The Effect of Shading Louvers and Compact Silencers as Noise Barriers in a Ventilated Double Skin Façade

By

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List of Acronyms

ADT	Average Daily Traffic
ASTM	American Society for Testing Materials
CFD	Computational Fluid Dynamics
dB	Decibel
dB(A)	A-weighted Sound Level
DSF	Double Skin Façade
EPA	Environmental Protection Agency
HVAC	Heating Ventilation Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
L_{Aeq}	A-weighted Equivalent Continuous Sound Level
L_{dn}	Day-night Average Sound Level
L_{eq}	Equivalent Continuous Sound Level
LNP	Noise Pollution Level
M2SEC	Materials & Sustainable Environment Center
MI	Myocardial Infarction
NC	Noise Criteria
NIC	Noise Isolation Class
NIHL	Noise Induced Hearing Loss
NNIS	National Noise Information System
NRC	Noise Reduction Coefficient
OECD	Organization for Economic Cooperation and Development
OITC	Outdoor and Indoor Transmission Class
SBS	Sick Building Syndromes

SPL	Sound Pressure Level
STC	Sound Transmission Class
STL	Sound Transmission Loss
TMSK	Traffic Monitoring System of Korea
TL	Transmission Loss
TNI	Traffic Noise Index
UN	United Nations
WHO	World Health Organization
WWR	Window-to-Wall Ratio

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Acknowledgement

I praise the Lord who is my shepherd. His love, grace and mercy shall not be in want forever. He makes me lie down in green pastures, he leads me beside quiet waters. He restores my soul. He guides me in paths of righteousness for his name's sake. (Psalm 23)

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Abstract

Among environmental stressors, urban noise exposure has become a critical factor for building occupants' health along with rapid urban population growth. The World Health Organization (WHO) has warned that high external noise levels can cause numerous health problems such as sleep disturbance, high blood pressure, and psycho-physiological symptoms. Road traffic noise, among other urban noise sources, has been regarded as the major constraint degrading the acoustical quality of urban environments. However, it was found that there is a conflict between ventilation performance and noise transmission in naturally-ventilated buildings in urban areas. Therefore, this research topic aims to explain the effect of shading louvers and compact silencers as noise barriers in ventilated buildings for indoor air quality and acoustical quality.

This study is intended to investigate the multidimensional aspects needed to improve ventilation potentials and acoustical performance using a double skin facade (DSF) which is composed of an air cavity, two layers of glass, shading louvers, and air vents. This study employs a mixed-use research method composed of a preliminary simulation study and an experimental study. The preliminary simulation study focused on the ventilation performance of a DSF using computational fluid dynamics (CFD) software, and then an experimental study was designed to measure noise reduction of a DSF mock-up in a reverberation chamber based on shading louver orientation, type, and surface material, and the percentage of air vent open surface area of a DSF.

Research findings suggest that shading louvers and compact silencers are effective in noise reduction of a DSF. It implies that integrated shading louvers with sound absorbing materials and compact silencers for air vents can reduce noise transmission through ventilation openings in naturally-ventilated buildings.

CHAPTER 1: Introduction

1.1 Research Background

Global urban population growth is expected to increase from approximately 3.8 to 6.3 billion people between 2014 and 2050, due to an increase of economic concentration in the cities (U.N., 2014). This socio-cultural and demographic phenomenon has brought about various impacts on built environments; for instance, vertical buildings for more efficient land use, airtight curtain wall systems for lightweight structural facades, increased energy demands on heating, ventilation and air conditioning (HVAC) systems, and higher urban traffic intensity.

To study the relationship among urban population growth, urban traffic noise intensity, and negative effects of urban noise, a study was carried out in Seoul, South Korea. It stated that Seoul, as one of the largest cities among the Organization for Economic Cooperation and Development (OECD), has been facing accelerated urbanization (OECD, 2014). World Bank data also shows that the number of motor vehicles, as the largest generator of urban noise, gradually increased by about 43.9% between 2000 and 2011. Under these environmental situations, another study on well-being indices for the physical and psychological health of high-rise building occupants in South Korea indicated that indoor ventilation performance and acoustical comfort are regarded as more important factors than daylight, views, and indoor temperature and humidity. (Lee et al., 2011). In addition, the case study found 64% of building occupants in six selected sites regarded outdoor traffic noise as the main obstacle for their office-work productivity.

Although the current non-bearing curtain wall systems are designed to reduce the possibility of noise transmission by minimizing air infiltration (Sanders, 2006) the lightweight glass-sealed envelopes, which are vulnerable to fluctuating outdoor climate conditions, are dependent on the intensive energy use of HVAC systems (Khan et al., 2008). On the other hand, even though naturally-ventilated buildings can lower the concentration of indoor pollutants, they are prone to urban traffic noise transmission via ventilation windows (Ghiaus & Allard, 2005). In urban environments, the conflict between natural ventilation and noise transmission by ventilation openings has been a significant hurdle to achieving good indoor environmental quality (IEQ). Among the environmental stressors, urban noise exposure has become a critical factor for building occupant health (WHO, 1999; Ghiaus & Allard, 2005). In fact, the World Health Organization (WHO) has warned that high external noise levels can cause numerous health problems such as sleep disturbance, high blood pressure, and psycho-physiological symptoms. Road traffic noise, among other urban noise sources, has been regarded as the major constraint degrading the acoustical quality of urban environments (WHO, 1999; WHO, 2000; Ghiaus & Allard, 2005; Kang, 2007).

Therefore, this study explores not only the conflict between ventilation performance and noise transmission in naturally-ventilated buildings in urban areas, but also proposes the acoustical performance of shading louvers associated with ventilation openings. The reason for this is that indoor air quality (IAQ) and acoustic quality are directly and/or indirectly associated with building occupant health in the built environment. This study is intended to investigate the multidimensional aspects to improve ventilation potentials and acoustical performance using a double skin facade (DSF) which is composed of an air cavity, two layers of glass, shading louvers, and air vents.

1.2 Problem Statement

First, the relationship between ventilation rate and noise transmission loss in urban areas is not only a critical requirement for building occupant health but also a conflict between indoor air quality and acoustic quality. The case study found that an annual traffic data analysis of six sites in Seoul exceeds the national environmental noise criteria of 65 dB (A). In addition, the supplemental questionnaire survey targeting 92 building occupants in the sites showed that

89% utilized mechanical ventilation air conditioning systems and 51% experienced Sick Building Syndrome (SBS), which is composed of related symptoms such as skin irritation, eye irritation, respiratory illness, and headache. Survey participants responded that 35% were deterred from opening windows due to outdoor traffic noise; 44% regarded outdoor traffic noise as a main obstacle to opening windows; and 64% agreed that urban traffic noise had a negative impact on indoor acoustic quality. These outcomes imply that there are adverse health effects by noise transmission via ventilation openings in high noise areas. This study requires an exploration of building façade design to meet a balance between the two environmental requirements of ventilation and noise.

The initial findings from literature review states that DSFs take advantage of their properties of air cavity and two layers of glass for the purpose of thermal insulation, visual connectivity to the outdoors, acoustical barrier, and building energy performance (Oesterle et al., 2001; Lee et al., 2002; Safer et al., 2004; Harris, 2005; Harris, 2006; Gratia & Herde, 2004; Gratia & Herde, 2007; Hasse et al., 2007; Chan et al., 2009; Baldinelli, 2009). Among the several environmental benefits of DSFs, this research aims to investigate ventilation performance and acoustical performance of air cavity, shading louvers, and air vents of DSFs.

A hypothetical scenario is assumed where traffic noise transmitted via vent openings of a DSF travels to each room horizontally and vertically when air vents open to bring in fresh outdoor air during mild seasons and/or to dissipate heat during hot seasons. Based on these problematic situations, this study is designed to address several key questions as follows:

- How do DSFs work to meet both ventilation and acoustical performance?
- How does orientation (e.g., tilted degree angle), type (e.g., vertical and horizontal), and surface material of shading louvers work to achieve ventilation and acoustical performance in DSFs?

- How do the percentage of vent open surface area and absorbing materials in air vents work to achieve both ventilation and acoustical performance in DSFs?

1.3 Research Objective

The main objective of this study is to investigate the acoustical performance of shading louvers and air vents of a DSF under the hypothesis that noise transmission via ventilation openings can cause acoustical discomfort and/or adverse health effects. As described in Figure 1.1, IEQ is the ultimate target as a long term strategy, and indoor air quality and acoustic quality are the sub-targets in relation to building occupants health and comfort. Even though there exists a number of techniques to increase ventilation performance, as well as to decrease noise transmission, individual techniques do not simultaneously meet the two environmental requirements of ventilation and noise. Even if an operable window is one cost-effective way to provide ventilation for good IAQ, the unpredictable wind patterns and transportation noise in urban areas provides considerable reasons that diminish the use of wind-driven ventilation strategy.

Instead, DSFs are considered multifunctional aspects of ventilation and acoustical performance using air cavities, shading louvers, and air vents. Generally speaking, they are composed of shading louvers to control direct solar radiation and daylight, and air vents to control micro-climate conditions inside DSF air cavities. In particular, an air cavity is utilized for ventilation purposes with shading louvers and air vents. Orientation and type of shading louvers, and percentage of air vent open surface area are associated with air temperature and air speed for ventilation performance. However, it has not been sufficiently determined that shading louvers and air vents in DSFs would be effective in reducing noise transmission via ventilation openings. Therefore, this study is designed to explore the acoustical performance of shading louvers and air vents of DSFs.

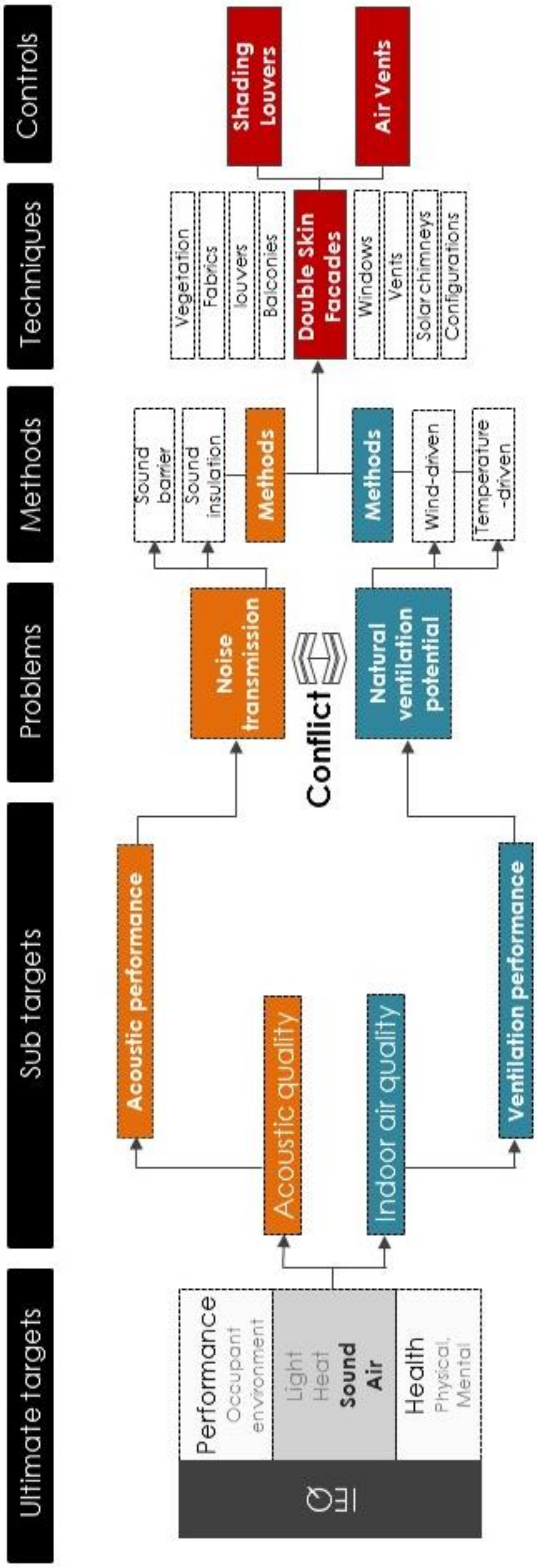


Figure 1.1 Research framework

1.4 Research Methods

Based on literature review, this study employed a mixed-use research method composed of a preliminary simulation study (see Chapter 3) and an experimental study (see Chapter 4). The preliminary simulation study aims to understand the relationship between ventilation potential and noise transmission loss through computational fluid dynamics (CFD) analysis. This simulation study was designed to predict ventilation performance in relation to air temperature, air velocity, and air patterns inside the air cavity. A hypothetically-designed DSF was modelled using the CFD software FloVENT, which generated air temperature and air velocity data based on shading louver orientation and type, and percentage of air vent open surface area. Initial findings from the simulation study were used in designing DSF mock-up tests on noise reduction based on several scenarios such as orientation, type, a surface material of shading louvers, and percentage of air vent open surface area.

However, existing acoustical software was limited in their ability to model and predict noise transmission loss of a DSF. The currently available acoustic software such as EASE, Insul, and SoundFLOW are not able to model the same scenarios that were possible with CFD simulation studies. In particular, the available acoustic software programs were limited in modelling and analyzing noise transmission loss by orientation, type, surface material of shading louvers, and the percentage of air vent open surface area of the DSF modelling. Other commercial simulation software such as Odeon, SoundPLAN, and CADNA were not financially feasible for the research.

Therefore, supplemental DSF mock-up tests were carried out in the reverberation chamber of the University Of Kansas School Of Engineering's Building Materials & Sustainable Environment Center (M2SEC).

1.5 Hypothesis

Preliminary simulation study of a DSF addressed the issue that ventilation performance is highly associated with orientation, type of shading louvers, and the percentage of air vent open surface area. Depending on orientation and type of shading louvers, air temperature and airflow inside a DSF air cavity showed noteworthy outcomes. It was found that a percentage of air vent open surface area contributes to air temperature inside DSF as one descriptor of ventilation performance. These preliminary findings are described in Chapter 3: Preliminary Study.

Based on a preliminary simulation study on ventilation performance and noise reduction via air vents in a DSF modelling, it was hypothesized that orientation, type, surface material of shading louvers, the percentage of air vent open surface area, and absorbing material of air vents are effective in noise reduction.

- It is conjectured that cases with shading louvers tilted at a 90 degree angle, which parallels to two layers of glass wall, are effective in significant noise reduction.
- It is conjectured that cases with horizontal shading louvers are effective in reducing transmitted noise via air vents than are cases with vertical shading louvers.
- It is conjectured that higher percentage of air vent open surface area can reduce noise transmission significantly.

1.6 Research Scope

The scope of this study is limited to the acoustical performance of shading louvers and air vents in naturally-ventilated buildings which are vulnerable to traffic noise transmission. DSF mock-up tests were designed under controlled conditions to understand the mechanism of sound propagation and/or sound transmission through a DSF. Even though there are a number of studies on DSF performance regarding ventilation and energy, an experimental study in Chapter 5 was aimed at noise reduction using orientation, type, and surface material of shading louvers, and the percentage of air vent open surface area, according to the American Society for Testing Materials (ASTM).

1.7 Research Significance

First, the major significance of this study is to investigate the mechanism between ventilation potentials and acoustical performance of the DSF, while achieving two environmental requirements including indoor air quality and acoustic quality.

Second, sustainable strategies of building façade design in naturally-ventilated buildings provide solutions designed to cope with a diversity of environmental requirements thermally, visually, and acoustically. Even if there are a number of studies on the impact of shading louvers on visual and thermal comfort and building energy performance, additional experimental investigations of acoustical performance for shading louvers are necessary in the field for the integrated design of building façades.

Third, experimental tests for sound-absorbing air vents are noteworthy contributions to improving the weakness of window ventilation in naturally-ventilated buildings in high noise areas. Development of sound-absorbing air vents can lead to the integrated applications of natural ventilation strategies for various building purposes.

CHAPTER 2: Literature Review

2.1 Urbanization

2.1.1 Urban Population in Asian Regions

The United Nations (UN) reports that world urban population growth is expected to increase from about 3.8 to 6.3 billion people between 2014 and 2050. Figure 2.1 shows that urbanization has been taking place in Europe, Northern America, and Asia (U.N., 2014). The 2016 annual report by Demographia, as shown in Table 2.1, which contains population, land area, and population density, states that 55% of the world has been urbanized and 70% of the world's population lives in the urban area. To be specific, a total number of urban populations in Asian regions as of 2014 accounts for approximately 53.1% of the total world urban population. This data indicates that Asian regions have been experiencing the greatest accelerated urbanization process.

Table 2.1 Largest urban areas in the world (Source: Demographia)

Rank	Continent	Geography	Urban Area	Population Estimate (A)	Land Area: Km^2 (B)	Population Density (C=A/B)
1	Asia	Japan	Tokyo-Yokohama	37,750,000	8,547	4,400
2	Asia	Indonesia	Jakarta	31,320,000	3.225	9,700
3	Asia	India	Delhi	25,735,000	2,163	11,900
4	Asia	South Korea	Seoul-Incheon	23,575,000	2,590	9,100
5	Asia	Philippines	Manila	22,930,000	1,632	14,100
6	Asia	India	Mumbai	22,885,000	881	26,000
7	Asia	Pakistan	Karachi	22,825,000	945	24,100
8	Asia	China	Shanghai	22,685,000	3,885	5,800
9	North America	United States	New York,	20,685,000	11,642	1,800
10	South America	Brazil	Sao Paulo	20,605,000	2,707	7,600
11	Asia	China	Beijing	20,390,000	3,937	5,200
12	South America	Mexico	Mexico City	20,230,000	2,072	9,800

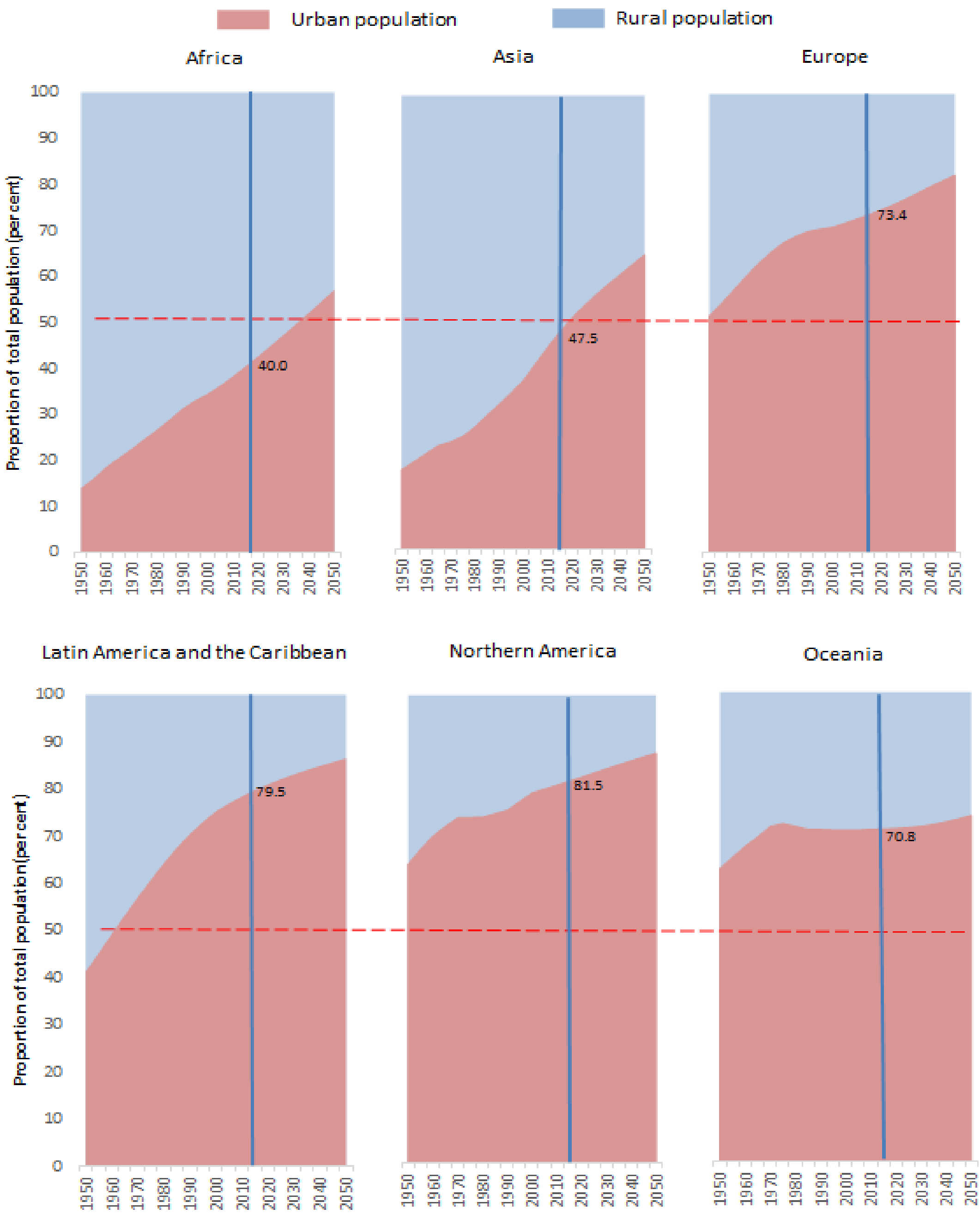


Figure 2.1 Urban and rural population as proportion of total population, by major areas (Source: 2014 UN report)

Figure 2.1 illustrates the percentage of population growth between urban areas and rural areas. As a result of rapid urban population growth, several environmental issues have been raised related to (i) the spread of vertical building structures with light-weight glass envelopes,

(ii) lack of natural ventilation potentials and increased energy consumption of HVAC systems, and (iii) the adverse health effects of noise due to urban transportation noise.

2.1.2 Vertical Buildings

High-rise buildings are a result of rapid urban population growth and industrialization. The development of construction and structure technologies for efficient land use also made possible the growth of vertical buildings. As one of the key elements of building facades, curtain wall systems make them possible not only to address the heavy load-bearing of modern building facades, but also to minimize air and water infiltration by equalizing the substantial wind pressures on high-rise buildings (Sanders, 2006). These tendencies in building facades, however, have driven a number of buildings over the past three decades to be equipped with mechanical ventilation systems for year-round climate control. The availability of outdoor air ventilation was driven toward the operation of HVAC systems (Godish, 2001).

2.1.3 Airtight Glass-sealed Building Enclosure

Curtain wall systems, of which large glass and aluminum structures act as exterior wall systems, offer multiple benefits apart from non-load-bearing. To enhance natural lighting, high window-to-wall ratio (WWR) buildings are designed and constructed as building façade elements. However, Joseph and Francis (2009) point out that highly glazed curtain wall systems are subject to not only thermal discomfort but also visual discomfort. Solar heat gain in high WWR buildings provides a major cause for the use of dominant air-conditioning loads. Even though natural ventilation strategies produce a physical cooling effect, the glass-sealed building envelopes cause building occupants to the mechanically-driven environmental systems, such as HVAC systems, that can cause sick building syndrome (SBS) and a major portion of buildings' energy consumption.

2.1.4 HVAC Systems and Energy Consumption

Urban buildings with high WWR and the indiscreet energy consumption of HVAC systems bring about greater building energy consumption. HVAC systems are an energy intensive assembly comprised of large fans, ductwork systems, and air-conditioning and heating units. Along with the rapid economic growth of China, its building energy consumption in 2011 was approximately 28% of the total national end use and will increase to about 35% in 2020. This figure means that HVAC systems energy use will account for about 65% of the energy use in the building sector. In the U.S.A., its energy use accounts for about 50% of building energy consumption and 20% of total energy consumption (Pe´rez-Lombard et al., 2008).

In contrast to active mechanical systems such as HAVC systems, passive design strategies are carefully designed to integrate with the local climate conditions for building occupant comfort. Although the feasibility of natural ventilation strategies is highly associated with outdoor air quality, local climate conditions, building layouts, and numerous factors, natural ventilation strategies may be one of the cost-effective methods for building energy savings and human comfort (Khan et al., 2008). Where natural ventilation is feasible, operable ventilation windows can offer fresh air flow without the need for energy input.

However, urban traffic noise transmitted via ventilation windows deters building occupants from opening windows and justifies the use of mechanical ventilation systems (Nicol & Wilson, 2004; Ghiaus & Allard, 2005).

2.1.5 Urban Transportation Noise

As the first consequence of urbanization, the number of motor vehicles such as cars, buses, and trucks has gradually increased in the cities. Transportation noise is the main source of environmental noise pollution including road, rail, and air traffic (WHO, 1999). The WHO reports that traffic-related noise has become the most health-threatening environmental stressor in Europe. According to the 2011 WHO report, 33% of individuals had been annoyed during the daytime, and 20% of respondents experienced sleep disturbance during the night because of traffic noise (WHO, 2011). The Environmental Protection Agency (EPA) in 1981 estimated that 19.3 million people in the United States are exposed to a day-night average sound level (Ldn) greater than 65 dB from highway traffic. In Japan, road traffic noise was the most annoying source among other urban noise sources (Yano et al., 1996). In China, survey data (China EPA, 1995) shows that 71.4% of residents in cities with more than one-million in population are exposed to noise levels above 70 dB(A) due to the accelerated growth of the number of motor vehicles. In Egypt, 73.8% of respondents in a survey complain of noise annoyance by road traffic noise (Ali & Tamura, 2002).

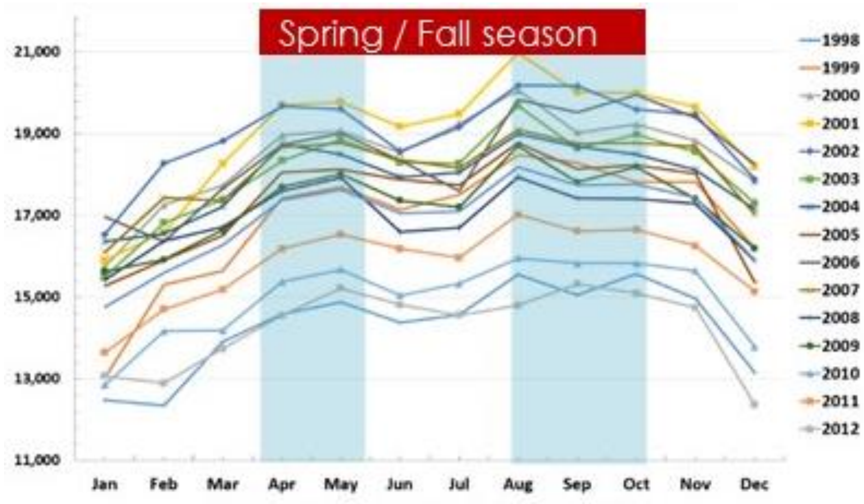
2.2 A Case Study on Urban Noise in South Korea

2.2.1 Urbanization and Urban Transportation Noise

The UN reported that South Korea has been experiencing higher urban population growth compared to other Asian countries. The proportion of the urban population as of 2014 accounted for roughly 82% which is higher by about 37.5% than that of other Asian countries and of other countries world-wide. The estimated urban population growth rate of South Korea might gradually reach about 88% in 2050 (U.N., 2014). This accelerated urban population growth is concurrent with the growth of traffic density in cities.

