of air velocity and air temperature distributions, the case with two outer air vents (see Figure 8b) improved the large volume of outdoor air inflow with a comfort air velocity of 1.5 m/s to indoor space. The top air vent helped dissipate the heat inside the DSF air vent by circulating airflow through the top air vent (see Figure 8d). Therefore, it is notable to apply sound-absorbing materials to air vents for noise reduction as well as natural ventilation through air vents based on the outcomes of DSF mock-up tests.

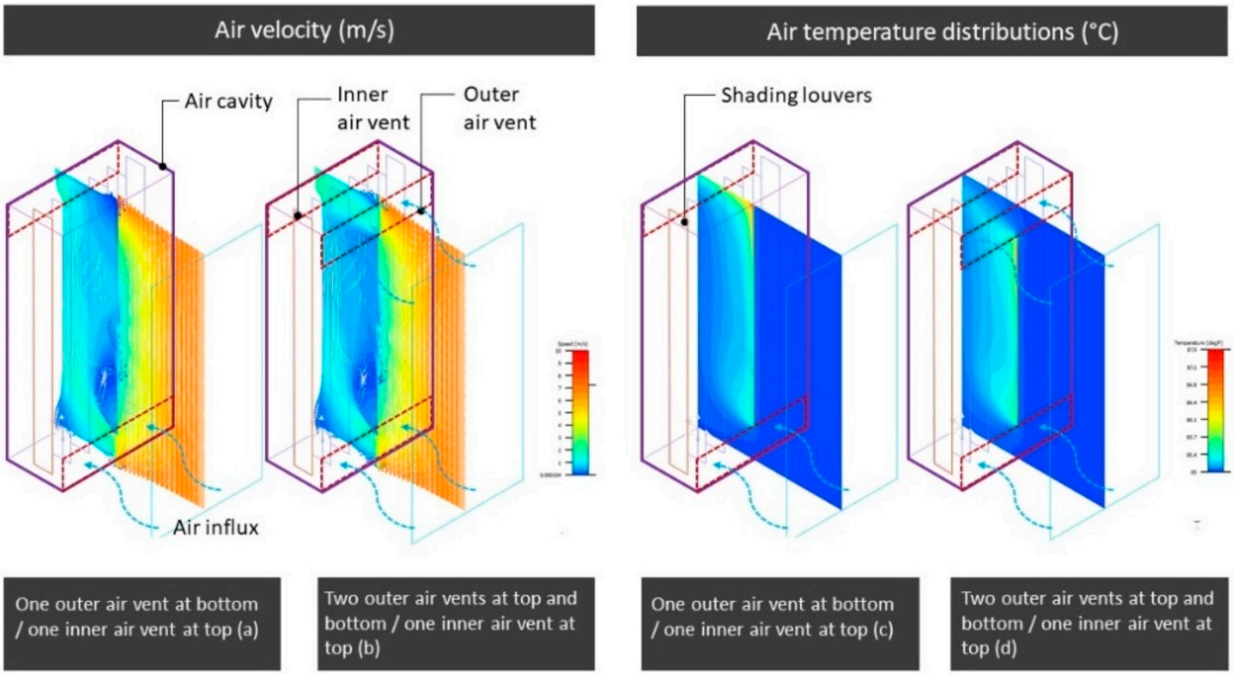


Figure 8. Airflow behaviors and air temperature distribution through air vents.

CONCLUSIONS

A DSF mock-up test showed effective noise reduction ranging 33 between 36 dB(A) depending on several control variables such as the percentage of air vent open surface area, configuration and orientation of shading louvers, and surface material of shading louvers. It was found that a DSF mock-up significantly takes advantage of two layers of glass and air cavity as noise barriers. Shading louvers oriented at a 90-degree angle (closed position) achieved the overall NR values by 3 to 4 dB(A) across 1/1 octave band center frequency compared to ones at a 0-degrees (open position). The NR values are highest by 6 dB(A) at a higher mid-frequency (2000 Hz). However, there was no significant noise reduction between cases with shading louvers tilted between 0 and 30-degree angles. In terms of the view to outdoor, translucent sound-absorbing materials can allow building facades to optimize daylight harvesting and visual connectivity to outdoor environments.

Between vertical and horizontal shading louvers, there was a slight difference in noise reduction by about 1 dB(A). As for the percentage of air vent open surface area, there was no significant acoustical difference between 40% of air vent open surface area and 100% of air vent open surface area. There was also a slight acoustical difference by 1 dB(A) in cases for shading louvers with a 1 mm (0.0625 inches) thick acoustic fabric. These findings imply that the development of air vents applied with sound-absorbing materials is expected to reduce noise at a low-frequency (125 Hz) via ventilation openings.

The outcomes of the preliminary CFD simulation showed air vents improved not only to induce the amount of outdoor air volume with a comfort air velocity of 1.5 m/s concerning natural ventilation performance but also to dissipate the heat inside the DSF air cavity. To improve natural ventilation performance, it also needs to conduct the additional mock-up test for airflow resistance of air vents depending on the percentage of air vent open surface area. This study needs further experimental investigations on advanced noise-controlling ventilation systems for optimized controls of indoor air quality and acoustic quality in a naturally-ventilated building.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

JL, JDC and RC designed the study and analyzed the data. JL constructed and performed the experiments and simulations.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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