The Traffic Monitoring System of Korea (TMSK) provides the Average Daily Traffic (ADT) which represents the average number of vehicles passing a specific point in a 24-hour period. According to the ADT data in South Korea between 1998 and 2012, the ADT during warm and hot periods is higher than that of the cold periods, as shown in Figure 2.2a. Also the ADT during the daytime (07:00~18:00) is greater than the night time (19:00~06:00), as shown in Figure 2.2b. When it comes to seasonal and daily traffic volume, a study stated that noise annoyance is greater in summer than in winter (Recuero et al., 1996), and that the effects of noise are greater in the evening and at the beginning of the night period (Vallet et al., 1996). For these reasons, TMSK's ADT data suggests that road traffic volume highly affects natural ventilation availability and ventilation behavior to improve IAQ and thermal comfort mostly during the spring and fall periods. In addition, building occupants in workplaces are exposed to urban traffic noise transmission during working hours when the value of ADT becomes high.

Another study on noise annoyance in Seoul demonstrated that the daytime and night-time equivalent sound levels (L_{eq}) are higher during the spring season than in winter. It was found that the value of Traffic Noise Index (TNI) is also higher during the fall than the winter (Ryu et al., 2012). These outcomes imply that there is a conflict between natural ventilation availability and noise transmission via ventilation openings in naturally-ventilated buildings.



Average Daily Traffic by month (1998~2012) (a)

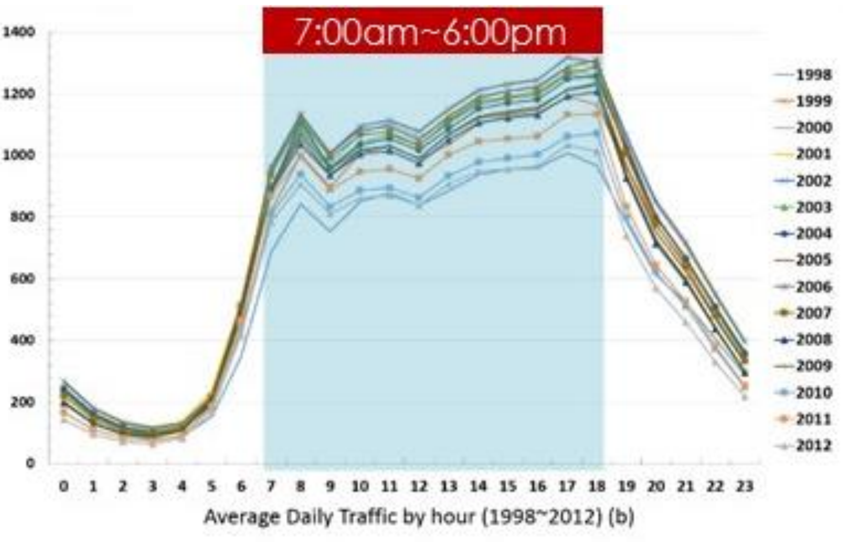


Figure 2.2 Average Daily Traffic by month (a) and hour (b)
(Source: The World Bank Data)

2.3 Natural Ventilation

2.3.1 Significance of Natural Ventilation

The IAQ of urban buildings is highly related to the concentration of harmful contaminants from human activities and building materials, which emit a variety of compounds. The WHO reported that indoor air pollution to overall human exposure is often higher than outdoor concentrations, and the main reason for the concentration of indoor air pollutants in developed European countries is a result of low ventilation rates (Air Quality Guidelines, 2000). The U.S. Environmental Protection Agency reported that most Americans spend up to 87% of their time indoors as working hours in an office environment (U.S. EPA, 1997). Smith stated that human exposure to indoor particulate pollutants in urban environments is seven times higher than in rural environments (1994). Thus, natural ventilation is one of the noteworthy techniques for improving building occupants' health and comfort because a lack of ventilation rate can cause excessive humidity, overheating, and concentration of indoor pollutants (Khan et al., 2008).

Considering the relationship between natural ventilation and the building occupants' health, it is postulated that natural ventilation highly affects human health and comfort including respiratory allergies and task performance. A number of studies demonstrate that naturally-ventilated buildings have more advantages to reduce the prevalence of SBS symptoms than do mechanically ventilated buildings. Fisk et al. stated that 16~37 million cases of colds and flu, which are equivalent to $6–$14 billion annual savings in the United States, could be avoided by improving indoor environmental quality. They assumed that SBS symptoms might be reduced approximately 20% to 50% through natural ventilation strategies (Fisk et al., 2002).

When it comes to the relationship between IAQ and productivity, Seppänen and Fisk (2002) indicated that HVAC systems should be properly designed, installed, and maintained to avoid poor IAQ. They studied the relationship between natural ventilation and task performance in office workplaces, and found that the increased outdoor air ventilation rate of 10 l/s per person is effective in improving about 1% to 3% of work performance. Wargocki et al. (2000) found a significant improvement in typical office tasks of typing as well as in creative thinking at a ventilation rate of 10 liters per second per person compared to a ventilation rate of 3 liters per second per person. Other similar experimental studies performed at schools, call centers, and hospitals showed that ventilation rate leads to a positive effect on a significant improvement in work performance.

2.3.2. Natural Ventilation Techniques

Natural ventilation strategies utilize natural forces such as wind and thermal buoyancy force to bring outdoor air into the indoor space through building envelope openings. Many studies introduced common devices for natural ventilation such as operable windows, louvers, vents, stack ducts, wind catchers, and double skin facades.

Windows

Santamouris and Georgakis (2006) described that occupants use windows not only for IAQ control through ventilation rate but also for thermal comfort. However, window ventilation is very dependent on weather conditions such as outside temperature, wind, and rain infiltration.

Cho et al. (2008) categorized the number of window types based on a survey of 114 high-rise buildings in South Korea. Based on this simulation study on the opening ways of windows, they found that pull-down and casement-in windows are better than project-out windows for the ventilation effect. They concluded that the opening direction of windows is a more important factor than the opening size of them for wind-induced natural ventilation. However, they mainly stated the opening direction of windows for natural ventilation in high-rise buildings without taking into consideration noise transmission in urban environments.

Allard and Ghiaus (2005) stated that side-hung casement windows allow a full opening. Hinge windows are good at driving rain protection and bottom-hung windows offer good ventilation potential by removing the heated air because the largest openings are high to the ceiling. Horizontal pivot-hung-windows offer good ventilation by the stack effect. Double sliding windows are effective in controlling the airflow rate of air velocity by adjusting the positions of the two opposite window panes.

Vents

The appropriate air inlets provide a controlled airflow rate and refrain from the infiltration of rain, dust, insects and urban noise. To be specific, external noise transmission into the indoor space in high noise areas is one of the reasons for the preference of mechanical ventilation use instead of natural ventilation use. Santamouris and Georgakis (2006) tested that vent light positioned at 1.8-meter above the floor level is most effective because airflow works well at the height by the stack effect over a wide range of temperature.

Inlet grilles

Santamouris and Georgakis (2006) showed that IAQ control can be achieved by manually controlled inlets. Typical sizes of the trickle vent's ventilation opening are in the range of 15~40 cm^2 and that of grilles are 15~40 cm^2. These devices were developed for reducing noise transmission and air pollution infiltration, and sound attenuated inlets feature a sound reduction up to 25 dB(A). There are different types of inlets such as active air, humidity-controlled, and pollutant-controlled inlets.

Atrium

An atrium is a space with glazed roofs; typically, in the middle of a deep plan building, offering daylight and natural ventilation through the stack effect. Operable windows of atriums are designed for an air supply path to get rid of the heated air.

These devices are used to induce outdoor air into buildings or to extract contaminated air from rooms, which is enhanced by the use of wind catchers or fans. Usually, individual ducts are preferred against noise, pollution and fire. Prajongsan and Sharples (2012) studied a ventilation shaft located at the rear of a room, increasing the average air velocity across the room. The use of this technique achieved thermal comfort hours during the summer by up to 56% in the test room compared to 38% in the reference room. They also concluded that the ventilation shaft using cross-ventilation technique is an effective wind-induced ventilation system allowing enhancement of thermal comfort.

Wind scoops and catchers

Kleiven (2003) stated that wind scoops catch omni-directional wind and direct fresh air into the buildings. But, the drawback of this technique is that the airflow rate is dependent on wind speed. Wind catchers on top of buildings take advantage of higher wind velocity in windy areas. This system can be supplied with co-axial fans to assist mechanically during extreme weather conditions.

Double Skin Facade

Shading louvers are used to avoid overheating inside air cavity. Kleiven stated that DSF takes advantage of protecting against wind and outdoor noise as well as air supply path (2003). Details on elements, functions, and advantages of DSFs are described in Sub-Chapter 2.5 Building Façade. Among the several techniques from literature review, noteworthy findings are that vents, inlet grilles, and double skin façades work concurrently for natural ventilation performance and noise transmission loss.

2.4 Outdoor Noise

2.4.1 Outdoor Noise and Adverse Health Effects

Noise is generally defined as an unwanted sound whose effect can register physiologically and psychologically, such as noise annoyance (Kang, 2007; Muzet, 2007). Several studies on acoustical quality in urban environments mentioned the adverse health effects of noise, which can be characterized as any temporary or long-term deterioration in physical, psychological, or social functions associated with noise exposure (Kang, 2007).

Table 2.2 Adverse health effects of noise

Kinds of effect	Symptoms
Physical effects	Noise-induced hearing loss, hearing impairment, threshold shift
Physiological effects	Startle and defense reaction leading to potential increase of blood pressure
Sensory effects	Aural pain, ear discomfort, tinnitus
Interference with speech communications	Reduction in intelligibility of conversation, radio, music, television and others
Sleep disturbance	Difficulty in falling asleep, alterations in sleep rhythm, awakening
Psychological effects	Headaches, fatigue, irritability
Performance effects	Task performance, distraction, productivity
Annoyance	Feeling of displeasure; tolerances vary enormously; noise impulses more annoying than a steady noise

Among the adverse health effects of noise, several symptoms are described as shown in Table 2.2 (WHO, 1999). These health effects, in turn, can lead to social handicaps, reduced productivity, decreased performance in learning, absenteeism in the workplace and school, increased drug use, and accidents (Berglund et al., 1999). Transportation noise causes specific non-auditory stress effects such as changes in physiological systems (e.g., high blood pressure), cognitive degradation in memory, sleep disturbances, modifications of social behavior, psychosocial stress-related symptoms, and emotional effects, such as annoyance (Stansfeld et al., 2005). Table 2.3 describes several consequences of sleep disturbance.

Table 2.3 Consequences of sleep disturbances

Type	Short-term	Long-term
Behavioural	Sleepiness, Mood changes, Nervousness	Depression, Mania violence
Cognitive	Impairment of function	Difficulty in leering new skills, Short-term memory problems, Difficulty with complex tasks
Neurological	Mild and quickly reversible effects	Cerebellar ataxia, Slurred speech, Increased sensitivity to pain
Biochemical	Increased metabolic rate, Insulin resistance	Diabetes, Obesity
Others	Hypothermia, Immune function impairment	Susceptibility to viral illness

Regarding sleep disturbance, epidemiological data suggests that habitually short sleep (defined as less than 6 hours sleep per night) or too much sleep is associated with mortality. Kripke et al. (2002) found the lowest mortality risk between respondents sleeping 7 hours per night according to a questionnaire analysis targeting 1.1 million men and women ranging from 30 to 102 years of age.

Sleep disturbance may also contribute to the impairment of cognitive tasks and overall task productivity during the day following the disturbance with tiredness, lack of energy, and difficulty concentrating (Stansfeld & Matheson, 2003). A study targeting about 100 Belgian school children ages 9 to 12 years old showed that those with poor sleep (insomnia) achieved poorer school performances than good sleepers. It was found that children subjected to noisy environments not only showed decreased attention spans but also lowered task performance on cognitive assignments compared to children in quiet environments (Hygge et al., 2003; Shield and Dockrell, 2003). Ljung et al. (2009) also discovered that traffic noise significantly diminishes reading and comprehension ability as well as basic mathematical performance in children. These psychological and physiological effects due to noise could lead to decreased task productivity.

Chronic noise exposure can also cause permanent loss of hearing at specific frequency ranges. The number of people experiencing Noise Induced Hearing Loss (NIHL) as a result of exposure to continuous or intermittent loud noise was estimated at 10 million adults and 5.2 million children in the United States and 250 million people worldwide. It was stated that continuous exposure to sounds greater than 85 dB for 8 hours can lead to NIHL (Seidman & Standring, 2010).

A cohort study on the relationship between long-term exposure to road traffic noise and incident diabetes discovered that the 50,000 people exposed to residential road traffic noise had a higher risk of diabetes. Exposure to a 10 dB higher level of average road traffic noise during the five years was associated with an increased rise of incident diabetes (Sørensen et al., 2013).

In looking at the relationship between transportation noise and cardiovascular risk, epidemiological studies suggested a higher risk of cardiovascular diseases including high blood pressure is related to high levels of transportation noise. For noise levels greater than 60 dB (A), myocardial infarction (MI) risks increased continuously. It is stated that approximately 6,000 MI cases per year were attributed to road traffic noise (Babisch, 2006). Figure 2.3 shows a noise effects reaction scheme that simplifies the cause-effect chain. The mechanisms of 'direct' and 'indirect' indicates the nervous interactions and cognitive perception of sound, respectively. The objective noise exposure (sound pressure level) and the subjective noise exposure (annoyance) serve independently with the relationship between noise and health.

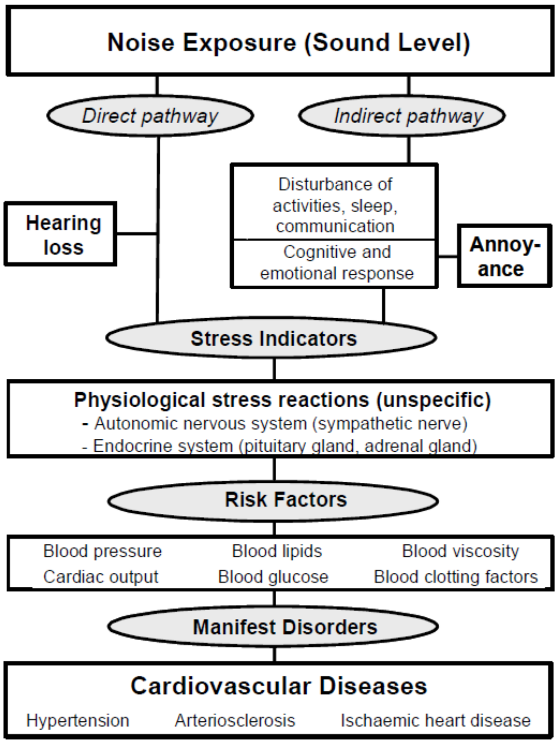


Figure 2.3 Noise effects reaction scheme (Source: Babisch, 2002)

2.4.2 Environmental Noise Regulations

In 1999, the WHO Regional Office for Europe established noise guidelines to protect the majority of people from being seriously annoyed as the adverse health effects of noise is dependent on its physical characteristics, including the Sound Pressure Level (SPL), spectral characteristics, and variations of properties with time (WHO, 1999). Table 2.4 shows the critical health effects based on the A-weighted Equivalent Continuous Sound Level (L_{Aeq}) and noise exposure time at specific environments.

Regulatory standards have been employed at the municipal, regional, national, and international levels because the adverse health effects of noise are critically related to physical, psychological, or social functions. Noise annoyance is highly related to SPL and exposure time (Kang, 2007). Tables 2.4 to 2.7 show regulatory standards of noise by country. South Korea established noise level standards on the Basic Act for Environmental Policy based on district and time periods as shown in Table 2.5. The recommended SPL of a roadside district is 65 dB (A) during daytime (06:00-22:00) and 55 dB (A) during night time (022:00-06:00) respectively.

Table 2.4 WHO noise guideline for community noise

Specific environment	Critical health effect	L_{Aeq} (dB(A))	Time-base(h)	L_{Amax} (dB(A))
Outdoor living area	Serous annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors	Speech intelligibility and moderate annoyance, daytime and evening	35	16	-
Inside bedrooms	Sleep disturbance, night-time	30	8	45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
Hospitals, wardrooms, Indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evening	30 30	8 16	40 -
Industrial, commercial, shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment	100	4	110

Table 2.5 Regulatory standards of noise in United Kingdom

Planning Policy Guidance Note 24 for noise exposure categories for new dwellings					unit: dB(A)
Noise source	Time periods	Category A	Category B	Category C	Category D
Road traffic	07:00 – 23:00	<55	55-63	63-72	>72
	23:00 – 07:00	<45	45-57	57-66	>66

Table 2.6 Regulatory standards of noise in Italy

Emission limits, Immission limits and Quality target						unit: dB(A)
Category of land use	Daytime (06:00-22:00)			Night time (22:00-06:00)		
	Emi-ssion	Immi-ssion	Quality target	Emi-ssion	Immi-ssion	Quality target
I: Noise sensitive premises	45	50	47	35	40	37
II: Residential areas	50	55	52	40	45	42
III: Mixed areas	55	62	57	45	50	47
IV: Intense activity areas	60	65	62	50	55	52
V: Industrial areas and low density of residential buildings	65	70	67	55	60	57
VI: Industrial areas only	65	70	70	65	70	70

Table 2.7 Regulatory standards of noise in South Korea

Noise level standards on the Basic Act for Environmental Policy					unit: dB(A)
Category of land use		Ga[1]	Na[2]	Da[3]	Ra[4]
General district	Daytime (06:00-22:00)	50	55	65	70
	Night time (22:00-06:00)	40	45	55	65
Roadside district	Daytime (06:00-22:00)	65		70	75
	Night time (22:00-06:00)	55		60	70

1. Residential area, area within 50-meters from hospitals and schools
2. Semi-residential areas
3. Commercial areas
4. Industrial areas

2.4.3 Noise Annoyance Descriptors

Noise annoyance, among the adverse health effect of noise, sound pressure level (SPL) in decibel (dB), is a significant descriptor even though sound type (e.g., continuous, intermittent, impulsive), sound intensity, sound frequency, sound spectrum and sound internal (e.g., duration, regularity, or expected) can affect noise annoyance and sleep disturbances in different ways (Kang, 2007). The U.S. EPA studied the relationship between sleep disturbance and noise exposure level, and a significant correlation was discovered, as shown in Figure 2.4 (1981). Another study discovered that nocturnal awakenings usually occur with noise levels greater than 55 dB (A) (Muzet, 2007).

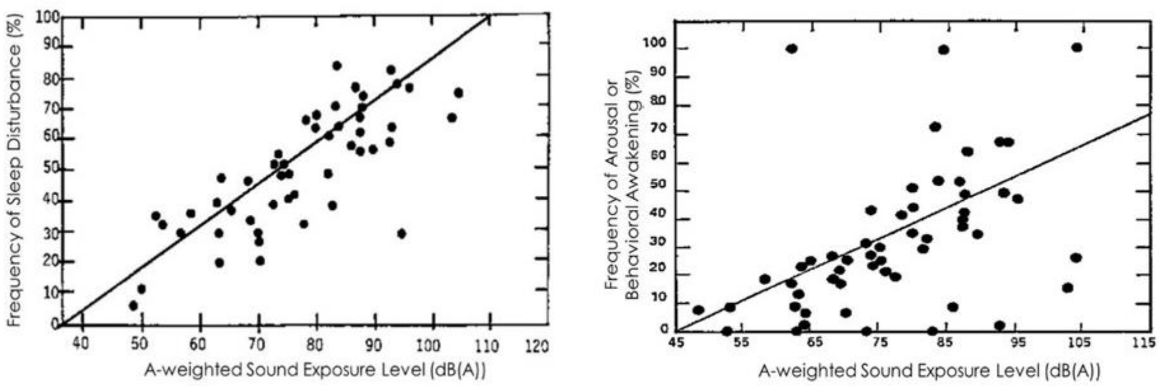


Figure 2.4 Probability of noise induced awakening
(Source: U.S Environmental Protection Agency)

The evaluation of acoustical discomfort is a highly complicated matter, pertaining to acoustics, physiology, and psychology. For the numerical evaluations of road traffic noise, Equivalent Continuous Sound Level (L_{eq}), Noise Pollution Level (LNP), and Traffic Noise Index (TNI) have been widely used. The L_{eq} is used to describe sound level (dB) and to measure continuing sounds such as road traffic noise that varies considerably over the period of time resulting in a single decibel. (Kang, 2007; Ryu et al., 2012). A-weighted Equivalent Continuous Sound Level L_{Aeq} used as dB (A) is a measurement parameter similar to the response of the human ear at the lower levels of noise annoyance.

$$L_{eq} = L_{50} + (L_{10} - L_{90})/56 \qquad (2.1)$$

The TNI is an index that takes noise variability with respect to L_{10} into consideration. The L_{10} is a useful descriptor of road traffic noise because it correlates with noise annoyance because the A-weighted level (exceeded for 10% of the time of the measurement duration) takes into account any annoying peaks of noise. The L_{90} or the L_{95} is taken to be the ambient or background noise level (Kang, 2007; Marathe, 2012). For instance, if the value of TNI is over 74, it indicates that more than 50% of residents are annoyed acoustically (Kang, 2007; Ryu et al., 2012).

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \text{ dB (A)} \qquad (2.2)$$

The LNP is a new parameter to measure noise annoyance because Equivalent Continuous Sound Level (L_{eq}) based on an energy basis is not a sufficient measurement indicator to explain the degree of annoyance caused by fluctuating noise (Ryu et al., 2012; Marathe, 2012).

$$LNP = L_{eq} + (L_{10} - L_{90}) \qquad (2.3)$$

2.4.4 Relationship Between Noise Annoyance and Decibel (dB)

Noise annoyance, among the adverse health effects of noise, is dependent on its physical characteristics, including SPL, spectral characteristics, and variations of properties with time (WHO, 1999). Therefore, defining noise annoyance needs a complex mechanism related to a number of disciplines such as acoustics, physiology, sociology, psychology, and statistics. According to a study on factors of noise annoyance, the gender, income, education level, and family size are insignificant factors for noise annoyance. By contrast, cultural heritage, construction methods, lifestyle, weather, behavior, and habits are related to noise annoyance (Kang 2007). In addition, Kang (2007) indicated that noise annoyance is affected by several factors including a multiplication of the acoustic events, regularity of the acoustic events, maximum sound level, periods of occasional events, and spectral distribution of sound energy.

When it comes to the relationship between the adverse health effect of noise and SPL, Lambert et al. (1984) quantified the degree of noise annoyance based on SPL. They tested the noise annoyance of three groups based on SPL exposure. The first group, which was exposed to SPL lower than 55 dB(A) felt less noise annoyance, second group which was exposed to SPL between 55 and 60 dB(A) felt some noise annoyance, and the third group which was exposed to SPL higher than 65 dB(A) felt noise annoyance for sure.

2.4.5 Noise Control Strategies

Building configurations/barriers

According to the noise control manual in Vancouver, building orientation and configuration has effectiveness in noise shielding. Noise barriers take the forms of walls, earth berms, or berm/wall combinations where are created outside of buildings. When the barriers are higher, its effectiveness increases by roughly 1.5 dB per extra meter of height. However, the noise barriers have limitations in that they cannot stand high enough to effectively shield the upper floors of multi-storey buildings.

Building forms

Large and hard building envelops can effectively reflect sound energy, and it is possible to arrange buildings so that reflections can be directed to less sensitive areas. Also, building forms can be designed to be self-protective from external noise. For example, the podium for commercial use functions as a noise barrier for main buildings for residential area. Van Renterghem, et al. (2013) stated that green envelops of roofs and walls benefit noise reduction, and on certain roof shapes, it attenuated noise levels by up to 7.5 dB.

Acoustical use of glass facade

The acoustic benefits particularly conflict with window openings of naturally-ventilated buildings in high noise areas. With a single skin facade, windows can reduce sound insulation performance dramatically from excessive levels of noise intrusion such as road traffic and aircraft. For these reasons, the outer glass of DSFs enhances the sound insulation performance significantly, allowing natural ventilation. The sound insulation performance of DSFs is highly related to glass properties, the size of opening, and the depth of air cavity between two layers of glass.

The sound attenuation of glass relies on its mass and stiffness. With regard to a single glass pane, the only effective way to enhance its acoustical performance is to increase the thickness of the glass. Thicker glass tends to provide greater sound reduction in spite of sound transmission at specific frequencies. And it is proven that a laminated glass can attenuate sound transmission more than a monolithic glass of the same mass. A combination of thickness between two different panes and wide air space distance provides the maximum noise attenuation.

Vegetation

According to a study by Parry et al. (1993), tall vegetation is effective in reducing sound transmission compared to open fields. For instance, Egan (1988) studied matured vegetation wider than 7-meters which provides a modest attenuation of 2 up to 4 dB(A), and dense trees with a depth of 15-meters up to 40-meters show the effectiveness of sound attenuation of 6 to 8 dB(A) (Kang, 2007). Kang and Oldham (2003) stated that vegetation is more effective in urban areas such as in a street canyon or in a square through three mechanisms such as sound absorption, sound diffusion, and sound reduction.

Acoustic enclosures

Kang (2007) stated that porous materials as acoustic enclosures take advantage of sound absorption, but they do not effectively prevent its transmission. Therefore, proper materials of acoustic enclosure should be solid with sufficient mass, and sealed airtight around the edges. Also, a solid enclosure lined with porous absorbers is more effective for SPL reduction rather than without lining because sound a sound absorber reduce the reflected sound energy.

Silencers for ventilation openings

An effective way of reducing noise transmission through ventilation openings is to use silencers which are classified into an absorptive or reactive type. The former type is a porous material for noise reduction in higher frequency, and the latter is a chamber to attenuate the incident of sound energy. For example, Maillard and Guigou-Cater (2000) used a combination of passive and active treatment to reduce noise at mid-high frequency with porous materials and at low frequency with a single-channel active control system (Kang, 2007).

Acoustic windows

Window ventilation in noisy urban environments should be controlled with care to avoid noise transmission loss via ventilation openings. Kang (2007) stated in his book that Mohajeri (1998) proposed the ‘intelligent’ window system which opens and closes depending on the type of sound being monitored. Jones and Evans (1994) investigated the ‘interactive’ window system with a baffle, positioned outside the window opening for noise reduction. In addition, simple methods to reduce noise transmission through operable windows include sealing the windows and using a silencer within the window aperture. Cotana (1999) found out that a window system equipped with porous materials shows the effectiveness of sound reduction. Kang and Li (2007) investigated the effects of window opening size, air gap, and louvers for noise transmission loss, and it was found that the external and internal opening sizes and the air gap width influences the SPL difference by about 2 dB.

Window design

The sound insulation offered by any type of window is limited to STC 10 to 15, reducing outdoor sounds by roughly 10 to 15 dB(A). For instance, in order to meet acceptable indoor noise levels for bedrooms, 35 dB (A), the outdoor noise environment should not exceed 45 to 50 dB (A). To obtain STC values more than about 15, windows must be closed. As additional sound absorbing layers for windows, acoustic baffles can also work as a noise screen as well as an obstacle of sight from ventilation windows to noise sources. There are two possible acoustic baffle designs such as double hung vertically and hinged horizontally around ventilation openings of building facades.

Lintel, canopy, and louver

Lintels and louvers barely achieve acoustical performance, but a significant acoustical improvement can occur with an absorbent surface. Cheng et al. (2000) studied a horizontal canopy over windows as noise barriers, and they found out that noise attenuation by a horizontal canopy is most effective when they are tilted at a 15 to 45 degree angle. Cheng (2000) studied window lintels with reflective surface as noise barriers which can reduce noise by an average of 3 to 5 dB. De Salis et al. (2002) suggested that louvers as noise barriers for ventilation openings are proven to reduce noise by screening the direct sound path using angled blades. Absorptive materials applied to underside of blades attenuated the indirect reflected path. They indicated that the noise reduction of louvers is effective at the higher frequencies rather than at the low frequencies due to sound diffraction.

Balconies

In the case of high-rise buildings with balconies, noise exposure on high-rise balconies and indoor spaces can be reduced by increasing the height of railings, hanging heavy curtains across the glass doors, and applying sound absorption materials to the underside of balconies and inside solid railings. Kim (2007) studied balconies fitted with windows as buffer zones against noise transmission. They indicated that double windows of balconies with a width of 1.0 to 1.5-meters have effectiveness in noise reduction at the 1000 and 2000Hz octave band center frequency. Cheng (2000) investigated the acoustical performance of balconies in residential buildings, and found they achieved noise reduction by 5 dB in canyon streets. Naish et al. (2012) investigated the impact of noise annoyance on the potential fiscal benefits using acoustical treatments on a balcony with the use of parapet and sound absorbing materials. They concluded that acoustical treatments on a balcony allowed significant health-related cost savings by eliminating noise annoyance of building occupants.

2.4.6 Conclusions

Even though naturally-ventilated buildings enable building occupants to lower the concentration of indoor pollutants by the ventilation rate, they are vulnerable to urban traffic noise transmission via ventilation windows (Nicol & Wilson, 2004). A number of natural ventilation techniques are working for ventilation performance in their own methods as mentioned above, however, one of the significant limitations in urban areas is noise transmission via ventilation openings.

Therefore, the building façade of naturally-ventilated buildings needs to be carefully designed to minimize the conflict between natural ventilation potentials and noise transmission loss via ventilation openings. From literature review, the key strategies for natural ventilation and noise transmission control are summarized as follows:

First, window ventilation strategy is one of several cost- effective ways to control the ventilation rate which contributes IAQ. Depending on glass properties, opening ways, and window size, the degree of noise reduction varies. However a single pane window has vulnerability to efficiently meet outdoor climate conditions and noise transmission loss.

Second, air vents and inlet grilles are the suitable ventilation opening design not only to control the airflow rate inside buildings but also to screen unacceptable noise transmission. In particular, air vents and inlet grilles would be appropriate ventilation strategies for air tightened high-rise buildings due to unpredictable wind patterns and noise transmission.

Third, structural elements and shading devices around ventilation windows such as lintels, louvers, and balconies can be used as an effective façade design to absorb and reflect sound paths by their orientations, thickness, and surface materials. The direct sound path can be blocked and/or absorbed to reduce noise transmission by a certain degree angle of louvers.

Fourth, an effective means of reducing noise transmission through ventilation opening is to use sound absorptive materials such as silencers. Sound absorptive materials are effective in reducing SPL at the higher frequencies rather than at the low frequencies due to sound diffraction.

Finally, DSFs have the dual functions of natural ventilation performance and acoustical barrier using a ventilation air cavity and shading louvers. An air cavity is used not only as a ventilation channel by the stack effect but also as an acoustical buffer zone. In addition, shading louvers inside air cavity enable control of airflow rate and sound path, and air vents can make micro-climate conditions inside air cavity depending on outdoor climate conditions.

2.5 Building Facade

2.5.1 Introduction

Among the several environmental requirements of thermal, visual, and acoustical demands, ventilation opening and/or windows as environmentally vulnerable envelopes of buildings should be constructed with proper ventilation strategies and sound insulation. However, urban buildings with a high window-to-wall (ratio) are vulnerable to improper control of indoor environmental quality (IEQ). As shown in Figure 2.5, air temperature, solar radiation, humidity, wind velocity, noise, and any other outdoor obstacles should be controlled properly for thermal, visual, and acoustical comfort (Aksamija, 2013). Among the outdoor obstacles, noise is the major factor limiting natural ventilation applications because building occupants prefer the use of mechanical ventilating and air-conditioning systems to natural ventilation strategies in order to avoid unwanted noise transmission through operable windows.

In this chapter, the concept of DSFs is investigated as a case study to satisfy the conflicting aspects by air cavity, shading louvers, and air vents, which are used for natural ventilation and noise transmission loss.

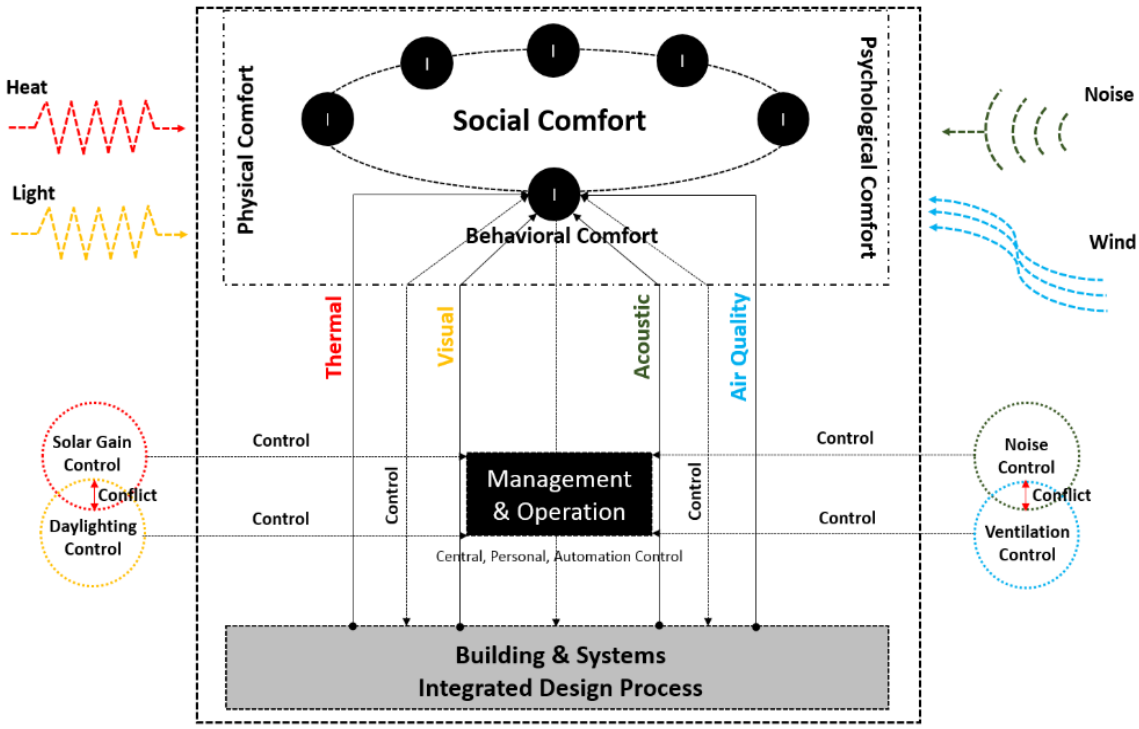


Figure 2.5 Conflicts among thermal, visual, and acoustical comfort
(Source: Aksamija, 2013)

2.5.2 Double Skin Façade

Generally speaking, the building envelopes which divide indoor and outdoor environments of buildings should fundamentally serve to maintain the satisfactory indoor environment against solar radiation, noise transmission, and unpredictable outdoor climate changes. The DFSs, as one of sustainable building facades, are comprised of elements: (i) air cavity and air vents between the two layers of glass to create micro-climate conditions depending on outdoor climate conditions and (ii) adjustable shading louvers to avoid direct solar radiation as thermal barriers. Also, (iii) air cavity volume acts as noise barriers against the outdoor noise transmission and (iv) the curtain wall glazing systems offer wide visual accessibility to the outdoor environments (Oesterle et al., 2001; Lee et al., 2002; Safer et al., 2004; Ghiaus & Allard, 2005; Harris, 2005; Harris, 2006; Gratia & Herde, 2004; Gratia & Herde, 2007; Hasse et al., 2007; Chan et al., 2009; Baldinelli, 2009).

Lee et al. (2002) suggested that a minimum distance of 15-centimeters between the shading louvers and the external glazing should be maintained for proper ventilation efficiency without overheating. Safer et al. (2004) found that horizontal shading louvers should be situated close to the internal glazing to minimize overheating of the external channel through a higher air velocity because the divided space of a DSF cavity by a horizontal blind affects air velocity. Oesterle et al. (2001) stated that adding outer glass alone to a DSF reduces a minimum of 10% of solar radiation while louver blinds inside a DSF air cavity achieve a further reduction of solar radiation by around 50% to 60% compared to a case of indoor blinds. Baldinelli (2009) also developed a new DSF design with the external glazing made of movable integrated glass-shading devices, and it works by decreasing cooling loads during warm periods.

Hasse et al. (2007) introduced the modified application of a DSF to hot and humid weather conditions in European countries, and they concluded the airflow inside a DSF air cavity is a significant factor to reduce energy consumption. Chan et al. (2009) found out that roughly 26% of the annual cooling energy in Hong Kong is saved in a DSF with the internal single clear glazing and external double reflective glazing compared to a conventional single glazed façade. Gratia and Herde (2007) achieved approximately 23% of cooling energy saving during the summer in consideration of blind position, blind size, and ventilation opening of a DSF.

2.5.3 Types of DSF

Box-window ventilated double façade (see Figure 2.6a)

One-story height facade modules, of which the air cavity is divided horizontally and vertically at the level of each facade module, and each box window element require their own air-intake and extracts openings. This type is suitable for lowering sound propagation by vertical fins inside air cavity.

Shaft-box ventilated double façade (see Figure 2.6b)

Vertical ventilation ducts are set up inside air cavity. Each façade module is connected to one of these vertical ducts, which improves the stack effect supplying air naturally drawn into the ventilation duct and then evacuated via the outlets. This type takes advantage of blocking noise propagation transmitted via air vents by vertical fins inside air cavity.

Corridor ventilated double façade (see Figure 2.6c)

The multi-story ventilated DSFs are not partitioned vertically. Metal floor slates are installed at the level of each story in order to access for cleaning and maintenance. Transmitted noise via air vents may travel to indoor areas horizontally and vertically.

Multi-story ventilated double façade (see Figure 2.6d)

The multi-story ventilated DSFs are characterized by an air cavity which is not partitioned either horizontally or vertically and an air cavity between two layers of glass forms one large volume. This air cavity has a wide access for cleaning and can be naturally ventilated. However, transmitted noise via air vents may travel to indoor areas horizontally and vertically.

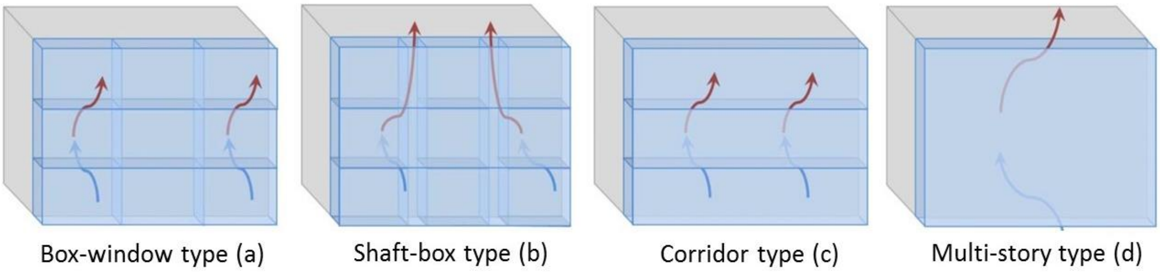


Figure 2.6 Types of DSF (Source: Hong et al., 2013)

The path of air and sound inside a DSF air cavity is highly related to each other as shown in Figure 2.7. Especially during the hot seasons when ventilation grilles open to dissipate the heat inside air cavity, DSFs are weak at the sound insulation of an air cavity because of transmitted noise through ventilation grilles. Therefore, sound absorbing materials in air cavity is recommended.

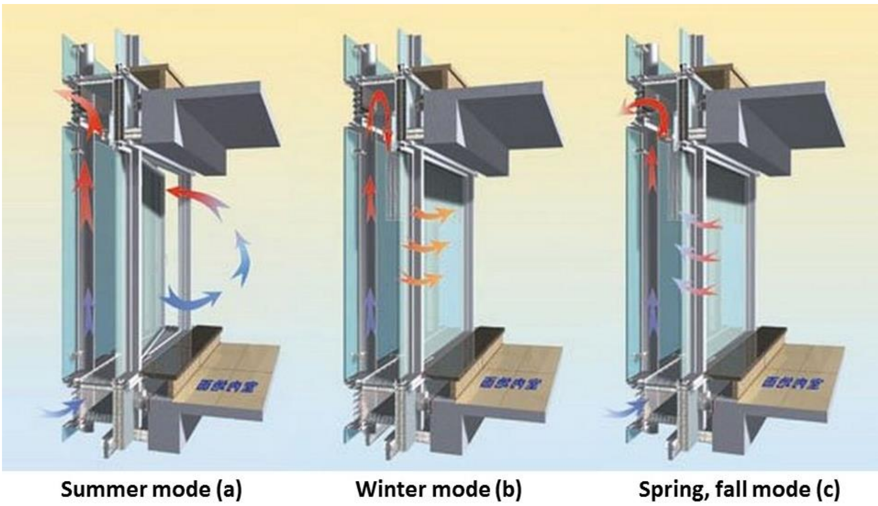


Figure 2.7 Ventilation modes by season (Source: IIT Building Science Blog)

2.5.4 Acoustical Performance of DSF

Another significant benefit associated with DSFs is improved sound insulation performance using air cavities and glass properties in noisy urban locations. Even though traditional single pane windows or operable windows can reduce sound insulation performance, the application of a second external layer of glass enhances sound insulation performance significantly, allowing natural ventilation. In general, better insulation performance of DSFs can be achieved through the use of heavier glass and a deeper air cavity. Figure 2.8 shows noise reduction based on thickness of glass and depth of air cavity at mid- and high-octave band center frequency. Therefore, DSF air cavities for ventilation performance and maintenance access can work as acoustical buffer zones against outdoor urban traffic noise.

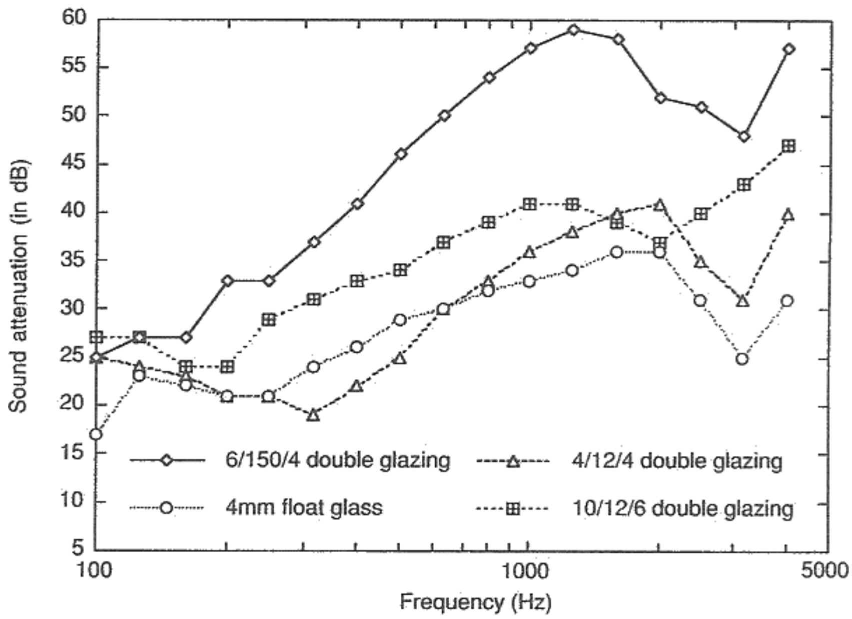


Figure 2.8 Sound attenuation across the frequency range by glazing types
(Source: College of Santa Fe Auditory Theory, http://www.feilding.net/sfuad/musi3012)

Table 2.8 summarizes the major advantages and disadvantages in relation to the ventilation and acoustical performance of DSFs. However, ventilation openings such as air vents may affect noise transmission or noise intrusion depending on ventilation seasons because transmitted noise via air vents travels to each room horizontally and acoustically. That is the reason that DSFs have advantages and disadvantages regarding acoustic insulation.

Table 2.8 A summary of advantages and disadvantages of DSFs

	Double Skin Facade	Arons (2000)	Kragh (2000)	Oesterle et al. (2001)	Compagno (2002)	Lee et al. (2002)	Jager (2003)
Advantage	Acoustic insulation	P	P	P		P	P
	Thermal insulation during the winter		P	P	P	P	
	Thermal insulation during the summer		P	P	P	P	
	Night time ventilation	P		P	P	P	
	Natural ventilation	P		P	P	P	P
	Better protection of the shading devices			P	P	P	P
	Transparency-Architectural design	P	P			P	
	Thermal comfort-temperature of the internal wall	P	P	P	P	P	
	Low U-Value and g-value	P	P		P		
Disadvantage	Overheating problem		N	N	N		N
	Increased airflow speed						
	Daylight		N	N			
	Acoustic insulation		N	N			N
	Higher construction costs	N	N	N			N
	Additional maintenance and operation costs		N	N			N

P: Positive, N: negative

From literature review on ventilation and acoustical performance of DSFs, a preliminary simulation study and an experimental study are designed to find the effect of control variables concerning ventilation and acoustical performance of DSFs as follows:

- What is the relationship between ventilation potential inside the air cavity and noise transmission via air vents based on the percentage of air vent open surface area?
- What is the relationship between ventilation potential inside the air cavity and noise transmission via air vents based on orientation, type, and material of shading louvers?
- What is the relationship between ventilation potential inside the air cavity and noise transmission via air vents based on air cavity volume ratios?

CHAPTER 3: Research Methodology

3.1 Research Framework

First, literature review showed that natural ventilation potential and acoustical performance of DSFs are dependent upon DSF air cavity properties, vent openings, shading louver orientation, and shading louver surface material. To understand the influence of vent openings and shading louver orientation on ventilation performance and noise reduction, a preliminary simulation study was framed to investigate the air temperature, air velocity, airflow patterns, and noise transmission loss of a DSF.

Second, for the preliminary simulation study, CFD was used to study a DSF's air cavity, shading louvers, and air vents based on the DSF of the Forum at Marvin Hall on the campus of the University of Kansas as shown in Figure 3.1.

Finally, a full scale DSF mock-up was used to experimentally study the impact of vent openings, shading louver orientation, louver surface material, and compact silencers on noise reduction. The study was conducted under highly controlled laboratory settings.

Figure 3.1 The Forum at Marvin Hall designed and constructed by Studio 804

The research framework as shown in Figure 3.2 is made up of two major parts: (i) a ventilation performance analysis of a DSF using CFD simulation and (ii) noise reduction analysis of a DSF by a mock-up test at the reverberation chamber. Ventilation performance was aimed to investigate air temperature, air velocity, and airflow patterns based on percentage of air vent open surface area, orientation and type of shading louvers, and air cavity volume ratios. An experimental study was then driven from a preliminary simulation study in order to obtain the empirical data of noise transmission loss based on percentage of air vent open surface area, orientation and type of shading louvers, shading louvers' surface materials and an application of compact silencers. Numerical data on A-weighted equivalent continuous sound levels and NIC were analyzed based on several test cases, and the detailed information on laboratory measurement settings are described in Chapter 5.

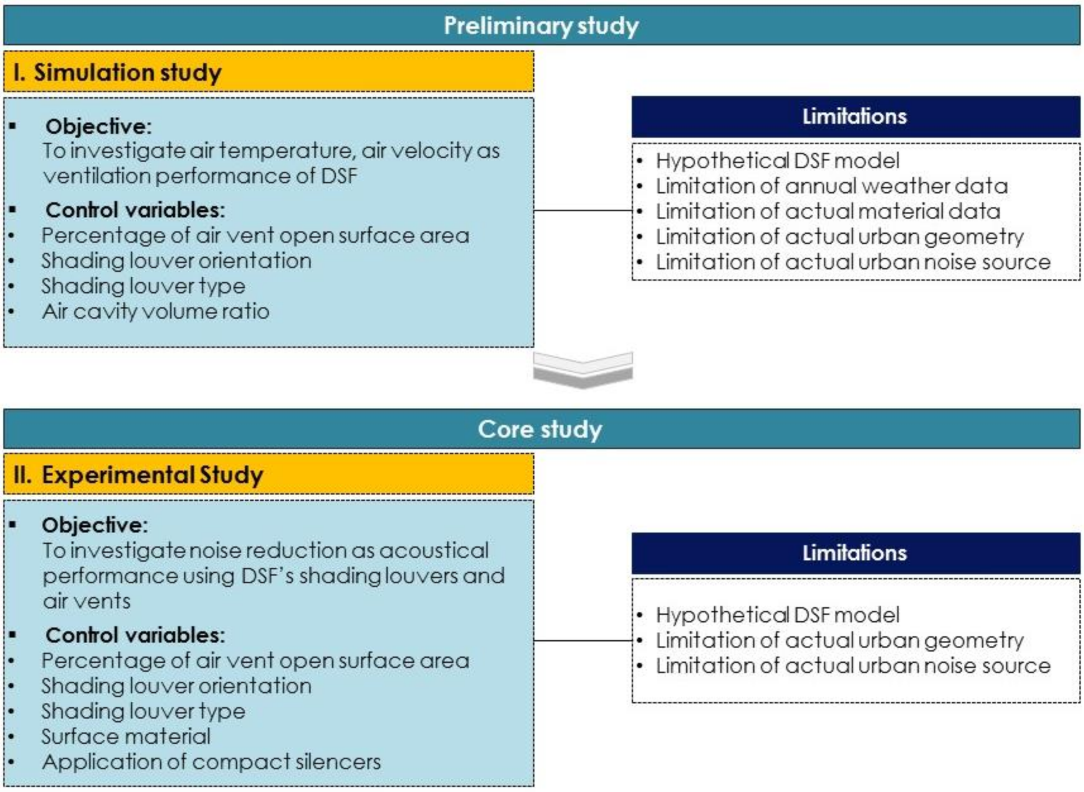


Figure 3.2 Preliminary and core study framework

3.2 Preliminary Study

3.2.1 Simulation Study

The CFD simulations were conducted using the software FloVENT developed by Mentor Graphics. FloVENT is a widely used CFD simulation program used to predict three-dimensional flow of liquids, heat transfer, contamination distribution, and comfort indices in and around buildings.

3.2.2 Limitations of Acoustic Simulation Software

The existing acoustic simulation programs are aimed at stimulating and measuring indoor acoustics. Acoustic simulation software mostly employs ray-based and wave-based modelling. Ray-based techniques approximate sound waves through particles and acoustic energy to determine the virtual sound field, whereas wave-based techniques make a more physically correct wave-based sound propagation model based on time domain finite difference meshes. The ray-based techniques are usually employed for lower frequency, while the wave-oriented techniques are used for the middle and higher frequencies. (Niklas et al., 2007).

During the last decade, ray-based modelling simulation software in three-dimensional space has been approximated to that of light and calculated to diffuse reflection. Image-source and beam tracing methods have been widely used with graphics processing techniques in rendering animation (Niklas et al., 2007). However, in rooms such as open plan offices designed with some surfaces with high absorption coefficients such as the ceiling, acoustic simulation could neglect diffraction phenomena and noticeably change the simulation results (Nicolas, 2010). In general, ray-based modelling simulation is not adequate to model diffraction effects, as they are low-frequency related. The simulations using wave-oriented techniques have some drawbacks which are a direction-dependent dispersion error and a finite mesh resolution to model a more complex boundary behavior. In addition, the preliminary simulation study showed limitations of modelling DSFs, collecting actual urban traffic noise, updating DSF materials, and applying compact silencers in place of DSF air vents

In addition, the existing acoustic simulation software has the limitation of modelling and predicting noise reduction based on shading louver orientation, shading louver surface materials, and the percentage of air vent open surface area as shown in Figure 3.3.

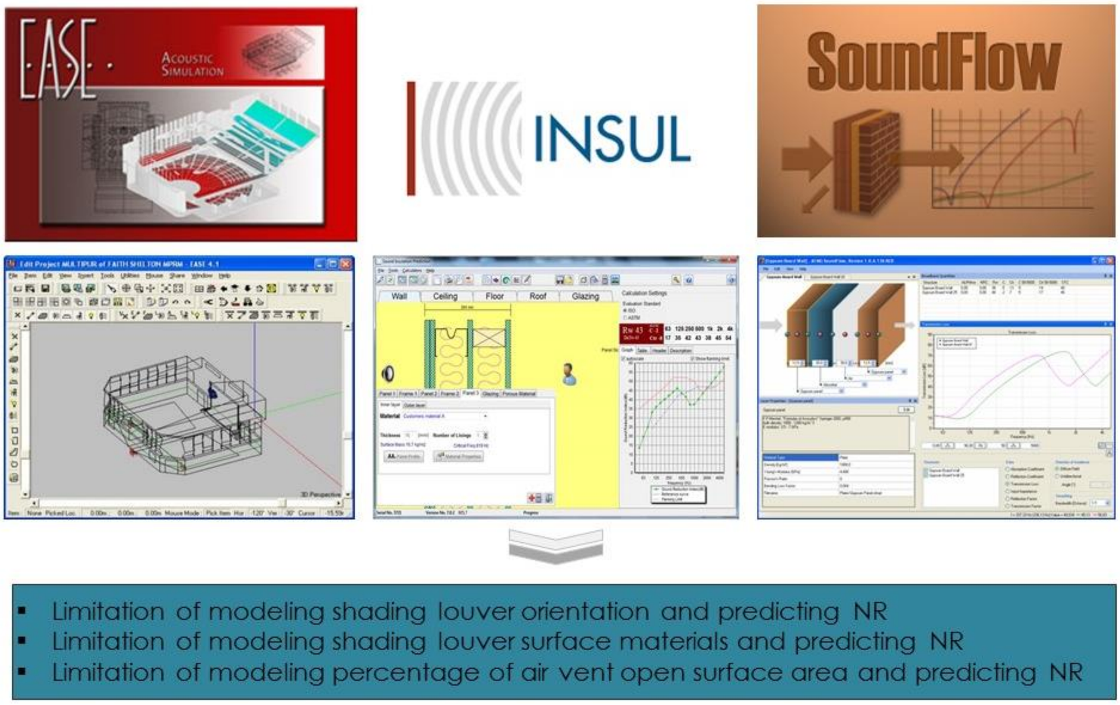


Figure 3.3 Acoustic simulation software

CHAPTER 4: Preliminary Study

4.1 Introduction

The main scope of this preliminary study was to evaluate the relationship between natural ventilation efficiency and noise reduction of a DSF building using CFD and acoustic simulation software. This study primarily focused on ventilation performance based on perforation percentage of air vents, shading louvers orientation and material.

4.2 Preliminary Simulation Study

4.2.1 Percentage of Air Vent Open Surface Area of Double Skin Façade

Summary

The main purpose of this study was to evaluate the correlation between natural ventilation efficiency and noise reduction based on a percentage of air vent open surface area. The airflow volume, air speed, air temperature, and sound pressure level (SPL) inside a DSF air cavity were numerically simulated. Computational fluid dynamics (CFD) simulation outcomes indicated that the degree of air vent open surface area has a proportional relationship to airflow volume and mean SPL in a DSF air cavity. It was found that the highest values of airflow volume and mean SPL applied to vents with 50% of air vent open surface area. However, the cases with 10% and 20% of air vent open surface area are recommended for maintaining a balance between airflow volume and average SPL.

Research Objective

The objective of this portion of the study was to evaluate the feasibility of a DSF to provide ventilation while reducing outdoor noise transmission in high traffic noise areas. Even though a DSF's air cavity can dissipate heat by stack effect, there's a smaller body of research that has investigated a DSF air cavity as an acoustical buffer zone.

Methodology

A corridor type DSF with no horizontal or vertical partitioning within the air cavity was modelled for this study. The DSF's air cavity measured 16-meters in length, 8-meters in width, and 4-meters in height. FloVENT was used to simulate airflow within the DSF air cavity. This CFD program was used to obtain numerical data of airflow volume, air speed, and air temperature in the DSF air cavity. Table 4.1 shows the boundary conditions used for the simulations.

Table 4.1 CFD and acoustical simulation model boundary conditions

Classification	Parameters (unit)	FloVENT
Ambient outdoor conditions	Temperature (°C)[1]	26
	Relative humidity (%)	50
	Noise level (dB)	N/A
Size and materials	External glazing thickness(mm)	10
	Internal glazing thickness(mm)	10
	Cavity width (mm)	1,000
	Cavity space volume (m^3)	64

1) Average ambient air temperature in June for Lawrence, KS

To examine the effects of percentage of air vent open surface area on ventilation and acoustic performances of a DSF, six different percentage of air vent open surface area were studied as shown in Table 4.2.

Table 4.2 Simulation cases based on percentage of air vent open surface area

Vent location	Percentage of air vent open surface area					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Top and bottom	5% each	10% each	20% each	30% each	40% each	50% each

Conclusions

Figure 4.1 shows the CFD findings for airflow volume (m3/s), air speed (m/s), and air temperature (°C) in the DSF air cavity. Both airflow volume (see Figure 4.1a) and air speed (see Figure 4.1b) increase along with the growth of percentage of air vent open surface area. Figure 4.1c illustrates a large mean air temperature difference between Case 1 through Case 6. It was found that the smaller percentage of air vent open surface area in Case 1 impedes the airflow needed to effectively dissipate the heat from the cavity.

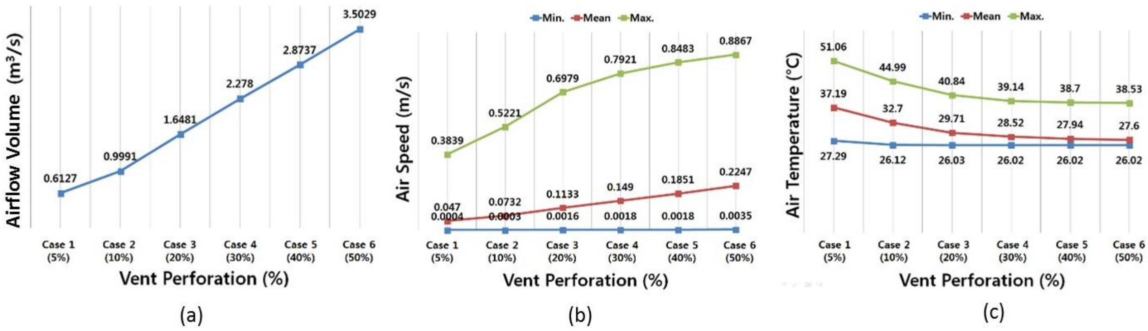


Figure 4.1 CFD data for airflow volume (a), air speed (b), and air temperature (c)

The simulation data indicated that airflow patterns of cases with 5% and 10% of air vent open surface area respectively resulted in circular convection currents causing heat stagnation inside the air cavity. On the other hand, airflow patterns of cases with 40% and 50% of air vent open surface area showed vertical convection currents allowing more effective heat dissipation as illustrated in Figure 4.2.

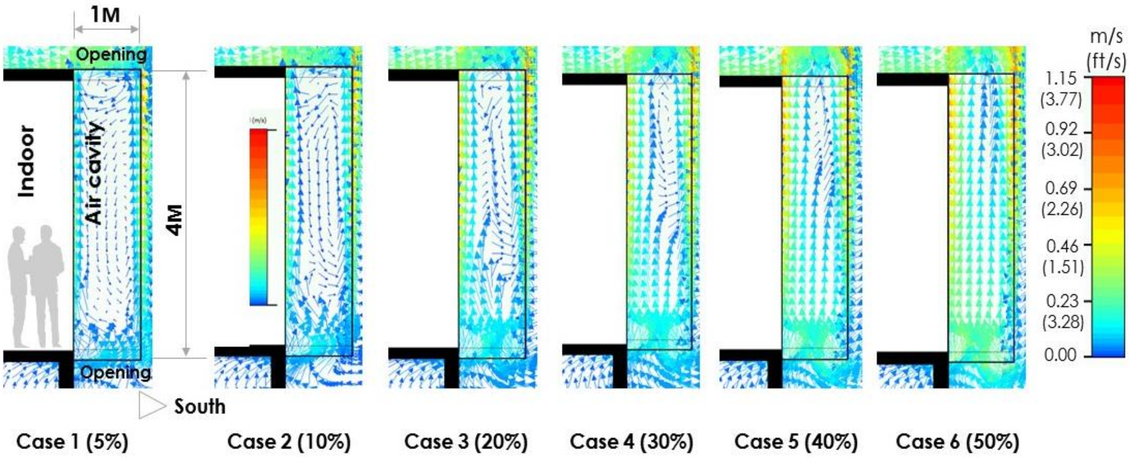


Figure 4.2 Airflow pattern by percentage of air vent open surface area

For noise reduction by vent perforation percentage, calculations were made based on the equation shown in equation 4.1. Approximate numerical data of noise reduction was obtained from measured traffic sound over the entire octave band center frequency.

$$TLw - TLo = 10 \log [(1-p) + p10\ 0.1(TLw - TLp)] \quad (4.1)$$

where TLw - TLo is the transmission loss of a wall (in dB) caused by the presence of an opening in the wall, TLw is transmission loss of the wall (dB), TLp is transmission loss of opening and p is the area of opening divided by the total area of wall-opening assembly.

As shown in Figure 4.3, calculations indicate a mean noise reduction of 10 dB and 7 dB for 5% and 10% of air vent open surface area respectively compared to the measured traffic noise. However, this study has an uncertainty of outcomes for noise reduction of DSFs because the opening size of air vents was theoretically calculated based on equations without considering sound characteristics and surrounding geometry.

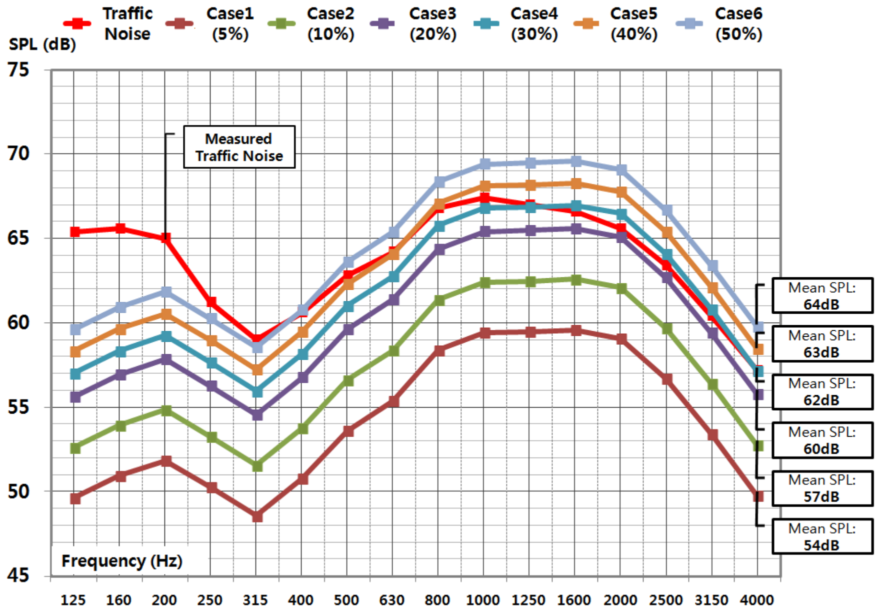


Figure 4.3 Sound pressure level (SPL) of 1/3 octave band center frequency for each case

4.2.2 Shading Louver Orientation of Double Skin Façade

Summary

A number of studies have shown that DSF shading louvers are able to minimize direct solar heat radiation, but only few a studies have tested the acoustical performance of shading louvers as noise barriers. This study was aimed to test the effect of configurations of shading louvers affecting airflow patterns, air velocity, air temperature, and noise transmission loss in DSF cavities. Research is assumed that appropriate orientations of shading louvers in a DSF can contribute to not only the efficient ventilation performance by the stack effect but also noise transmission loss inside a DSF air cavity.

Research Objective

The objective of this study is to evaluate the correlation between ventilation efficiency and noise reduction based on seven cases of orientation and thickness of vertical shading louvers in a DSF air cavity. The findings indicated vertical shading louvers oriented between a 0 degree angle (which is parallel to the outer glass) and a 15 degree angle (which is perpendicular to the outer glass) is considered to balance the need for ventilation efficiency and noise transmission loss.

Methodology

Using the same CFD model as described in the section 4.2.1 vertical shading louvers measuring 25-centimeters in width, 1-centimeter in thickness, and 4-meters in height were equally spaced inside the DSF air cavity as shown in Figure 4.4.

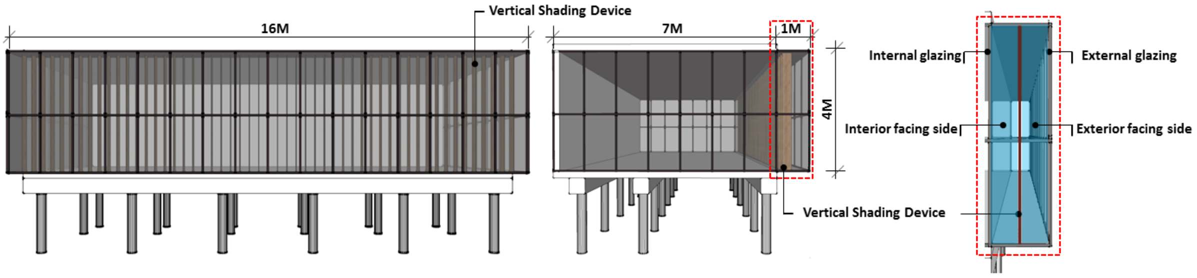


Figure 4. 4 South elevation (a), west elevation (b), and section details (c)

FloVENT was used to simulate airflow within the DSF air cavity and sound transmission was simulated using the acoustic software SoundFlow. These two programs provided numerical data on air temperature, air speed, and sound transmission loss in the DSF air cavity. Table 4.3 shows the boundary conditions for the simulations.

Table 4.3 CFD and acoustical simulation model boundary conditions

<table>
<tr><th>Classification</th><th>Parameters (unit)</th><th>FloVENT(material)</th><th>SoundFlow(material)</th></tr>
<tr><td rowspan="2">Ambient outdoor conditions</td><td>Temperature (°C)[1]</td><td>26</td><td>26</td></tr>
<tr><td>Relative humidity (%)</td><td>50</td><td>50</td></tr>
<tr><td rowspan="4">Size and materials</td><td>External glazing thickness(mm)</td><td>10 (glass)</td><td>10 (glass)</td></tr>
<tr><td>Internal glazing thickness(mm)</td><td>10 (glass)</td><td>10 (glass)</td></tr>
<tr><td>Vertical shading louver thickness(mm)</td><td>10 (wood)</td><td>10 (wood)</td></tr>
<tr><td>Cavity width (mm)</td><td>1,000 (air)</td><td>1,000 (air)</td></tr>
</table>

1) Average ambient air temperature in June for Lawrence, KS

To explore the effects of vertical shading louver orientation and thickness on air temperature, air speed, and sound transmission loss, seven cases of orientation and thickness were studied. Table 4.4 shows the different test cases ranging from 0 to 90 degree angles as well as from 0-milimeter (no shading louvers) up to 40-milimeters in thickness.

Table 4.4 CFD simulation cases for ventilation efficiency and sound transmission loss

Vertical shading louvers	Cases of orientation (degree) and thickness at 0 degree angle (mm)						
Orientation (degree)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
	0	15	30	45	60	75	90
Thickness at 0 degree angle (mm)	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
	0	5	10	15	20	30	40

Conclusions

Figure 4.5 shows the CFD findings for air temperatures in the interior facing side (see Figure 4.5a) and exterior facing side of the vertical shading louvers (see Figure 4.5b). The air temperature in the exterior side drastically decreased at monitoring points V2 (+2.0m: 2-meters high from the air cavity bottom) and V3 (+3.5m: 3.5-meters high from the air cavity bottom) relative to an increase in shading louver orientation angle. When vertical shading louvers were oriented to 0 degree (closed position), air temperature in the exterior side of the shading louvers was the highest. When they were tilted at a 90 degree angle (open position), air temperature was the lowest.

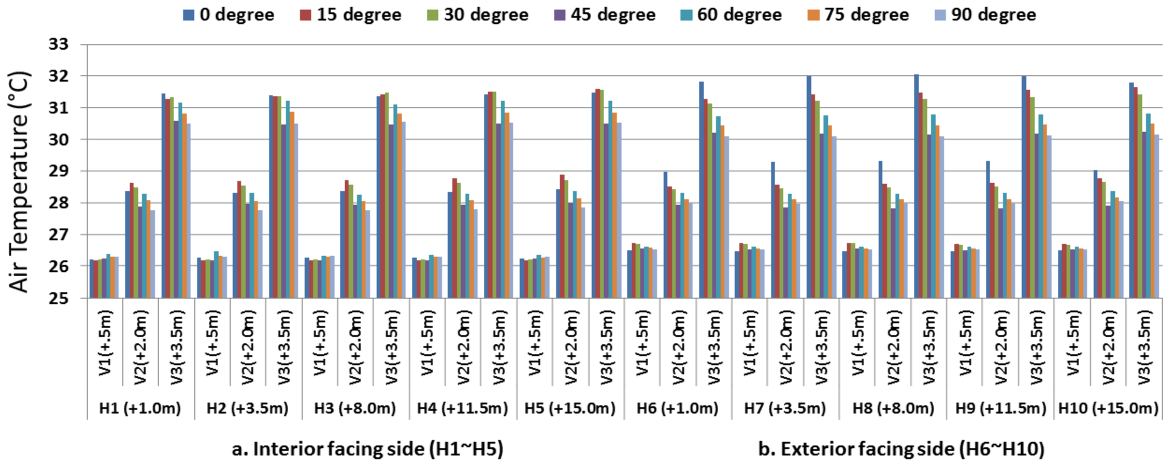


Figure 4.5 CFD data for air temperature of interior (a) and exterior facing side of shading louvers (b)

Figure 4.6 shows CFD findings for vertical air velocities in the interior facing (see Figure 4.6a) and exterior facing sides of the vertical shading louvers (see Figure 4.6b). The air velocity in the exterior facing side was greater than the air velocity in an interior facing side of the shading louvers.

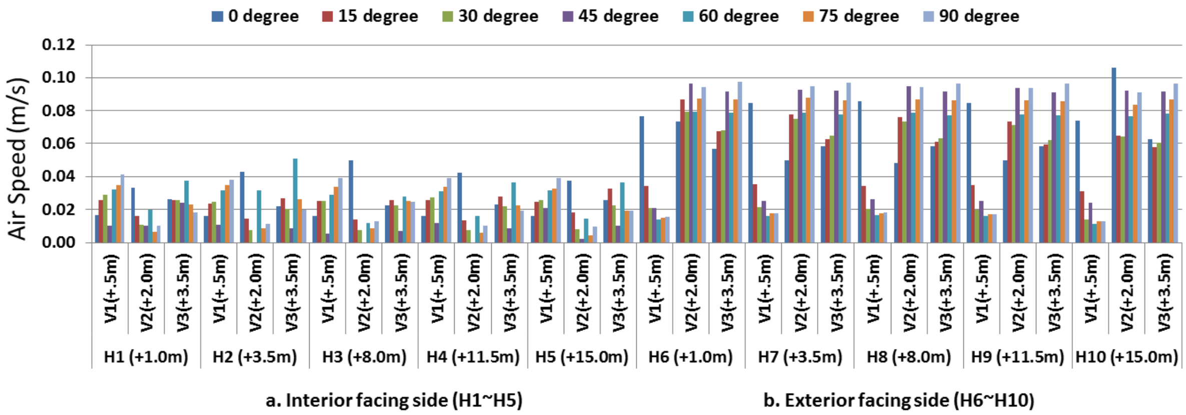


Figure 4.6 CFD data for vertical air speed of interior (a) and exterior facing sides of shading louvers (b)

Figure 4.7 shows the CFD findings for air speed in plan (see Figure 4.7a) and airflow patterns in section (see Figure 4.7b). When shading louvers were oriented at a 0 degree angle, parallel to a glass wall as shown in Case 1, higher air speed distribution and linear airflow patterns were observed. On the other hand, when the shading louvers were tilted at a 90 degree angle, perpendicular to glass wall as shown in Case 7, higher air speed distribution was divided into two sides in the center of the louvers and an eddy formed around the louvers.

This change implies that ventilation performance by stack effect is dependent on the orientation of vertical shading louvers. To be specific, it was found that vertical shading louvers tilted at a 0 degree angle in the middle of DSF air cavity can achieve increased ventilation performance compared to louvers at 90 degrees.

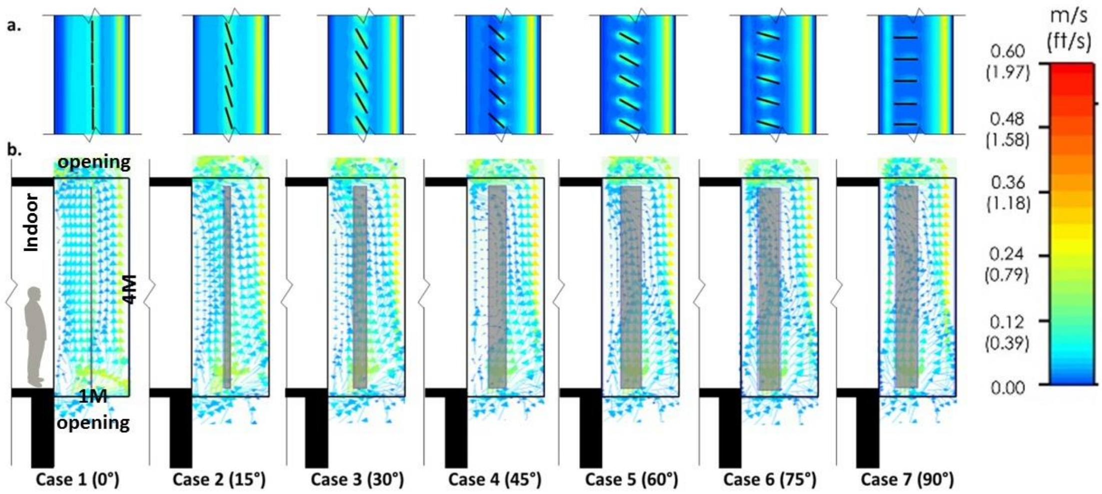


Figure 4.7 Air speed in horizontal (a) and airflow in vertical section (b)

Figure 4.8 shows the CFD results for air temperature in the horizontal (see Figure 4.8a) and vertical planes (see Figure 4.8b). When vertical shading louvers were oriented at a 0 degree angle as shown in Case 1, it was found that air temperature increased near the outer glass rather than the inner glass inside the DSF air cavity because the solar radiation was blocked by the louvers. On the other hand, when the louvers were oriented at a 90 degree angle as shown in Case 7, there was an increase in air temperature near the inner glass side of the DSF air cavity.

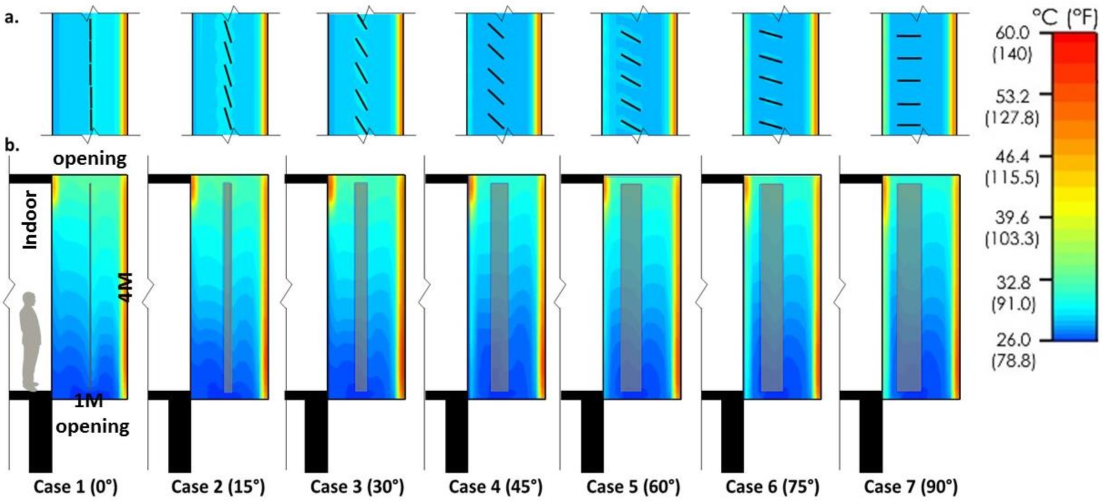


Figure 4.8 Air temperature distribution in DSF: horizontal (a) and vertical (b)

In terms of acoustical performance, Figure 4.9 shows sound transmission loss relative to an increase in the thickness of vertical shading louvers at a 0 degree angle, closed position parallel to glass wall. When there are no shading louvers inside a DSF cavity as shown in Case 8, sound transmission loss at the mid and high frequency ranges was the lowest compared to other cases.

However, this study has an uncertainty of outcomes for the acoustical performance of the DSF because shading louver thickness was simulated with acoustical simulation software without consideration of sound characteristics and shading louver orientation. Therefore to address the limitations of the simulation, it is necessary to experimentally study the degree of noise reduction caused by the materiality and orientations of the shading louvers.

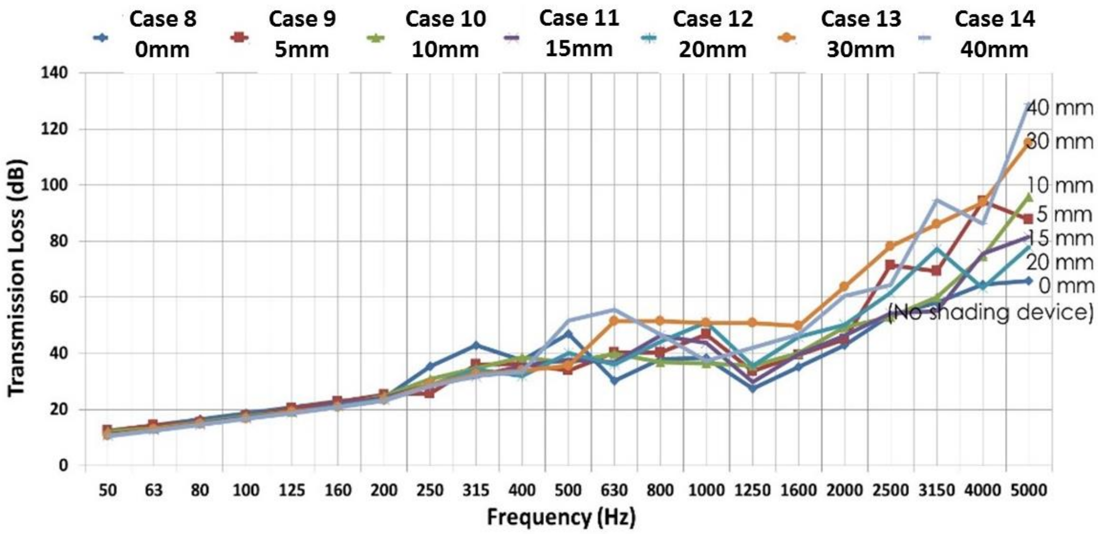


Figure 4.9 Transmission loss based on shading louver thickness

4.2.3 Air Cavity Volume Ratio of Double Skin Façade

Summary

The CFD simulation test cases were designed based on different volume ratios of the DSF air cavity partitioned by vertical glass fins, affecting changes in air temperature and airflow inside the air cavity. The simulations showed that volume ratios of DSF air cavity influenced the efficiency of heat dissipation inside DSF air cavities. It was observed that air temperature in Case 4, which has the ratio of 8-meters in length to 1-meter in depth of a DSF air cavity, has a higher potential of overheating inside air cavity than that of Case 1 (1-meter in length to 1-meter in depth) and Case 2 (2-meters in length to 1-meter in depth). Case 1 and Case 2 showed relatively lower mean air temperature inside the DSF air cavities caused by efficient heat dissipation. In addition, it was found that the thicker the vertical glass fins are, the higher the Sound Transmission Loss (STL) values.

Research Objective

This preliminary simulation study demonstrated that the DSF air vent openings resulted in decreased acoustical performance because airborne noise transmitted via the air vent openings travels both horizontally and vertically. This study examined the effects of DSF air cavity volume ratios determining ventilation performance as well as reducing noise transmission via air vent openings. Vertical glass fins inside the DSF air cavities were tested for reducing noise propagation, while zoning DSF air cavity volume.

Methodology

A box-window type DSF with vertical shading louvers and vertical glass fins inside the air cavity was modelled for the simulation. Ventilation inlet grilles with 40% perforation were applied to the top and bottom of the DSF air cavity for ventilation and heat dissipation. The total spatial volume of the DSF air cavity was 16-meters in length, 4-meters in height, and 1-meter in depth as shown in Figure 4.10.

The glass fins were situated at distances of 4-, 5-, 6-, and 10-meters to create the different air cavity volumes as shown in Figure 4.10b. Monitoring points to measure air temperature and air velocity were placed at the height of 0.5(P1), 2.0(P2), and 3.5-meters (P3) inside the air cavity as shown in Figure 4.10b. To examine the air temperature distribution inside the air cavity, the CFD visual analysis planes were positioned at distances of 0.1-, 0.3-, 0.55-, 0.7-, and 0.9-meters along the depth of the DSF as shown in Figure 4.10b.

The aim of the different cases as shown in Table 4.5 was to see the impact of air cavity volume ratio on air temperature and sound transmission loss caused by the glass fin thickness. The CFD simulation software FloVENT was used to simulate air temperature and air velocity inside the DSF air cavity. The simulation model boundary conditions are shown in Table 4.5.

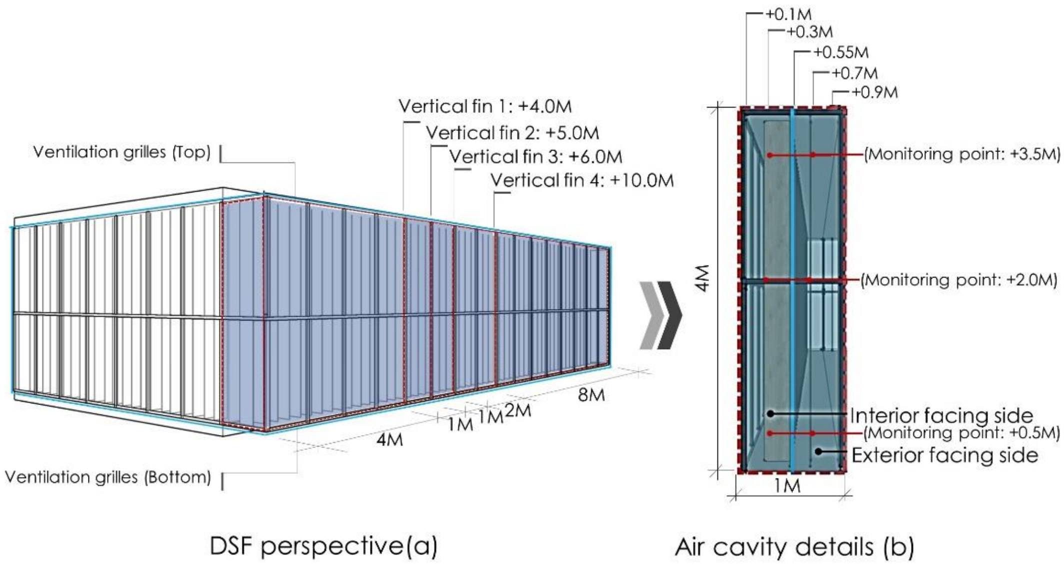


Figure 4.10 DSF perspective (a) and air cavity details (b) for CFD simulation

Acoustic software SoundFlow simulated sound transmission loss based on the thickness of the vertical glass fins. The surrounding buildings, outdoor temperature, relative humidity, and actual traffic sound sources were not considered in this part of the study.

Table 4.5 CFD and acoustic simulation cases

Classification		Cases			
Air temperature, Air velocity	DSF air cavity [Length (m) : Depth (m)]	Case 1	Case 2	Case 3	Case 4
		1:1	2:1	4:1	8:1
Sound transmission loss	Glass fin thickness (mm)	Case 5	Case 6	Case 7	Case 8
		5	10	15	20

Table 4.6 CFD and acoustic simulation model boundary conditions

Classification	Parameters (unit)	FloVENT	SoundFlow
Ambient outdoor conditions	Air temperature (°C)	29	29
	Relative humidity (%)	50	50
Size and materials	External glazing thickness(mm)	10	N/A
	Internal glazing thickness(mm)	10	N/A
	DSF air cavity depth (mm)	1,000	N/A
	Glass fin thickness (mm)	10	see Table 4.5

Outcomes

Figures 4.11a and 4.11c illustrate the air temperature distributions within the DSF. The highest air temperature was observed in Case 4 with shading louvers tilted at 90 degrees, parallel to the glass wall. It implies that ventilation performance for heat dissipation by stack effect was better in Cases 1 and 2 than Case 4.

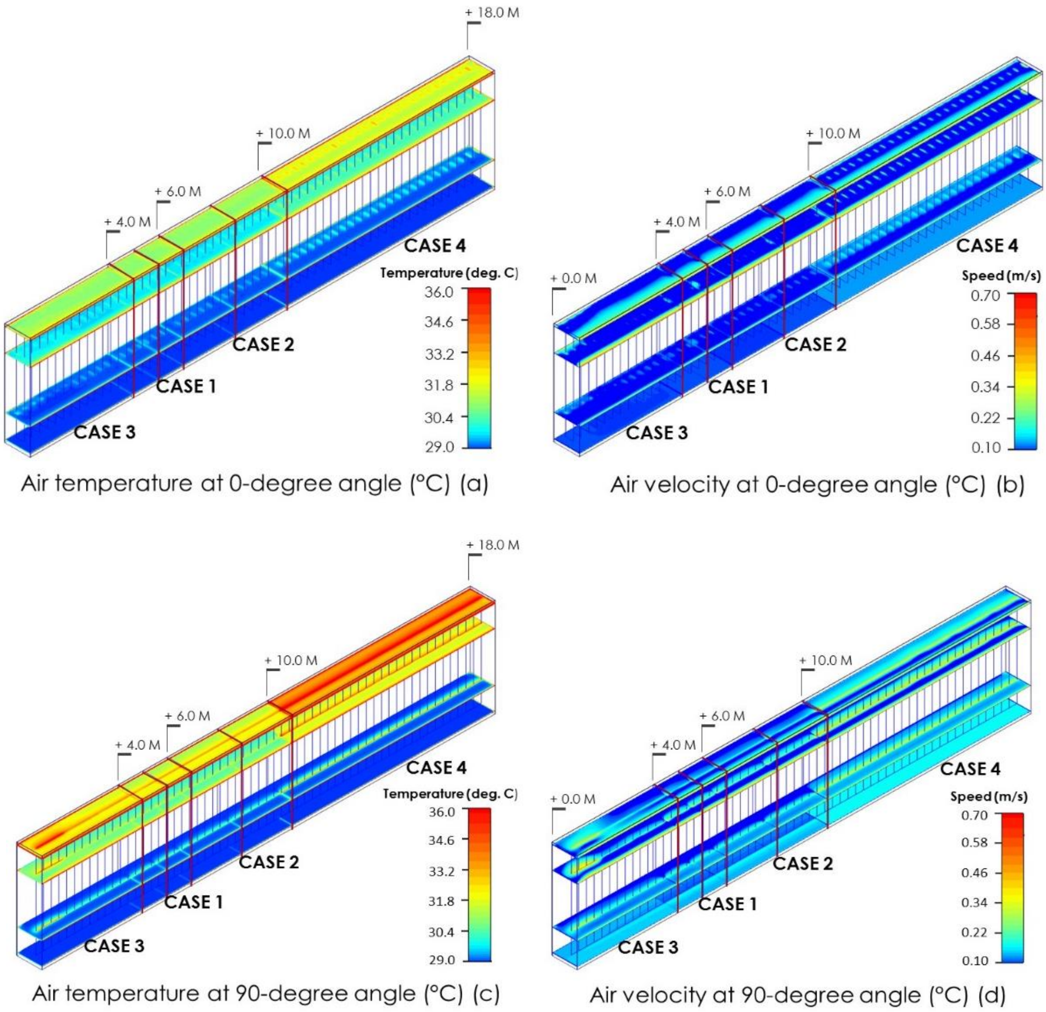


Figure 4.11 Distributions of air temperature and air velocity at 0 degree angle (a, b) and 90 degree angle (c, d)

With regard to air temperature distributions, Figures 4.12a and 4.12c show that the highest air temperatures were in Case 4 compared to other cases when the shading louvers were in the closed position at 90 degrees. The DSF's air cavity length to depth ratios of Case 1 (1-meter in length to 1-meter in depth) and Case 2 (2-meters in length to 1-meter in depth) are recommended over Case 4 (8-meters in length to 1-meter in depth) for efficient heat dissipation during the summer period.

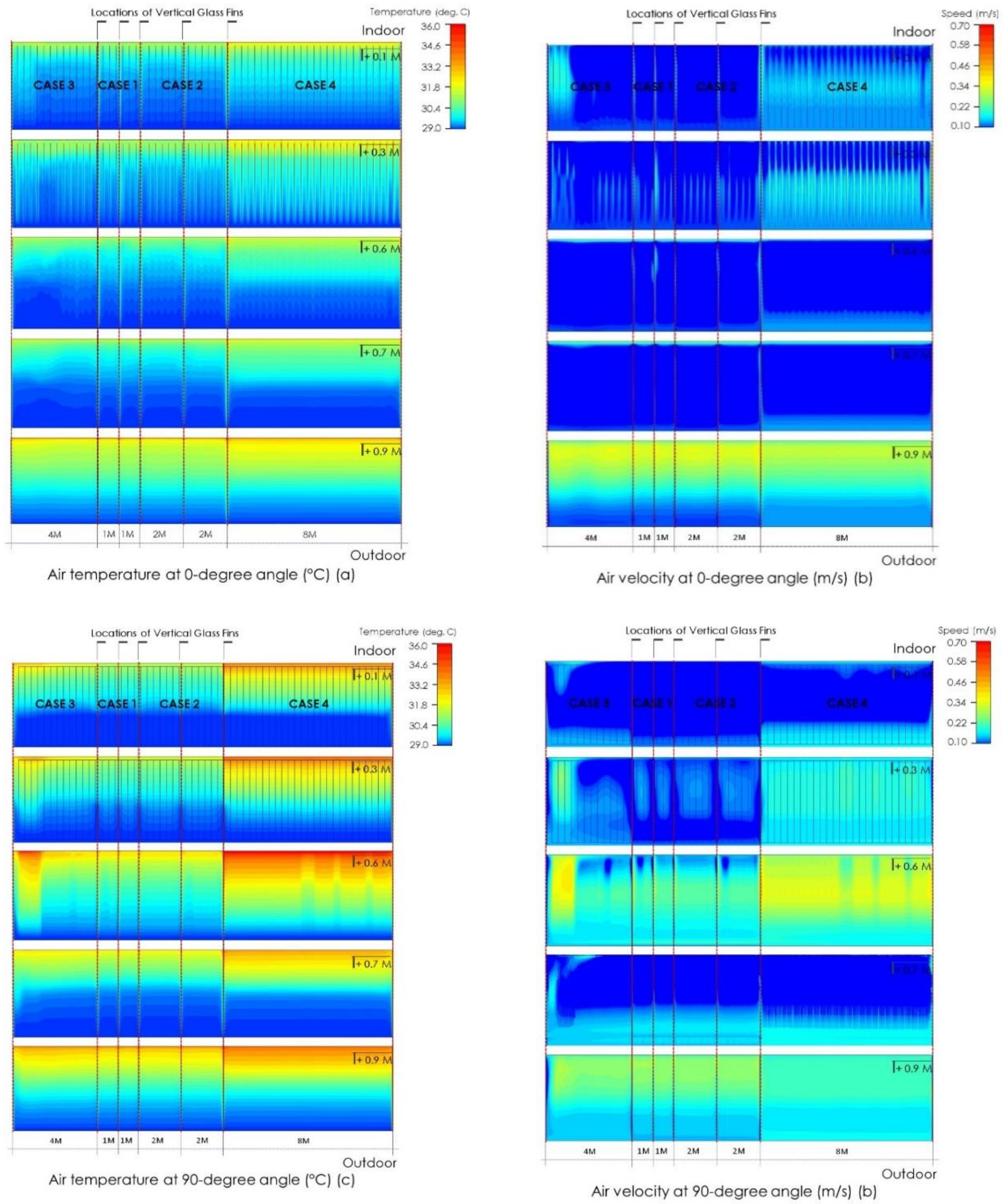


Figure 4. 12 Air temperature and air velocity when louvers are at 0 degree angle (a, b) and 90 degree angle (c, d)

Regarding the differences in mean air temperature at the highest monitoring points, P3 (H: +3.5-meters, 3.5-meters high above the air cavity bottom) , it was found that cases with louvers at 90 degrees resulted in higher mean air temperature by 1.1 to 1.5 degree Celsius than that of cases with louvers at 0 degree (see Figures 4.13a and 4.13c). This outcome implies that Case 4 (air cavity ratio of 8-meters in length to 1-meter in depth) is not as effective as the other cases in dissipating heat during the summer period.

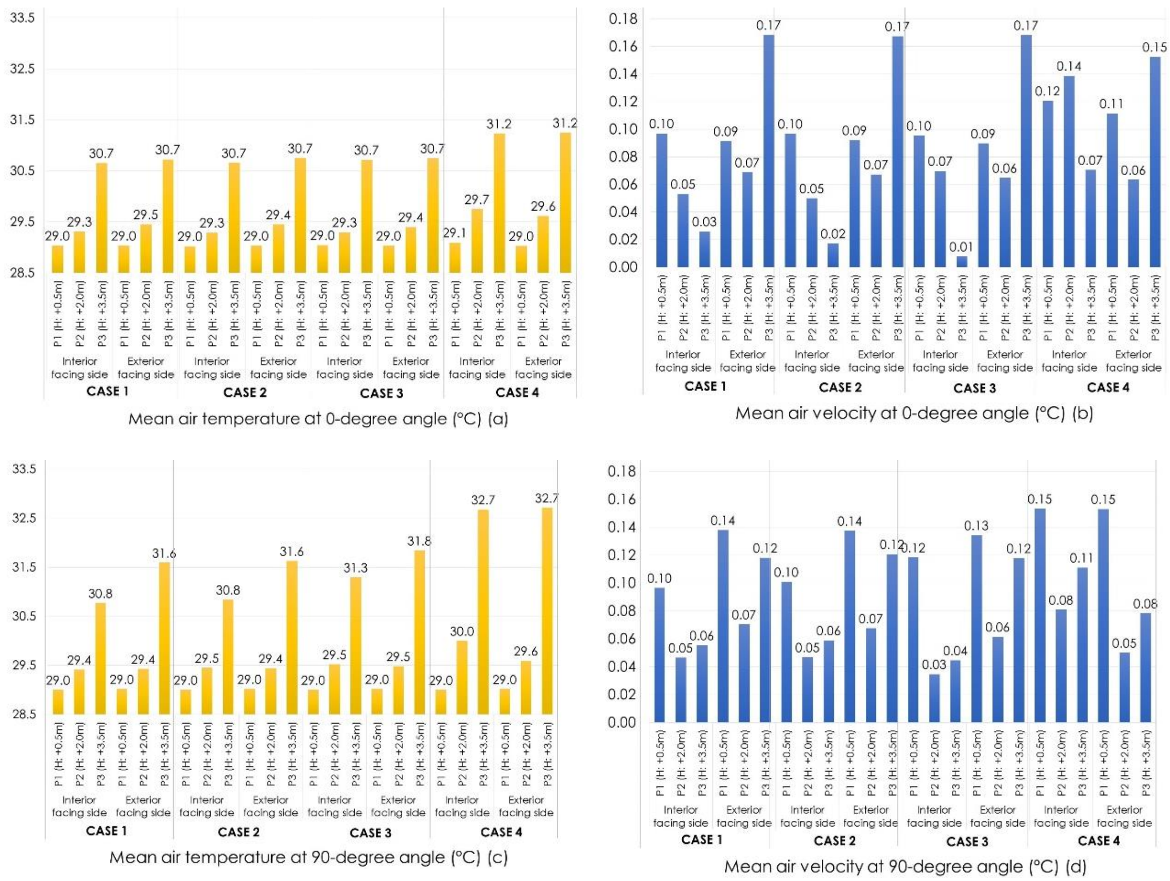
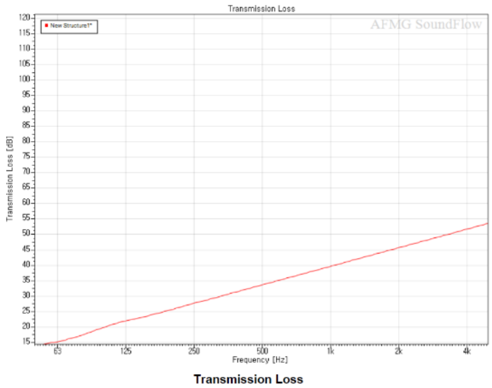
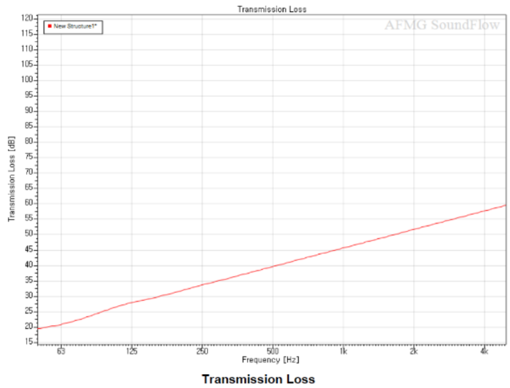


Figure 4. 13 Mean air temperature (a, c) and mean air velocity (b, d) at 0 and 90 degree angle.

In terms of the acoustical performance of glass fins as shown in Figure 4.14, SoundFlow data found that Case 8 showed a higher STC value compared to Case 5, which implies that an increase of glass fin thickness is more effective in sound transmission loss across the entire octave band center frequency (Hz) range. However, the difference of STC or sound transmission loss based on the four cases was slight.

Case	Case 5 (5mm in thickness, STC 30)	Case 6 (10mm in thickness, STC 32)
STC Graph		

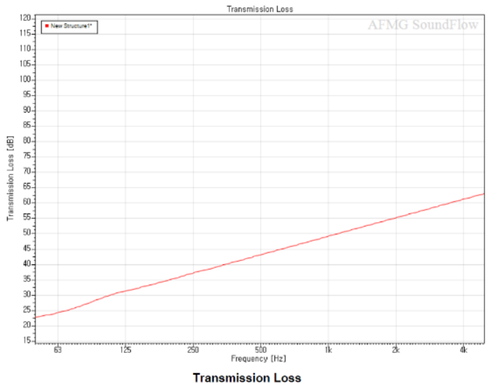
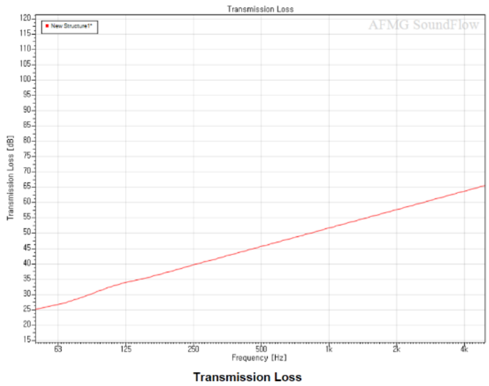
Case	Case 7 (15mm in thickness, STC 33)	Case 8 (20mm in thickness, STC 34)
STC Graph		

Figure 4.14 STC values by glass fin thickness

Finally, the CFD simulation results suggested that box-window type DSF air cavity with a 1 to 1 or 2 to 1 (length to depth) ratios are recommended for achieving efficient heat dissipation through ventilation. It was found that thicker glass fins can achieve higher STC values that in turn decrease noise transmission to indoor spaces via air ventilation openings. This preliminary simulation study implies box-window DSFs with air cavity ratios of 1 to 1 or 2 to 1 (length to depth) is appropriate for designing a DSF mock-up for an experimental study.

CHAPTER 5: Experimental Study

5.1 Introduction

First, a series of findings from literature review suggest noise transmission by the use of window ventilation in high noise areas is a significant environmental problem causing adverse health effects. Among a number of techniques for ventilation performance and noise transmission loss, the use of grilles or louvers at the inlet vent helps control ventilation rate and noise transmission loss. It is also noteworthy that shading louvers around ventilation windows are effective in blocking the sound path. In addition, it was found that the air cavity, shading louvers, and air vents of a DSF can become control variables for a balance between ventilation performance and noise transmission loss.

Second, in the preliminary simulation study described in the preceding chapter, airflow and acoustic simulations were conducted to predict a conflict between ventilation performance and noise transmission loss in a DSF. CFD simulation was aimed to collect quantitative data concerning the effects of percentage of air vent open surface area, orientation and type of shading louvers, and air cavity volume ratio on ventilation performance. Acoustic simulation was designed to estimate noise transmission loss based on vent opening size and shading louver thickness.

As discussed in the preliminary study, the available acoustics simulation programs such as EASE, Insul, and SoundFlow are limited in their abilities to properly model and simulate a DSF with louvers. Therefore it was necessary to conduct an experiment using a full scale mock-up of a DSF set in a reverberation chamber to properly study the effects of shading louvers and ventilation openings on noise reduction. The next few sections of this chapter define several terminologies such as Noise Reduction (NR), Transmission Loss (TL), Noise Isolation Class (NIC), Sound Transmission Class (STC), Outdoor and Indoor Transmission Class (OITC), and

Noise Criteria (NC) used in the experiment along with measurement standards, equipment, and other experimental settings.

5.1.1 Noise Reduction (NR) and Transmission Loss (TL)

Sound is the propagation of mechanical energy in the form of pressure variations. When sound transfers from a certain component of a building to another component, it is conveyed in the form of air-borne transmission, structure-borne transmission, and flanking transmission as shown in Figure 5.1. Most sounds generated by human conversation, musical instruments, and mechanical equipment in a building are air-borne sounds that travel form one room to another room through the medium of air (Mehta et al., 1998). Also, outdoor air-borne sounds such as urban traffic noise are transmitted through ventilation openings into a building. These involve the relationship among sound sending source, building medium, and sound receiving destination.

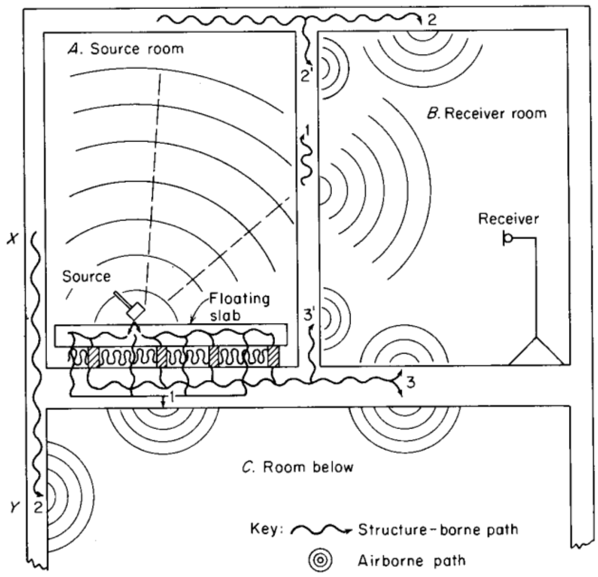


Figure 5.1 Sound paths between rooms (Source: Pennsylvania state university)

Noise reduction in a broad definition can be described by three aspects: (i) reduction of noise generation by the proper installation of equipment as sound sending source, (ii) reduction of noise transmission by proper construction materials as building medium, and (iii) reduction of noise by acoustical treatment of the space as sound receiving destination (Stein et al., 2014). Therefore, the NR can be understood as the difference in sound pressure level from one side of a partition (e.g., wall, floor, ceiling assembly, etc.) to the other side, typically measured in the field. Simply, the NR is the loss in SPL that occurs when sound energy passes including the effects of sound absorption in the sound receiving room and sound transmitted via flanking paths around the partition. The NR through the building façade component and this numerical number in decibels is obtained from a controlled laboratory test.

The value regarded as more significant is the actual NR between two rooms separated by a barrier. This NR is defined as the difference between the SPL levels in adjacent rooms as seen in the equation 5.1,

$$\text{NR} = \text{Sound Pressure Level 1} - \text{Sound Pressure Level 2} \tag{5.1}$$

NR can also be formulated in relation to the TL of as a barrier shown in the equation 5.2,

$$\text{NR} = \text{TL} - 10 \log (S/AR) \tag{5.2}$$

where NR is noise reduction in dB, the TL is barrier transmission loss in dB, S is area of the barrier in m^2, and AR is a total sound abortion of the receiving room in sabins.

In contrast, with air-borne sound transmission between adjacent rooms through a barrier, the transmitted sound level is dependent not only on the transmission loss of the barrier itself but also on the sound absorption of area of the barrier and the receiving room (Stein et al., 2014). However, the definition of the TL contains only sound transmission between spaces excluding the effects of sound absorption in the sound receiving room and sound transmitted via flanking paths around the partition. Therefore, the TL is expressed as the log ratio of the incident sound energy to the transmitted energy as seen in equation 5.3,

$$\text{TL} = \text{NR} + 10 \log (S/A_R) \tag{5.3}$$

where TL is transmission loss, NR is noise reduction in dB, S is area of the barrier in m^2, and AR is a total sound abortion of the receiving room in sabins. In the mock-up test, it is assumed that the value of 10 log (S/A_R) in the sound receiving room is insignificant and the definition of NR is substituted with the definition of TL.

5.1.2 NIC, STC, OITC, and NC

The measured NR data can determine the Noise Isolation Class (NIC) which is a single number rating. The rating provides an evaluation of the sound isolation between two enclosed spaces that are acoustically connected by one or more paths. The NIC measurement is carried out according to the ASTM E-413 and ASTM E-336 between 125 and 4,000Hz.

In contrast, TL data determines the Sound Transmission Class (STC) rating, which is typically applied to building partitions exposed to speech, television, radio, and office equipment in accordance with the ASTM E413-10. It is determined by comparing the set of TL across all 1/3 octave band center frequency ranging from 125 to 4000 Hz to a set of standard contours as described in Figure 5.2. The TL curve must fit the standard contour in such a way that will allow no more than 32 deficiencies below the appropriate contour. The maximum deficiency at any given frequency shall not exceed 8 decibels.

The STL is a single number rating for interior building partitions from speech, television, radio, and office equipment over the frequency range of 125 Hz to 4000 Hz. Higher values of the STC indicate better acoustical performance against noise transmission. Subjective hearing quality based on the STC values is described in Table 5.1.

Table 5.1 Subjective perception of STC values

STC	Subjective description
30	Most sentences can be clearly understood
40	Speech can be heard with some effort, Individual words and occasional phrases heard.
50	Loud speech can be heard with some effort. Music easily heard.
60	Loud speech essentially inaudible. Music heard faintly; bass not disturbing
70	Loud music heard faintly, which could be a problem if the adjoining space is highly
75 and above	Most noises effectively blocked sensitive to sound intrusion such as a recording studio, concert hall, etc.

The STC and NIC ratings are similar. The NIC is determined using the NR data and it relates to field performance. By contrast, the STC is determined using the TL data and it relates to laboratory performance. Typically, the field NIC ratings are lower than laboratory STC ratings by 7 to 10 dB. The STC is the STL value at 500 Hz on the STC contour which consists of the three straight line parts with different scope over the frequency range of 125 Hz to 4000 Hz as shown in Figure 5.2.

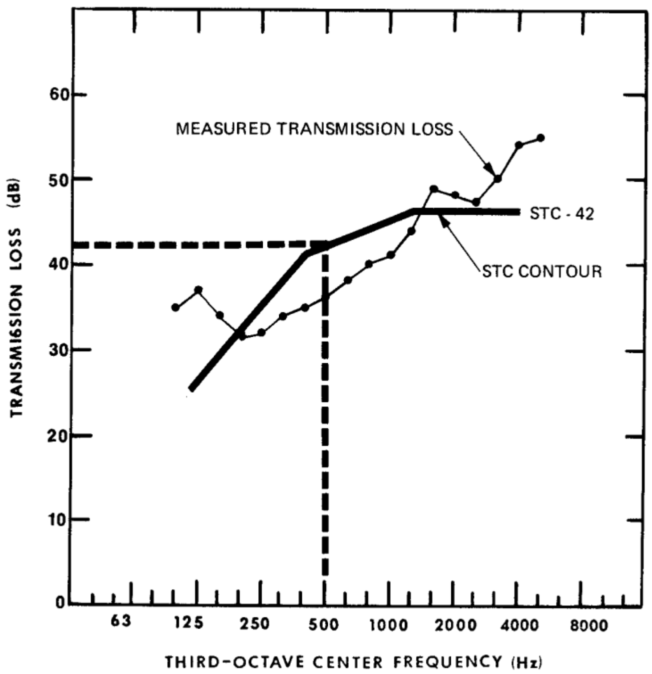


Figure 5.2 STC rating by the standard contours to the measured TL values

The Outdoor to Indoor Sound Transmission Class (OITC) rating is typically applied to façades and façade elements such as windows and doors exposed to transportation noises in accordance with the ASTM E1332. The OITC rating is determined by using the same measured TL data as is used for STC, except that the OITC includes data that extends from 80 Hz to 4000 Hz because the transportation noise is rich in the low frequency range. The OITC rating can be applied to elements tested in either the laboratory or in the field. Therefore, the OITC is recognized as a better single number rating of building envelop elements than STC (Mehta et al., 1998).

Another difference between the STC (ASTM E413-10) and OITC (E1332-10a) is that the former is used to test building façade elements in a laboratory and the latter is used in a laboratory or the field. The STC test does not take into account façade openings and gaps where sound travels, whereas the OITC test encompasses an entire assembly such as exterior walls, windows, and doors. The STC rating has its limitation as stated in the ASTM E413-10 and these single number ratings correlate with subjective impressions of sound transmission for speech, radio, and television. This classification method is not appropriate for sound sources including machinery, industrial processes, bowling alleys and power transformers (ASTM E413-10, 1970). Table 5.2 summarizes a comparison between the STC and OITC.

Table 5.2 Comparison between STC and OITC

Test method	Summary
STC (Sound Transmission Loss)	- Calculated in accordance with the ASTM E 413 (Published 1970) - Create a single number rating for interior building partitions that are subjected to noises from speech, television, radio and office equipment - Should not be used to evaluate partitions exposed to machinery, industrial and transportation nose such as motor vehicles, aircraft and trains - Calculated over the frequency range of 125 Hz to 4000 Hz
OITC (Outdoor and Indoor Transmission Class)	- Calculated in accordance with the ASTM E 1332 (Published 1990) - Create a single number rating for facades and façade elements that are subjected to transportation noise - Calculated over the frequency range of 80 Hz to 4000 Hz

The Noise Criteria (NC) is a standard that describes indoor ambient noise levels, as produced by HVAC systems and other continuous noise sources. The NC rating of a spectrum is designated as the value of the lowest NC curve above the measured 1/3 octave band center frequencies ranging from 63 to 8000 Hz as shown in Figure 5.3. The criteria curves define the limits of octave band spectra that must not be exceeded to meet the occupant's acceptance in certain spaces.

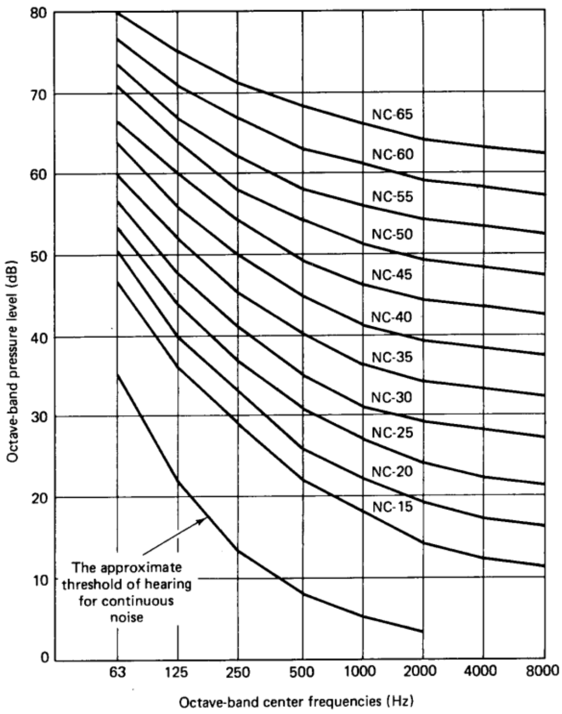


Figure 5.3 Noise Criteria curves

Table 5.3 shows that the recommended NC levels by space should not exceed the NC limits in different types of rooms. For instance, recommended NC levels range between 25 and 30 in the case of lecture hall and classrooms in schools. The lower NC values are, the less noise annoyance is required for the space.

Table 5.3 Recommended Noise Criteria by space

Type of building	Type of room	Recommended NC level	Equivalent Sound Level (dB(A)
Residential buildings	Apartment Houses	25-35	35-45
	Private Homes, urban	20-30	30-38
Hotels	Individual room	25-35	35-45
	Halls, corridors, lobbies	35-40	50-55
Offices	Conference rooms	25-30	35-40
	Open-plan areas	35-40	45-50
Hospital	Private rooms	25-30	35-40
	Laboratories	35-40	45-50
Schools	Lecture and classroom	25-30	35-40
	Open-plan classrooms	35-40	45-50

5.1.3 Measurement Standards

Regarding measurement methods of TL (or NR), the International Standard EN ISO 140-5 standard defines two types of measurement methods, the element method and global method. The former is used to estimate the STL of a façade element such as a window using a loudspeaker, whereas the latter aims to estimate the OITC which measures the outdoor and indoor sound level differences under actual traffic conditions or artificial sound sources (ISO, 1998; Burmistrova, 2012). The TL (or NR) values based on the ASTM E90-02 standard are used to calculate the STC and OITC ratings in accordance with the ASTM E413 and ASTM E 1322 standards respectively as shown in Table 5.4.

The DSF mock-up tests were designed to measure the TL (or NR) in the reverberation chamber based on the ASTM E90-02 (Standard Test Method for Laboratory Measurement of Air-borne Sound Transmission Loss of Building Partitions and Elements). The standard was designed to measure the TL (or NR) of a partition in a laboratory over a frequency range of speech from 125 to 4000 Hz.

Table 5.4 Acoustic standards for acoustic rating methods

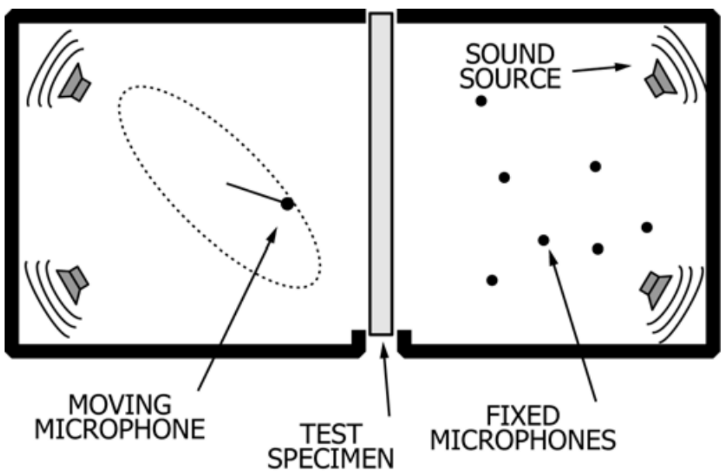
Standards	Code	Field of application
ASTM	C423	Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method
	C634	Terminology Relating to Building and Environmental Acoustics
	E336	Test Method for Measurement of Air-borne Sound Attenuation between Rooms in Buildings
	E90-02	Standard Test Method for Laboratory Measurement of Air-borne Sound Transmission Loss of Building Partitions and Elements
	E413	Classification for Rating Sound Insulation
	E492	Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine
	E966	Guide for Field Measurements of Air-borne Sound Attenuation of Building Facades and Facade Elements
	E1007	Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures
	E1289	Specification for Reference Specimen for Sound Transmission Loss
	E1332	Classification for Rating Outdoor-Indoor Sound Attenuation
ISO	ISO 140	Measurement of sound insulation in buildings and of building elements
	ISO 717	Rating of Sound Insulation for Dwellings3
ANSI	S1.6-1984 (R2006)	American National Standard Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurement

5.2 Measurement Methods

5.2.1 ASTM E90-02

The results of the DSF mock-up test are presented as NR which is defined as the difference of the average SPL through the specimen between two adjacent reverberation rooms. Table 5.5 shows the basic requirements for the ASTM E90-02 test settings including test room, specimens, sound source, equipment, and test equation. The test setting of the DSF mock-up was modified based on the ASTM E90-02 due to limitations of available measurement equipment. Detailed test settings are described in section 5.2.3 Mock-up Set-up.

Table 5.5 Requirements for ASTM E90-02

Test setting	Requirements
Test room	- The minimum volume of each room is 80 m^3
	- The sound absorption of the room should be no greater than $A=V^{2/3}/3$ (V= the room volume, m^3 and A = the sound absorption of the room, m^2)
	- The average temperatures shall be in the range 22 ± 5°C and the average relative humidity shall be at least 30 %
Test specimens	- Include all the essential construction elements in normal size of actual use
	- The minimum dimension (excluding thickness) shall be 2.4m
	- Being installed in a manner similar to actual construction
Test sound sources	- The sound signals shall be random noise having a continuous spectrum within each test frequency
	- Sound sources shall consist of one or more loudspeakers
Test equipment	- A single microphone for several measurement positions in sequence or several microphones for simultaneous measurements
	- A 13-mm (0.5-in.) random-incidence condenser microphone is recommended
	- Calibration checks of the entire measurement system
Test equation	- $TL(f) = L_S(f) – L_r(f) + 10 \log S/A_R(f)$ where: TL(f) = transmission loss, dB, $L_S(f)$ = average sound pressure level in the source room, dB, $L_R(f)$ = average sound pressure level in the receiving room, dB, S = area of test specimen that is exposed in the receiving room, m^2 $A_R(f)$ = sound absorption of the receiving room with the test specimen in place, m^2
Test setting	 For conceptual arrangement of a wall STC setting, the room on the right has fixed microphones to measure average sound pressure level and the room on the left has a continuously moving microphone to measure average sound pressure levels ranging 100 to 5000 Hz

5.2.2 Measurement Equipment

The major measurement devices used for the DSF mock-up tests are shown in Table 5.6. The Larson 831 sound level meter features various measurement parameters such as multiple time weightings (Slow, Fast & Impulsive) and frequency weightings (A, C & Z).

Table 5.6 DSF mock-up measurement equipment

Tools	Details
	Sound lever meter: Larson 831 - The various measurement parameters available
	Condenser microphone: 377B02 1/2” - Free-field pre-polarized microphone with 16 to 140 dB measurement range
	Dodecahedron loudspeaker - Full-range loudspeaker providing uniform sound radiation
	Pink noise generator - Frequency Range: 20 Hz - 20 kHz
	Mixing console

A condenser microphone was used to obtain the average SPL at four measurement positions in each room. It can measure SPL ranging from 16 to 140 dB. The dodecahedron loudspeaker has a full-range loudspeaker mounted in each of the 12 sides, providing uniform sound radiation. The output power level is up to 120 dB for a pink noise signal. A mixing console and a pink noise generator produce pink noise, of which each octave carries an equal amount of noise energy. It is substituted for the actual traffic noise in urban areas.

5.2.3 Mock-up Set-up

Reverberation Chamber Plan

Figure 5.4 shows the reverberation chamber located in the Measurement, Materials and & Sustainable Environment Center (M2SEC) includes two adjacent, acoustically reverberant rooms with a 1.22-meter (4-feet) wide by 2.44-meter (8-feet) high opening between two rooms.

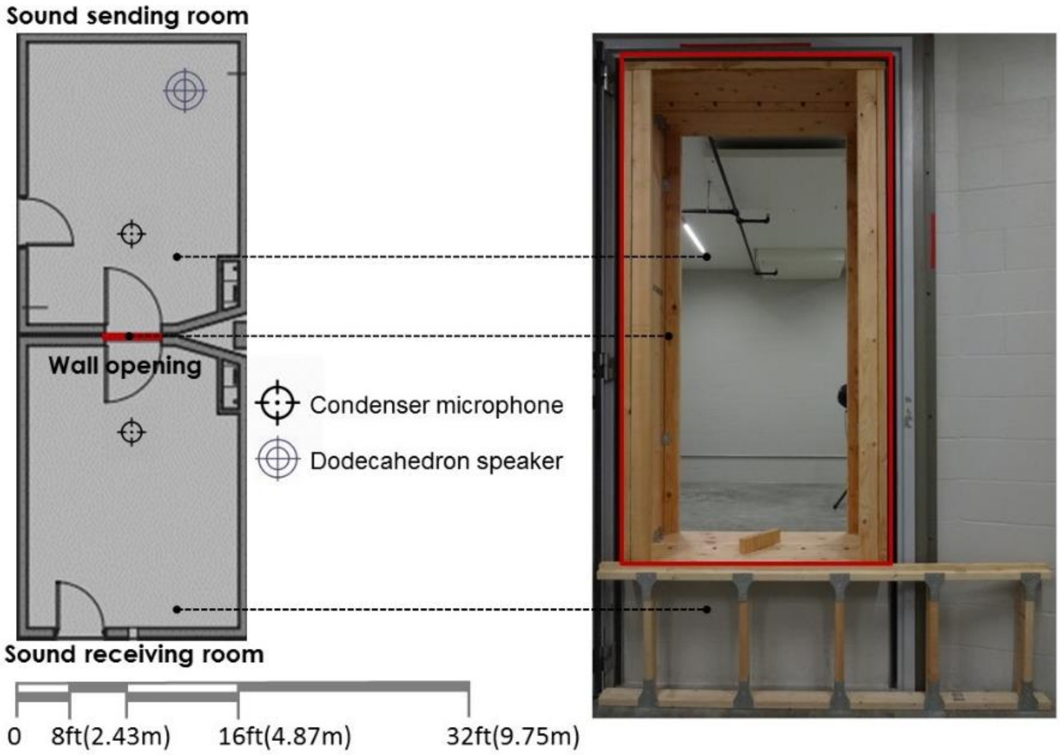


Figure 5.4 Reverberation chamber plan

The space is designed to measure the TL (or NR) and to evaluate the NR qualities of new materials and/or new noise reduction schemes. The difference in the measured SPL is described as the TL (or NR) on which the panel the STC or NIC rating is based.

DSF Mock-up Construction

The DSF mock-up is a hypothetically-designed box-window air cavity which is suitable for noisy environments. Figure 5.5 shows that the basic structures are made of 6.35-centimeter (2.5-inch) thick wood frames, and each element is connected with bolts. Two pieces of 0.635-centimeter (0.25-inch) thick glass were installed as the inner and outer glass layers which formed the air cavity of the DSF. Duct sealant and glass fiber were used to fill joint gaps to minimize sound leakage. The shading louvers are heat-treated pine fir measuring 22.86-centimeter (9-inch) wide and 6.35-centimeter (2.5-inch) thick. Five louvers were installed for testing in the vertical orientation and 10 louvers for testing in the horizontal orientation.

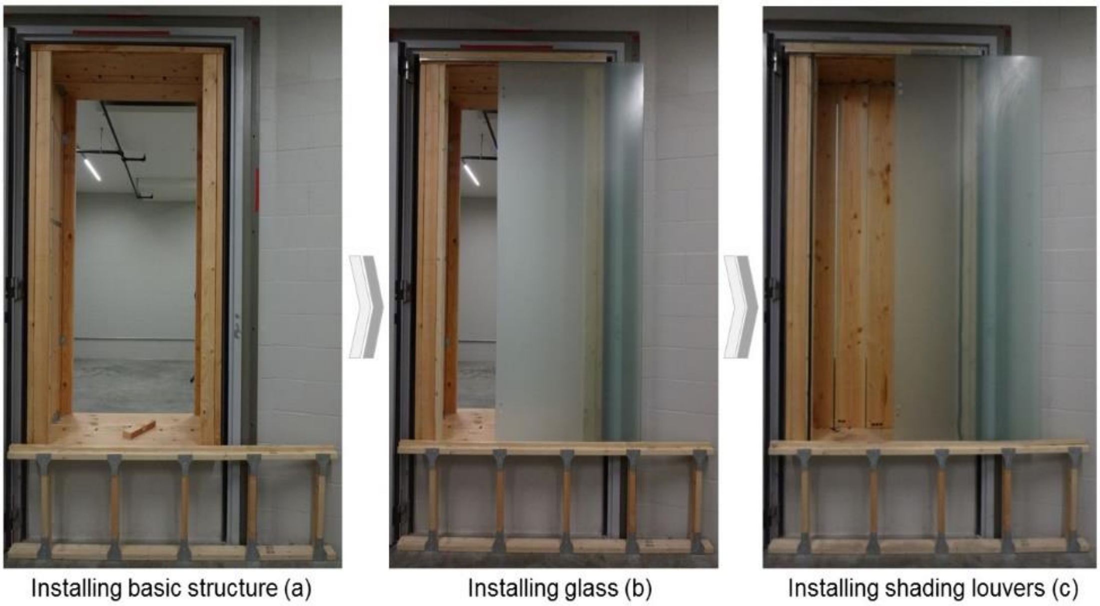


Figure 5.5 DSF mock-up construction of structure (a), glass (b), and shading louvers (c)

Shading Louvers and Air Vents

Figure 5.6 shows test cases of vertical and horizontal shading louvers tilted at a 90 degree angle, in closed position. Depending on test cases, they are also designed to be tilted at

0, 30, and 60 degree angles. Three air vents used for the DSF mock-up are about 60% of free area perforated steel louvers with 25 (10-inch) centimeters by 25-centimeters (10-inch).

Vertical solid wood shading louvers (a)   Horizontal solid wood shading louvers (b)

Figure 5.6 Vertical (a) and horizontal (b) shading louvers tilted at a 90 degree angle

Figure 5.7 shows test cases of vertical and horizontal solid wood shading louvers covered with 1.6-milimeter (0.0625-inch) fabric which can be oriented at a 0 degree angle which are perpendicular to inner and outer glass. This fabric is commercially named for Guilford of Maine Basketweave Fabric was produced by Acoustical Solutions. Its Noise Reduction Coefficient (NRC), which is an index of the amount of sound energy absorbed upon striking a particular surface, is 0.005.

Vertical shading louvers with fabric (a) Horizontal shading louvers with fabric (b)

Figure 5.7 Vertical (a) and horizontal shading louvers (b) wrapped with fabric tilted at a 0 degree angle

5.2.4 DSF Mock-up Test Settings

Phase I

The experimental measurement was conducted according to the ASTM E90-02. Figure 5.8 shows the locations of the air vents and shading louvers. The dodecahedron loudspeaker and condenser microphones were situated at 1.5-meter (4.92-feet) above the floor in the sound sending and sound receiving rooms. The average of A-weighted continuous sound levels in dB (A) of each case was obtained from four measurements of 30 seconds each at four different locations.

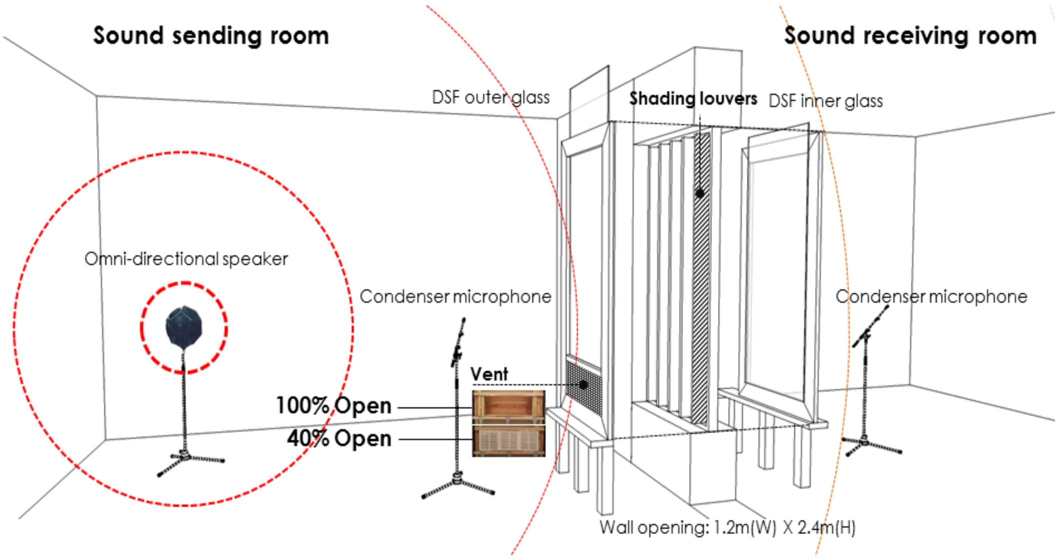


Figure 5.8 DSF mock-up setting for shading louvers as noise barriers

The DSF mock-up settings of Phase I as shown in Figure 5.9 were aimed to evaluate the relationship between the percentage of air vent open surface area and NR based on shading louver orientation. It was designed to investigate the NR values under the conditions of 100% and 40% of air vent open surface area and 0, 30, 60, and 90 degree angle of shading louvers.

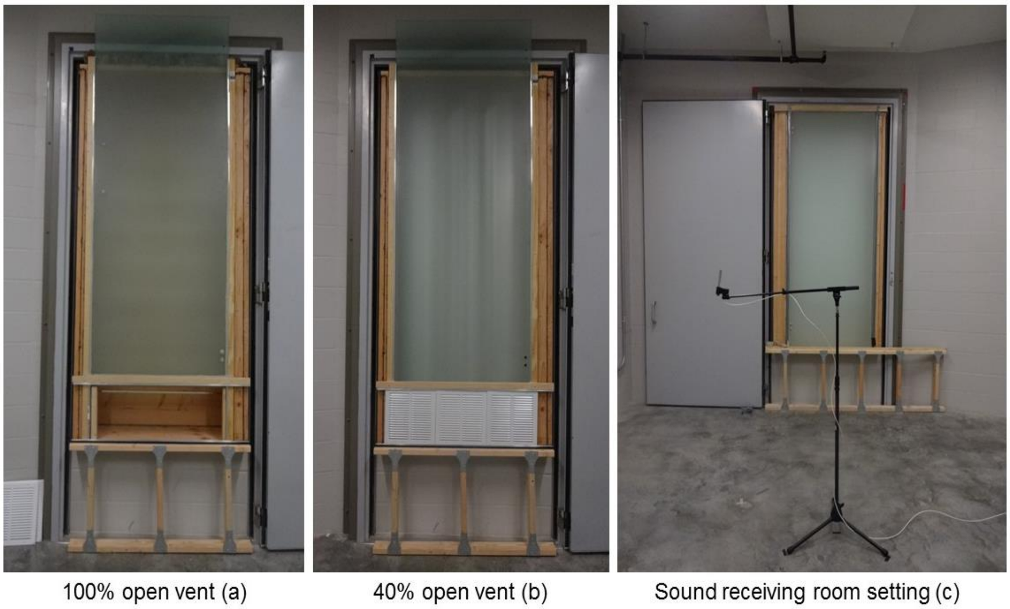


Figure 5.9 DSF mock-up setting of the sound sending (a,b) and receiving room (c)

Phase II

Phase II was also performed in accordance with the ASTM E90-2. Compact silencers, which are typically used in high volume fans and air handling units, were applied to the outer and inner glasses of the DSF. The testing and measurement set up was the same as those used in Phase I.

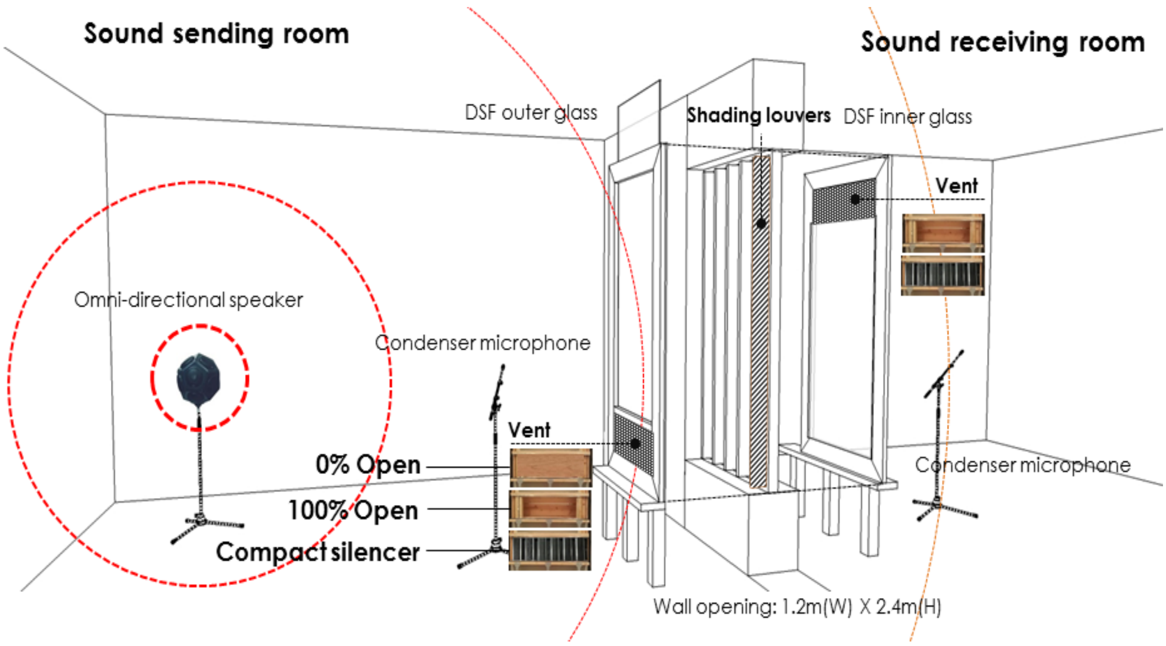


Figure 5.10 DSF mock-up setting for compact silencers as ventilation openings and acoustic barriers

The aim of this DSF mock-up setting as shown in Figure 5.11 was to test the acoustic performance of the compact silencers which replaced the existing DSF air vents. The ventilation openings were situated at the bottom of the outer glass and the top of the inner glass. Three ventilation cases were tested, 100% open surface area, 0% open surface area (closed), and compact silencers.

Figure 5.11 Vent types on inner glass (a) and outer glass (b)

5.2.5 Test Case

Shading louver orientation as noise barriers

Phase I was comprised of 36 cases which studied the relationship of the following variables on noise reduction: open surface area of air vent and the orientation and surface material of the shading louvers.

Table 5.7 shows the 18 cases for vertical shading louvers. The objective was not only to compare the NR between open with grilles and without grilles, but also to evaluate the acoustic performance of the DSF based on the orientation and surface materials of the shading louvers as a noise barrier in relation to the NR values. Table 5.8 shows 18 cases for horizontal shading louvers. The reason for comparing the NR between vertical and horizontal shading louvers was because the preliminary CFD simulation study on ventilation performance showed different outcomes for air temperature, air velocity, and airflow caused by the horizontal and vertical shading louvers.

Table 5.7 Test cases for vertical shading louvers

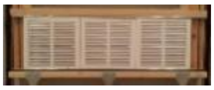
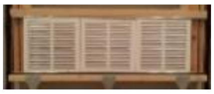
Test case	Air vents Grille application	Vertical shading louvers	
		Orientation	Surface material
Case 1		No shading louvers	
Case 2	 Open with grilles	0 degree angle	38 mm (1.5") thick timber
Case 3		30 degree angle	
Case 4		60 degree angle	
Case 5		90 degree angle	
Case 6		0 degree angle	1.6 mm (0.625") thick Fabric
Case 7		30 degree angle	
Case 8		60 degree angle	
Case 9		90 degree angle	
Case 10		No shading louvers	
Case 11	 Open without grilles	0 degree angle	38 mm (1.5") thick timber
Case 12		30 degree angle	
Case 13		60 degree angle	
Case 14		90 degree angle	
Case 15		0 degree angle	1.6 mm (0.625") thick Fabric
Case 16		30 degree angle	
Case 17		60 degree angle	
Case 18		90 degree angle	

Table 5.8 Test cases for horizontal shading louvers

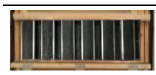
Test case	Air vents Grille application	Horizontal shading louvers	
		Orientation	Surface material
Case 19		No shading louvers	
Case 20	 Open with grilles	0 degree angle	38 mm (1.5") thick timber
Case 21		30 degree angle	
Case 22		60 degree angle	
Case 23		90 degree angle	
Case 24		0 degree angle	1.6 mm (0.625") thick Fabri
Case 25		30 degree angle	
Case 26		60 degree angle	
Case 27		90 degree angle	
Case 28		No shading louvers	
Case 29	 Open without grilles	0 degree angle	38 mm (1.5") thick timber
Case 30		30 degree angle	
Case 31		60 degree angle	
Case 32		90 degree angle	
Case 33		0 degree angle	1.6 mm (0.625") thick fabric
Case 34		30 degree angle	
Case 35		60 degree angle	
Case 36		90 degree angle	

Compact silencers as ventilation openings and acoustic barriers

The scenarios of Phase II as shown in Table 5.9 are comprised of 12 cases. The tested ventilation cases were 100% open, compact silencer, and 0% open depending on seasonal methods of operating a DSF. The DSF settings for Case 1 through Case 8 were designed to represent ventilation performance during hot and intermediate seasons. In contrast, settings for Case 9 to Case 12 were designed to represent the cold season.

Compact silencers are typically used for noise control in air duct systems, but for this study they were applied to the ventilation openings of a building enclosure. In terms of shading louver orientation, only a 0 degree angle (open mode) and 90 degree angle (close mode) were tested because it was found there was only a slight significance in the relationship between the TL (or NR) and shading louver orientation by 30 and 60 degree angle according to the outcomes of the mock-up Phase I.

Table 5.9 Test cases by vent combinations

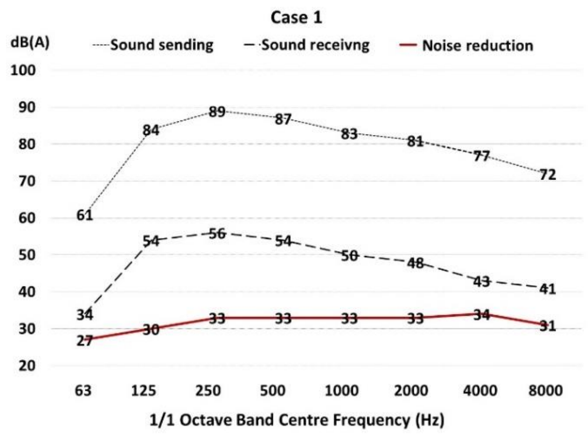
Test case	Air vent position		
	Outer glass side	Inner glass side	Orientation
Case 1	 Open	 Open	0 degree angle
Case 2			90 degree angle
Case 3	 Open	 Compact silencer	0 degree angle
Case 4			90 degree angle
Case 5	 Compact silencer	 Open	0 degree angle
Case 6			90 degree angle
Case 7	 Compact silencer	 Compact silencer	0 degree angle
Case 8			90 degree angle
Case 9	 Closed	 Open	0 degree angle
Case 10			90 degree angle
Case 11	 Closed	 Compact silencer	0 degree angle
Case 12			90 degree angle

5.3 Results and Discussions

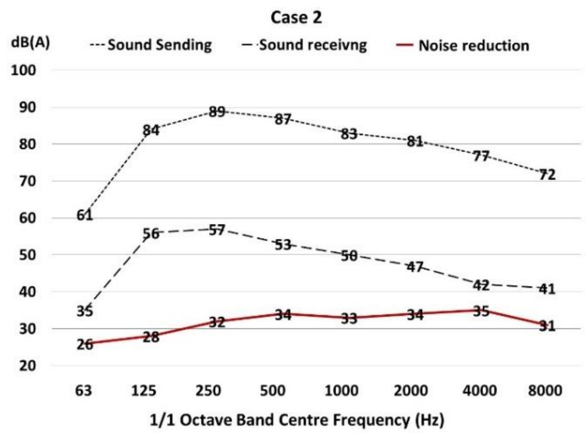
5.3.1 Shading Louvers Orientation as Noise Barriers

The graphs in Figure 5.12 show the SPL values for the sound sending and receiving rooms and the NR values for the first 18 cases. The NR simply refers to the difference in SPL between the sound sending room and receiving room. The experimental data of Phase I implied the DSF mock-up itself achieved the overall NR value across the entire octave band center frequency by 33 to 37 dB(A) when sending sound source with a pink noise spectrum is 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 was 3 to 4 dB(A) across 1/1 octave band center frequency than at 0 degree angle such as Cases 2, 6, 11, 15, 20, 24, 29, and 33. In particular, it was found that the horizontal shading louver achieved higher level of NR by 4 to 9 dB (A) at high frequency (4000 Hz) compared to low frequency (125 Hz). In Cases 5, 9, 14 and 18 with shading louvers tilted at a 90 degree angle, the maximum difference of the NR values between 125Hz and 4000Hz was 9, 8, 8, and 8 dB(A) respectively.

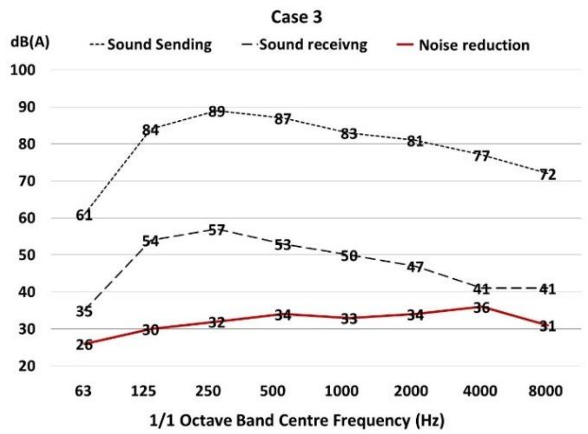
Case 1 (no shading louvers)



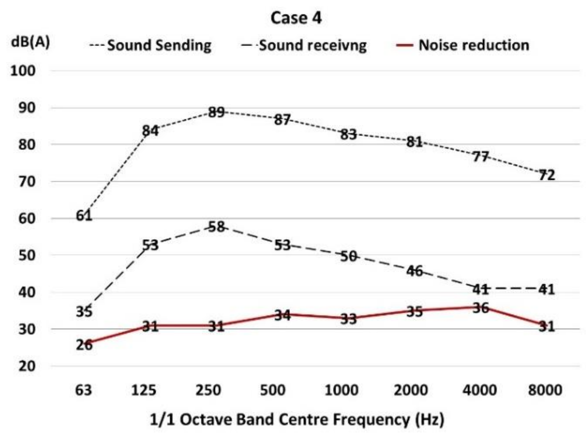
Case 2 (w/grilles, solid, 0 degree angle)



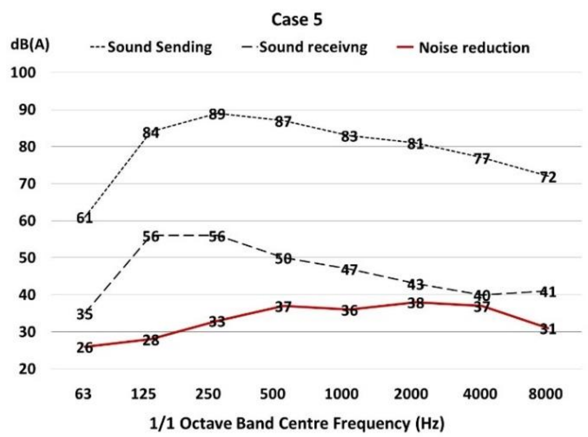
Case 3 (w/grilles, solid, 30 degree angle)



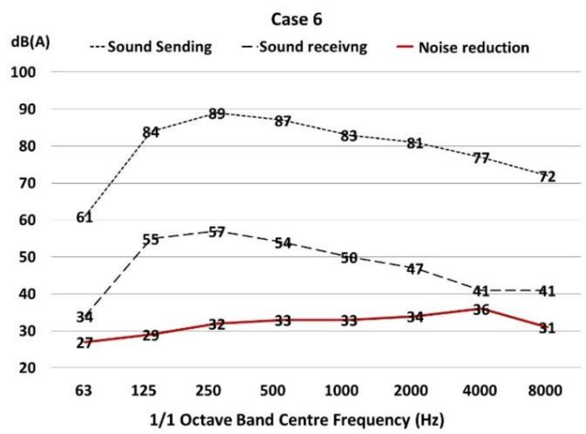
Case 4 (w/grilles, solid, 60 degree angle)

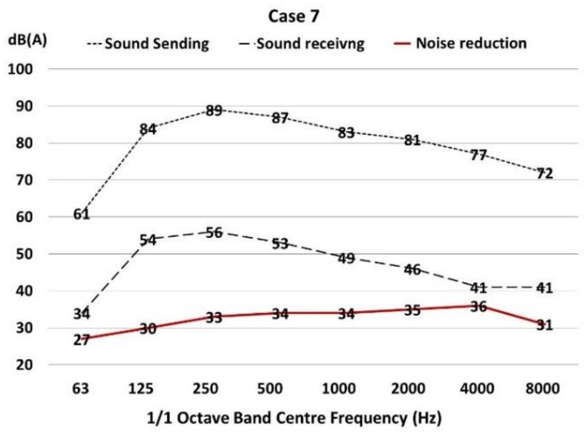
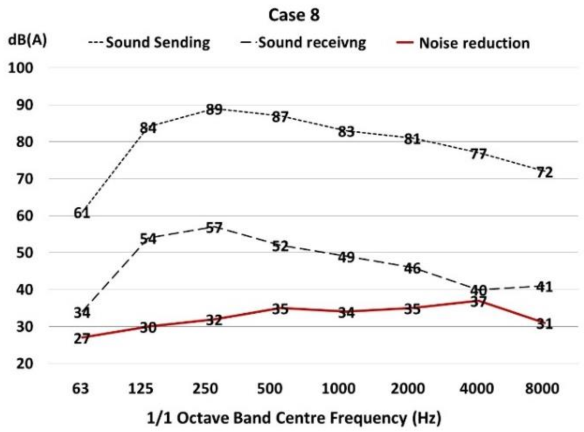
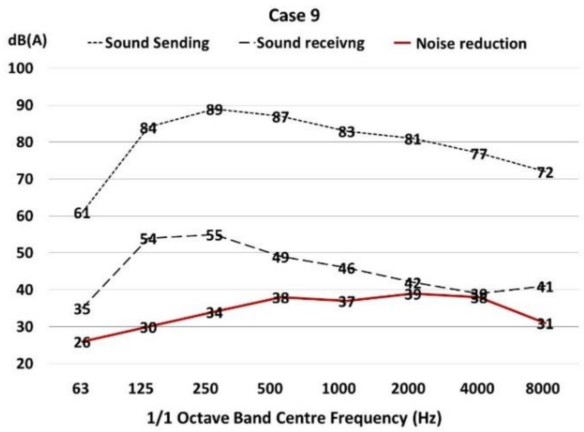
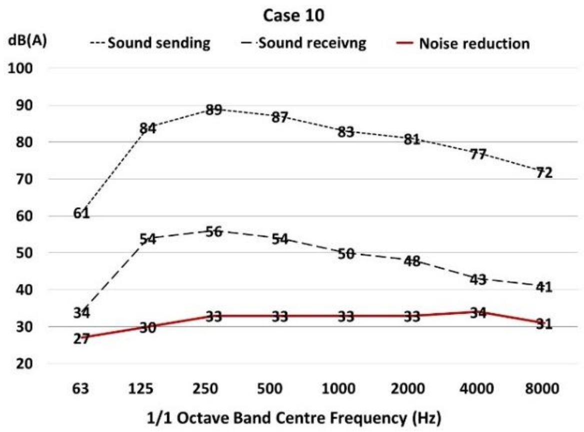
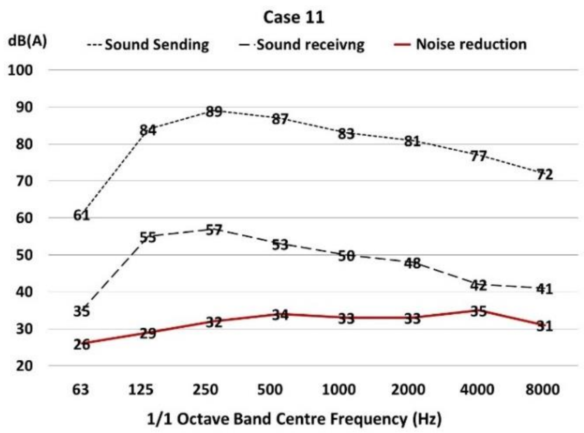
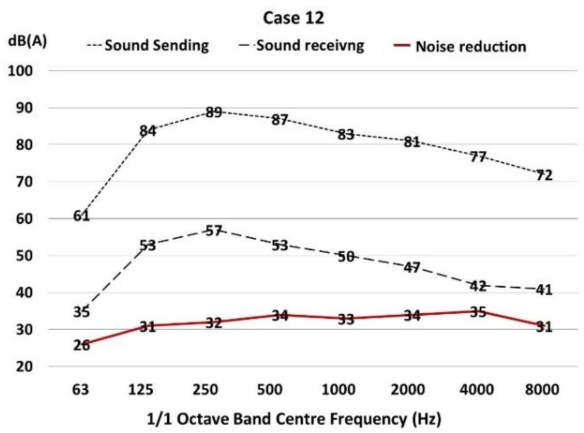


Case 5 (w/grilles, solid, 90 degree angle)

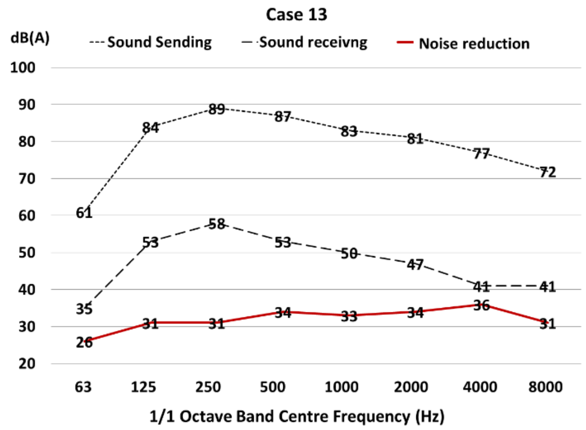


Case 6 (w/grilles, fabric, 0 degree angle)

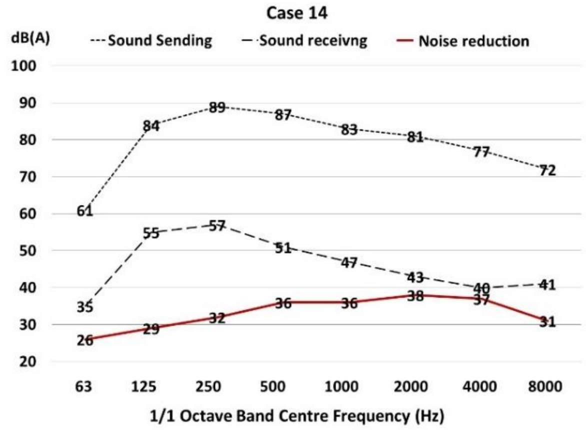


Case 7 (w/grilles, fabric, 30 degree angle)	Case 8 (w/grilles, fabric, 60 degree angle)
	
Case 9 (w/grilles, fabric, 90 degree angle)	**Case 10 (no shading louvers)**
	
Case 11 (w/o grilles, solid, 0 degree angle)	**Case 12 (w/o grilles, solid, 30 degree angle)**
	

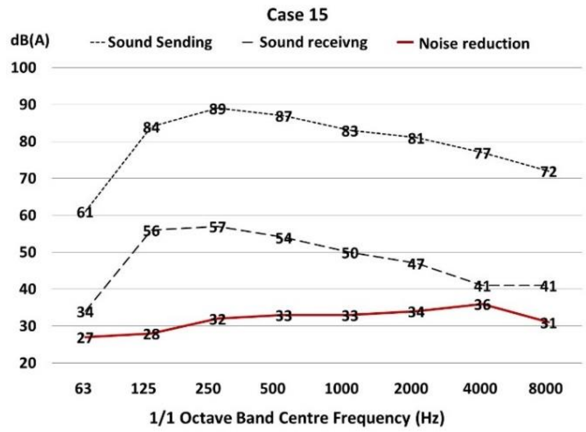
Case 13 (w/o grilles, solid, 60 degree angle)



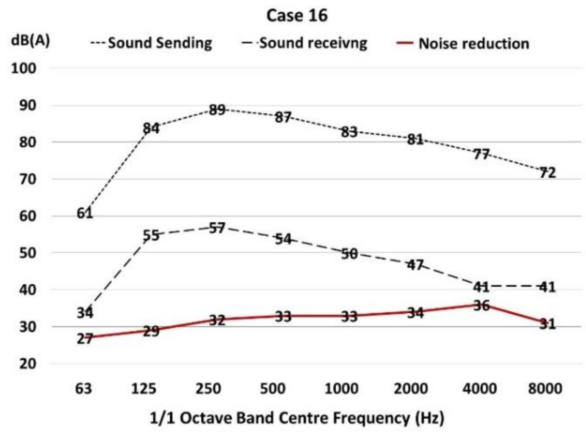
Case 14 (w/o grilles, solid, 90 degree angle)



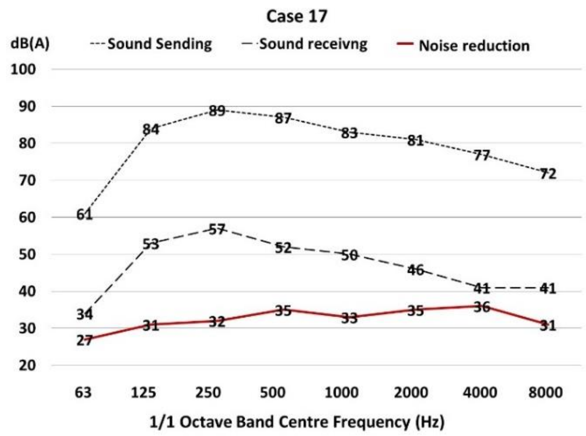
Case 15 (w/o grilles, fabric, 0 degree angle)



Case 16 (w/o grilles, fabric, 30 degree angle)



Case 17 (w/o grilles, fabric, 60 degree angle)



Case 18 (w/o grilles, fabric, 90 degree angle)

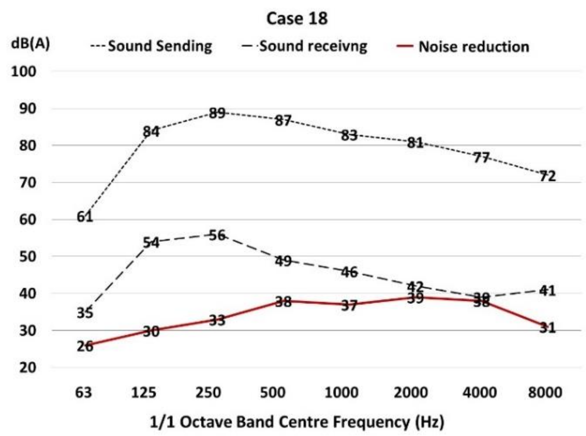
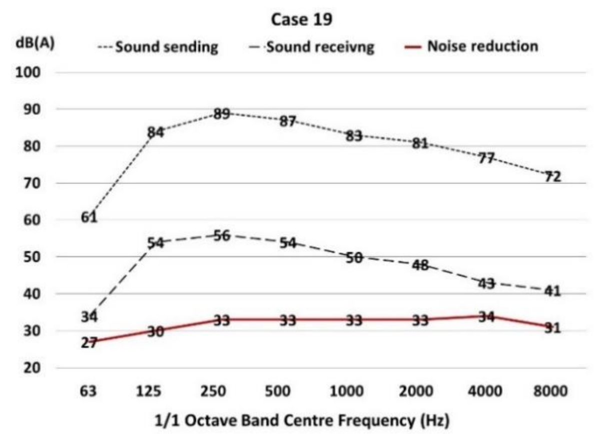


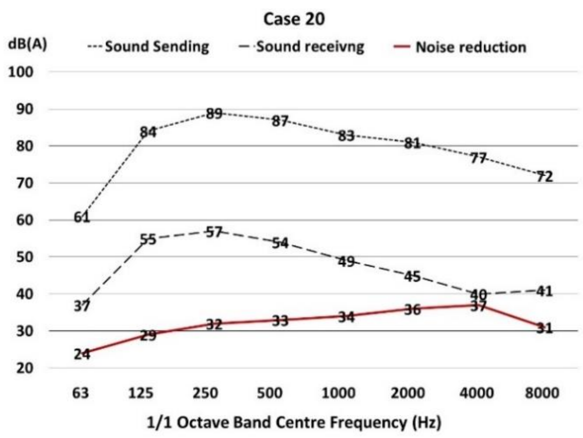
Figure 5.12 NR values based on air vent and vertical shading louver orientation

The graphs in Figure 5.13 show the SPL values for the sound sending and receiving rooms and the NR values for the remaining 18 cases. The DSF mock-up tests with horizontal shading louvers also achieved NR of 33 to 37 dB (A) when sending sound source with a pink noise spectrum is 89 dB (A). When vertical shading louvers are oriented at a 90 degree angle such as Cases 23, 27, 32 and 36, the overall NR was 3 to 4 dB(A) across 1/1 octave band center frequency compared to cases tilted at 0 degree angle. In particular, it was observed that the horizontal shading louver achieved higher level of NR by 4 to 9 dB (A) at high frequency (4000 Hz) compared to low frequency (125 Hz). In Cases 23, 27, 32 and 36 with shading louvers tilted at a 90 degree angle, the maximum difference of NR values between 125Hz and 4000Hz was 7, 8, 7, and 8 dB(A) respectively.

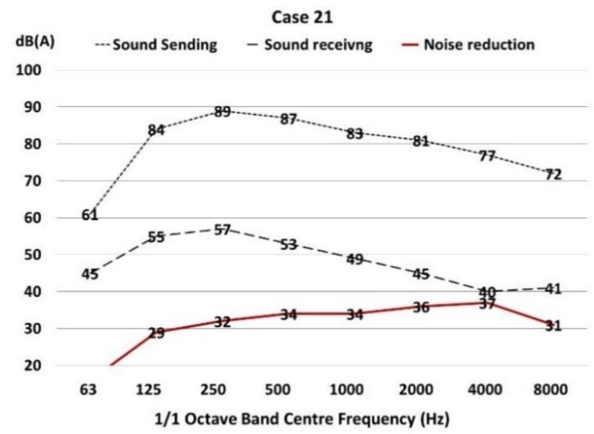
Case 19 (no shading louvers)



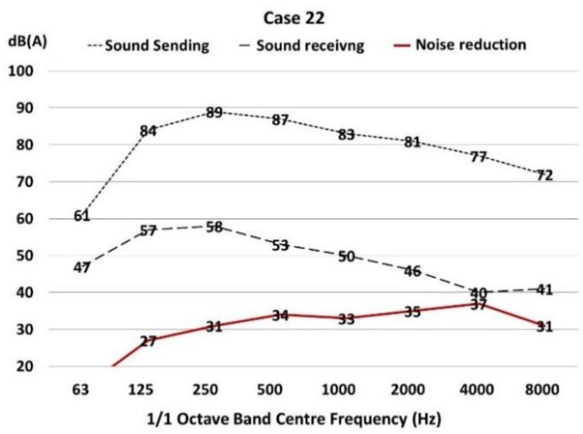
Case 20 (w/ grilles, solid, 0 degree angle)

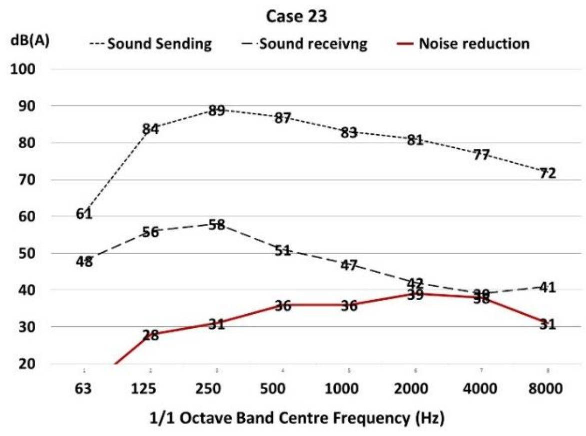
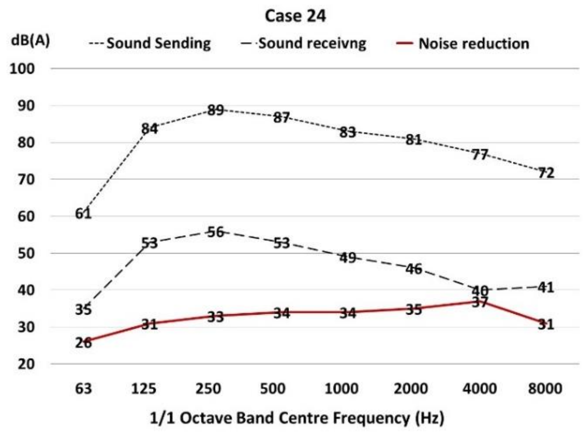


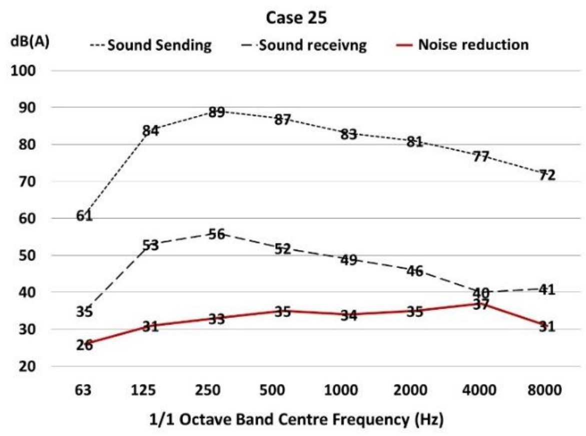
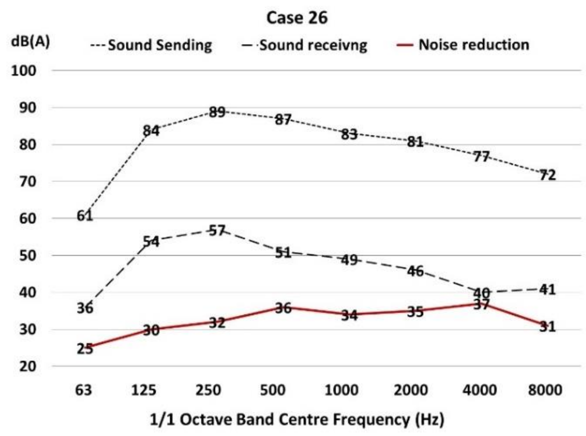
Case 21 (w/ grilles, solid, 30 degree angle)

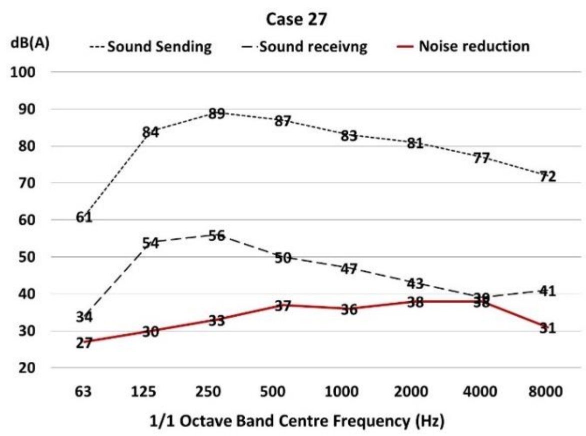
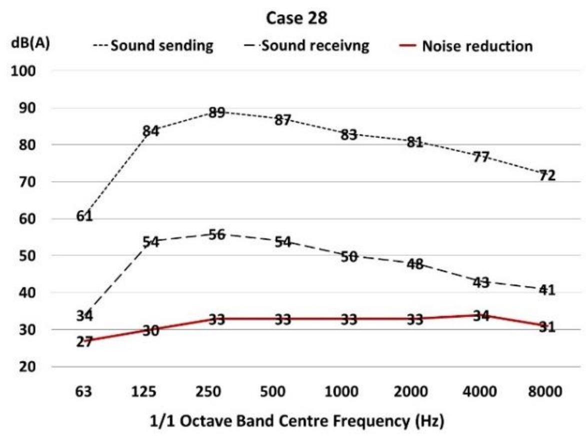


Case 22 (w/ grilles, solid, 60 degree angle)

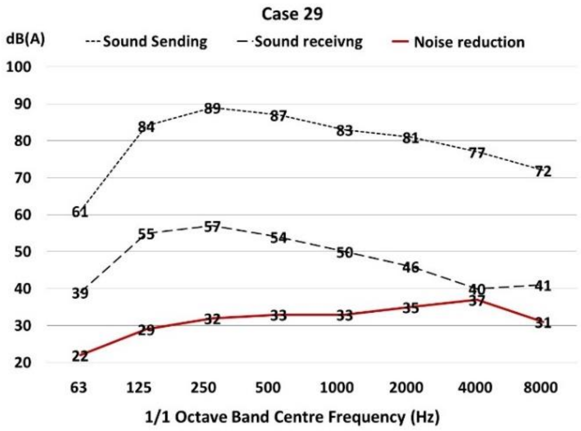


Case 23 (w/ grilles, solid, 90 degree angle)	Case 24 (w/ grilles, fabric, 0 degree angle)
	

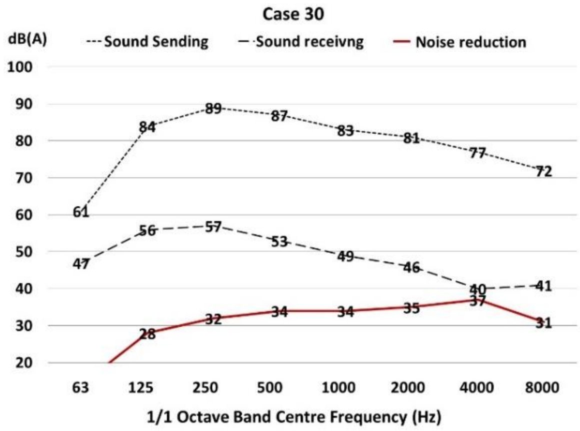
Case 25 (w/ grilles, fabric, 30 degree angle)	Case 26 (w/ grilles, fabric, 60 degree angle)
	

Case 27 (w/ grilles, fabric, 90 degree angle)	Case 28 (no shading louvers)
	

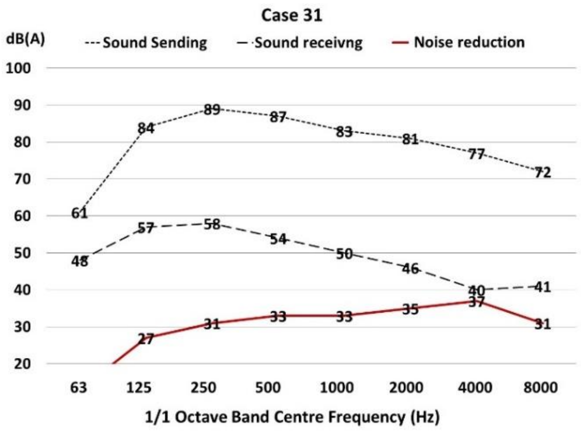
Case 29 (w/o grilles, solid, 0 degree angle)



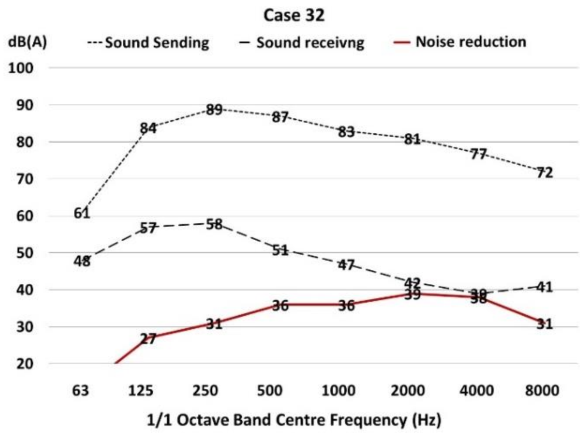
Case 30 (w/o grilles, solid, 30 degree angle)



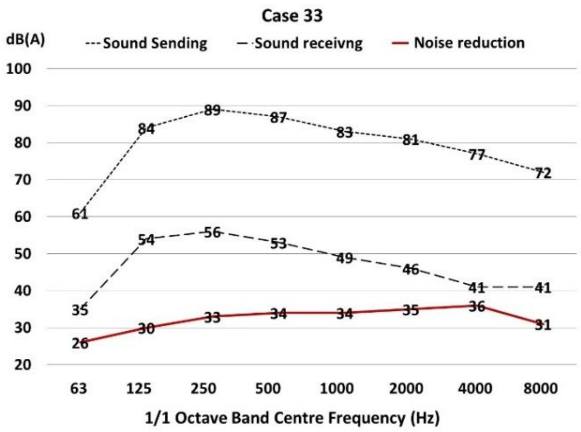
Case 31 (w/o grilles, solid, 60 degree angle)



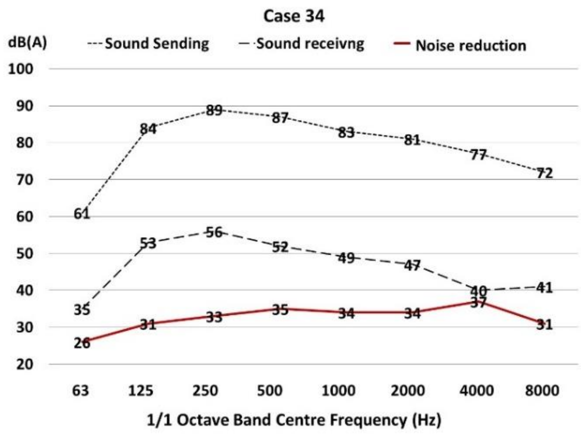
Case 32 (w/o grilles, solid, 90 degree angle)



Case 33 (w/o grilles, fabric, 0 degree angle)



Case 34 (w/o grilles, fabric, 30 degree angle)



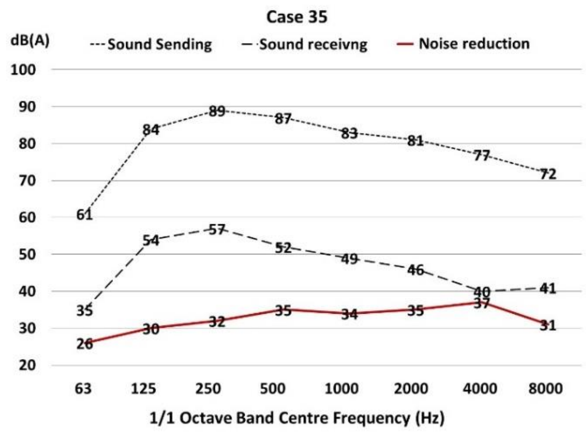
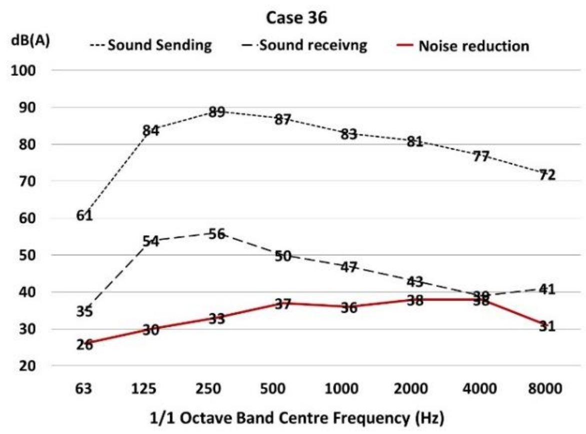
Case 35 (w/o grilles, fabric, 60 degree angle)	Case 36 (w/o grilles, fabric, 90 degree angle)
	

Figure 5.13 NR values based on air vent and horizontal shading louver orientation

Figures 5.14 and 5.15 show the SPL differences between open with grilles (a) and without grilles (b) with vertical shading louvers. No difference was found in NR regardless of percentage of air vent open surface area even though the porosity of air vents affected air temperature, air velocity, and airflow patterns inside DSFs as shown in the preliminary simulation study of Chapter 4.

Figure 5.16 shows NR values across 1/1 octave band center frequency. When shading louvers are oriented at a 90 degree angle which is closed position, NR values at mid- and high-frequency was high by 3 to 6 dB (A). However, there is no significant effect of NR in low-frequency which is associated with noise annoyance by traffic noise at 125 Hz.

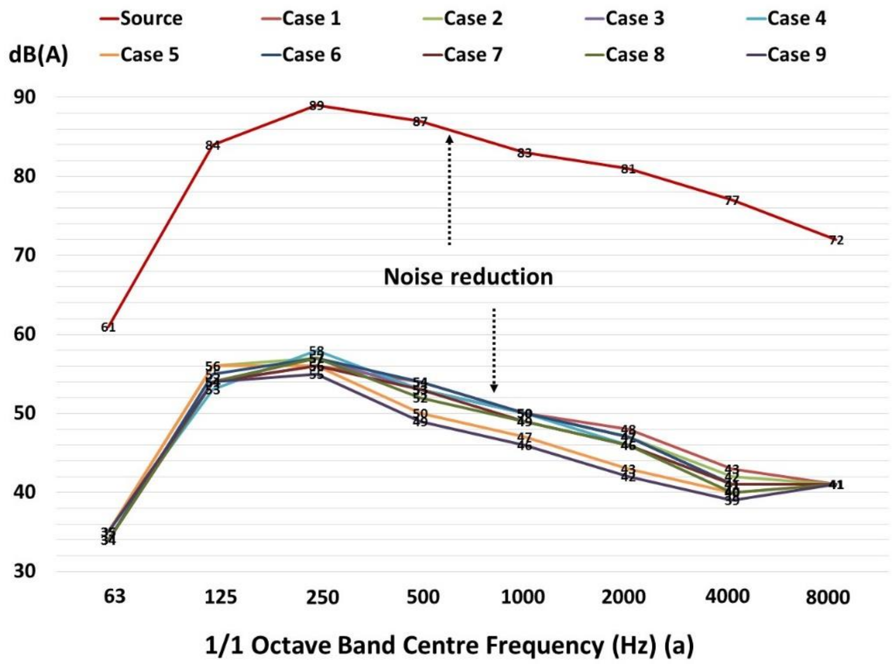
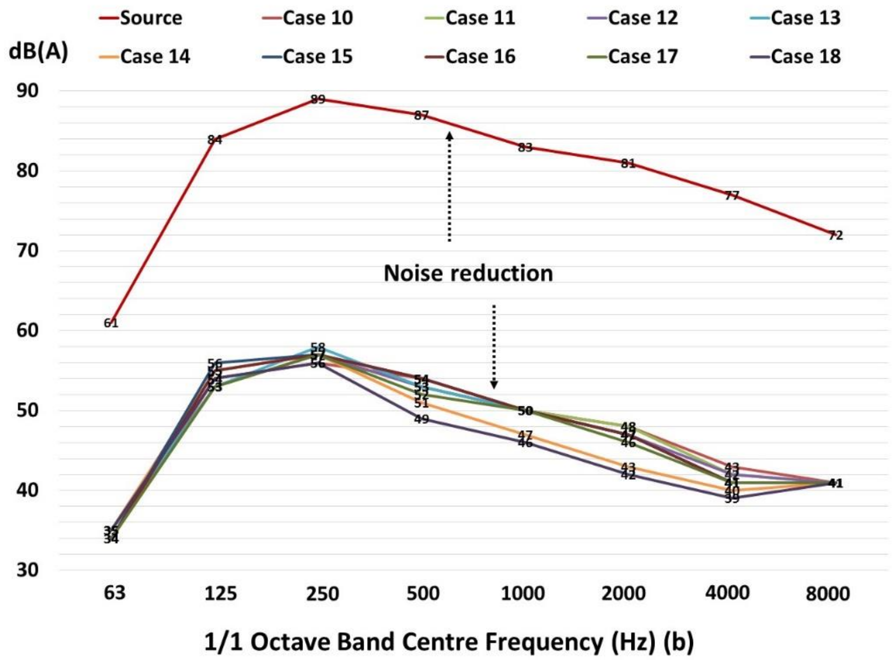
<table>
<tr><th>Air vent open surface area</th><th>Sound Pressure Level</th></tr>
<tr><td>Open with grilles</td><td>
</td></tr>
<tr><td>Open without grilles</td><td>
</td></tr>
</table>

Figure 5.14 SPL and NR for vertical shading louver cases with open with grilles (a) and without grilles (b)

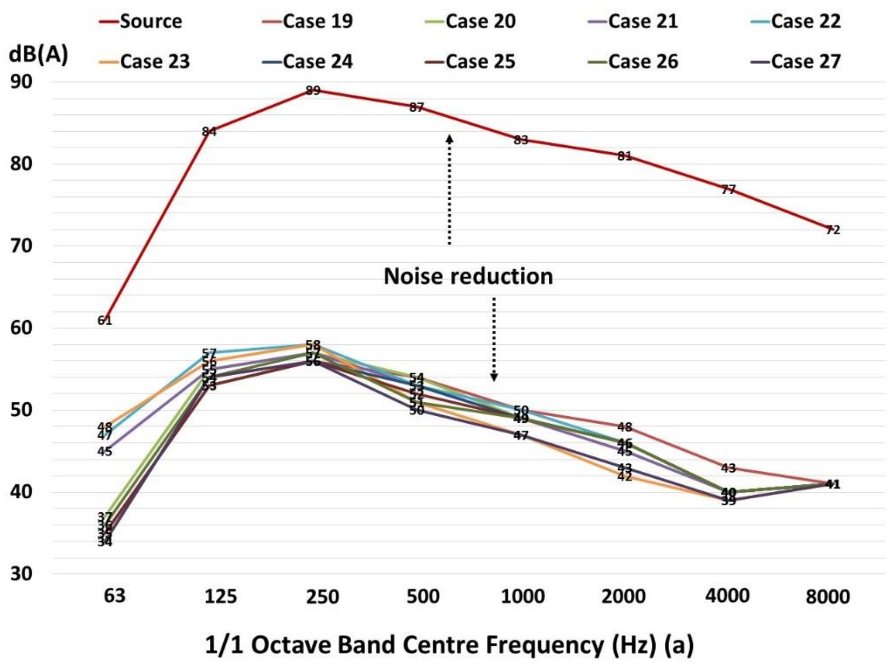
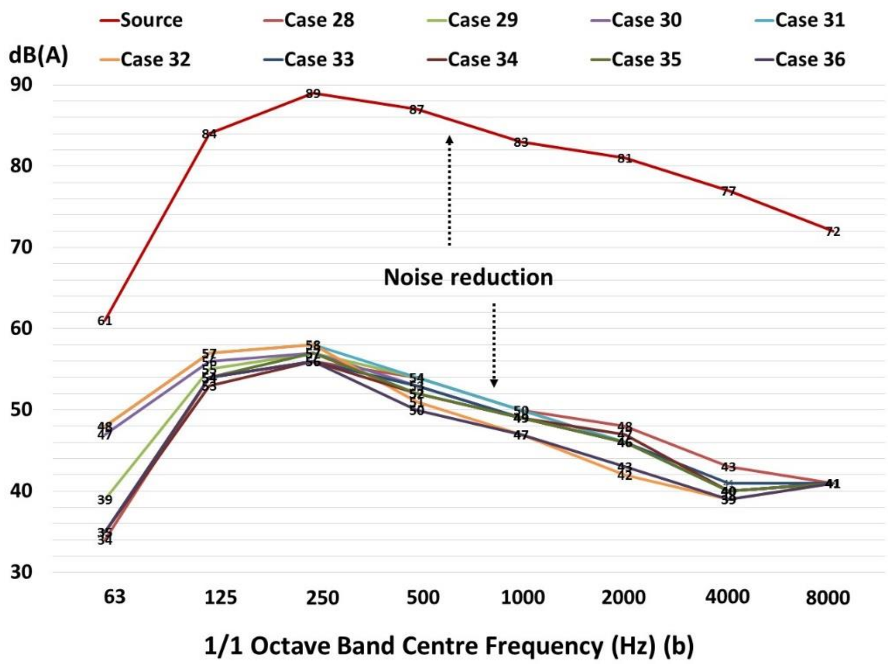
<table>
<tr><th>Air vent open surface area</th><th>Sound Pressure Level</th></tr>
<tr><td>Open with grilles</td><td>
</td></tr>
<tr><td>Open without grilles</td><td>
</td></tr>
</table>

Figure 5.15 SPL and NR for open with grilles (a) and without grilles (b) for horizontal shading louvers

Case	Condition	NR dB(A)	NR values (1/1 octave band center frequency (Hz))							
			63	125	250	500	1000	2000	4000	8000
Case 1	No shading louvers	0	0	0	0	0	0	0	0	0
Case 2	w/grilles, V-solid, 0°	0	-1	-2	-1	1	0	1	1	0
Case 3	w/grilles, V-solid, 30°	0	-1	0	-1	1	0	1	2	0
Case 4	w/grilles, V-solid, 60°	1	-1	1	-2	1	0	2	2	0
Case 5	w/grilles, V-solid, 90°	3	-1	-2	0	4	3	5	3	0
Case 6	w/grilles, V-fabric, 0°	0	0	-1	-1	0	0	1	2	0
Case 7	w/grilles, V-fabric, 30°	1	0	0	0	1	1	2	2	0
Case 8	w/grilles, V-fabric, 60°	1	0	0	-1	2	1	2	3	0
Case 9	w/grilles, V-fabric, 90°	4	-1	0	1	5	4	6	4	0
Case 10	No shading louvers	0	0	0	0	0	0	0	0	0
Case 11	w/o grilles, V-solid, 0°	0	-7	-4	-1	1	0	0	2	0
Case 12	w/o grilles, V-solid, 30°	0	-7	-2	-1	1	0	1	2	0
Case 13	w/o grilles, V-solid, 60°	1	-7	-2	-2	1	0	1	3	0
Case 14	w/o grilles, V-solid, 90°	3	-7	-4	-1	3	3	5	4	0
Case 15	w/o grilles, V-fabric, 0°	0	-6	-5	-1	0	0	1	3	0
Case 16	w/o grilles, V-fabric, 30°	0	-6	-4	-1	0	0	1	3	0
Case 17	w/o grilles, 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

NR Index
0
1
2
3
4
5
6

Case	Condition	NR dB(A)	NR values (1/1 octave band center frequency (Hz))							
			63	125	250	500	1000	2000	4000	8000
Case 19	No shading louvers	0	0	0	0	0	0	0	0	0
Case 20	w/grilles, H-solid, 0°	1	-3	-1	-1	0	1	3	3	0
Case 21	w/grilles, H-solid, 30°	1	-11	-1	-1	1	1	3	3	0
Case 22	w/grilles, H-solid, 60°	1	-13	-3	-2	1	0	2	3	0
Case 23	w/grilles, H-solid, 90°	3	-14	-2	-2	3	3	6	4	0
Case 24	w/grilles, H-fabric, 0°	1	-1	1	0	1	1	2	3	0
Case 25	w/grilles, H-fabric, 30°	2	-1	1	0	2	1	2	3	0
Case 26	w/grilles, H-fabric, 60°	1	-2	0	-1	3	1	2	3	0
Case 27	w/grilles, 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 grilles, H-solid, 0°	1	-5	-1	-1	0	0	2	3	0
Case 30	w/o grilles, H-solid, 30°	1	-13	-2	-1	1	1	2	3	0
Case 31	w/o grilles, H-solid, 60°	0	-14	-3	-2	0	0	2	3	0
Case 32	w/o grilles, H-solid, 90°	2	-14	-3	-2	3	3	6	4	0
Case 33	w/o grilles, H-fabric, 0°	1	-1	0	0	1	1	2	2	0
Case 34	w/o grilles, H-fabric, 30°	1	-1	1	0	2	1	1	3	0
Case 35	w/o grilles, H-fabric, 60°	1	-1	0	-1	2	1	2	3	0
Case 36	w/o grilles, H-fabric, 90°	3	-1	0	0	4	3	5	4	0

NR Index
0
1
2
3
4
5
6

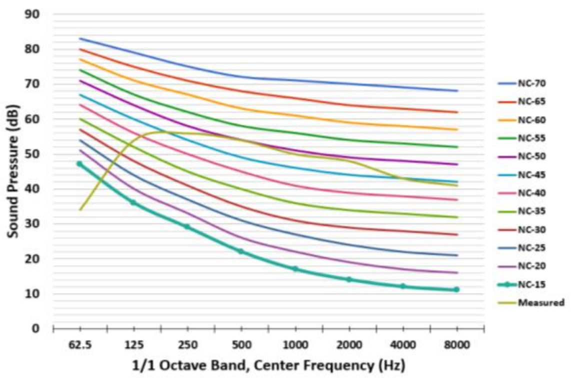
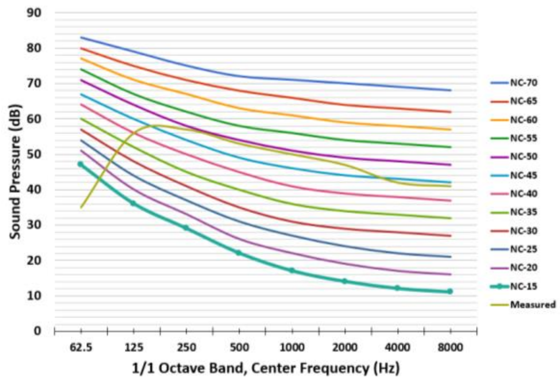
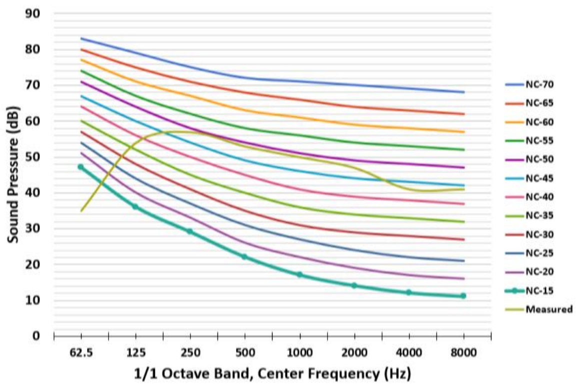
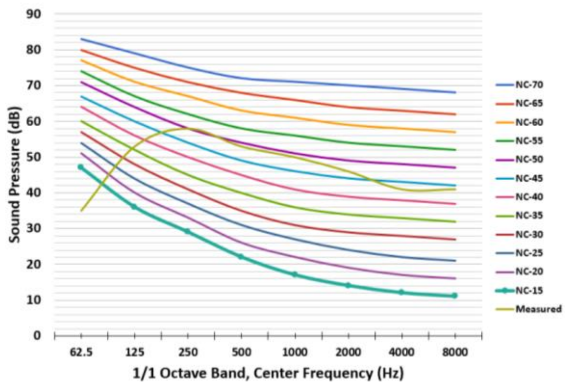
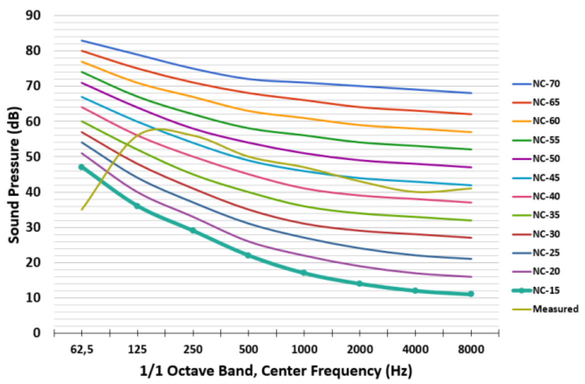
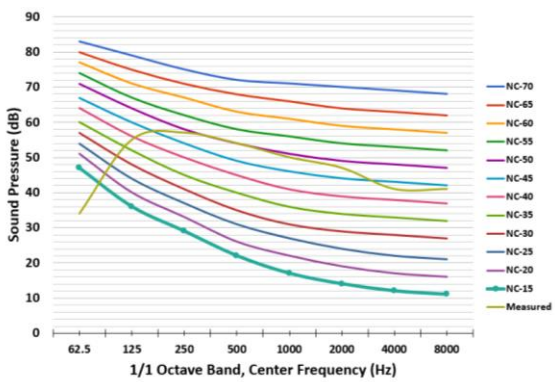
Figure 5.16 NR values across 1/1 octave band center frequency

Table 5.10 shows the NR values across the entire octave band center frequency based on percentage of air vent open surface area, shading louvers covered with fabrics, and shading louver orientation. This data shows that there is no significant difference in the NR between cases of "open with grilles," which are Cases 1 through 9 and Cases 19 through 27, and cases of "open without grilles," which include Cases 10 to 18 and Cases 28 to 36. In addition, applying fabrics to solid wood shading louvers as with Cases 6 to 9, Cases 15 to 18, Cases 27 through 30, and Cases 33 through 36 achieved the NR by 1 dB(A). The fabric applied to the shading louvers did not achieve significant noise reduction. It implies that shading louvers should be built with sound absorbing materials to achieve sufficient NR values.

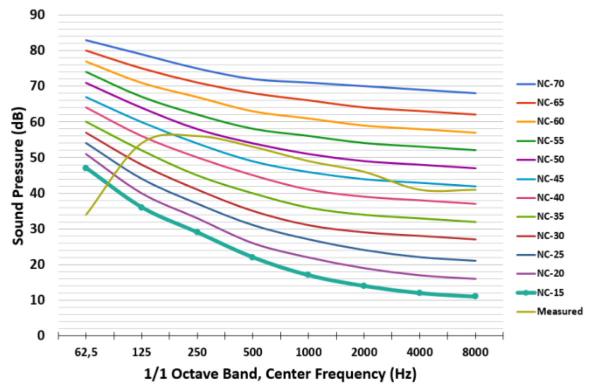
Table 5.10 NR across 1/1 octave band center frequency

Case	NR dB(A)	NR values (1/1 octave band center frequency (Hz))								NC
		63	125	250	500	1000	2000	4000	8000	
Case 1	33	27	30	33	33	33	33	34	31	50
Case 2	33	26	28	32	34	33	34	35	31	49
Case 3	33	26	30	32	34	33	34	36	31	49
Case 4	34	26	31	31	34	33	35	36	31	49
Case 5	**36**	**26**	**28**	**33**	**37**	**36**	**38**	**37**	**31**	**47**
Case 6	33	27	29	32	33	33	34	36	31	50
Case 7	34	27	30	33	34	34	35	36	31	49
Case 8	34	27	30	32	35	34	35	37	31	48
Case 9	**37**	**26**	**30**	**34**	**38**	**37**	**39**	**38**	**31**	**46**
Case 10	33	27	30	33	33	33	33	34	31	50
Case 11	33	26	29	32	34	33	33	35	31	49
Case 12	33	26	31	32	34	33	34	35	31	49
Case 13	34	26	31	31	34	33	34	36	31	49
Case 14	**36**	**26**	**29**	**32**	**36**	**36**	**38**	**37**	**31**	**48**
Case 15	33	27	28	32	33	33	34	36	31	50
Case 16	33	27	29	32	33	33	34	36	31	50
Case 17	34	27	31	32	35	33	35	36	31	49
Case 18	**37**	**26**	**30**	**33**	**38**	**37**	**39**	**38**	**31**	**47**
Case 19	33	27	30	33	33	33	33	34	31	50
Case 20	34	24	29	32	33	34	36	37	31	50
Case 21	34	16	29	32	34	34	36	37	31	49
Case 22	34	14	27	31	34	33	35	37	31	49
Case 23	**36**	**13**	**28**	**31**	**36**	**36**	**39**	**38**	**31**	**49**
Case 24	34	26	31	33	34	34	35	37	31	49
Case 25	35	26	31	33	35	34	35	37	31	48
Case 26	34	25	30	32	36	34	35	37	31	48
Case 27	**37**	**27**	**30**	**33**	**37**	**36**	**38**	**38**	**31**	**47**
Case 28	33	27	30	33	33	33	33	34	31	50
Case 29	34	22	29	32	33	33	35	37	31	50
Case 30	34	14	28	32	34	34	35	37	31	49
Case 31	33	13	27	31	33	33	35	37	31	50
Case 32	**35**	**13**	**27**	**31**	**36**	**36**	**39**	**38**	**31**	**49**
Case 33	34	26	30	33	34	34	35	36	31	49
Case 34	34	26	31	33	35	34	34	37	31	48
Case 35	34	26	30	32	35	34	35	37	31	48
Case 36	**36**	**26**	**30**	**33**	**37**	**36**	**38**	**38**	**31**	**47**

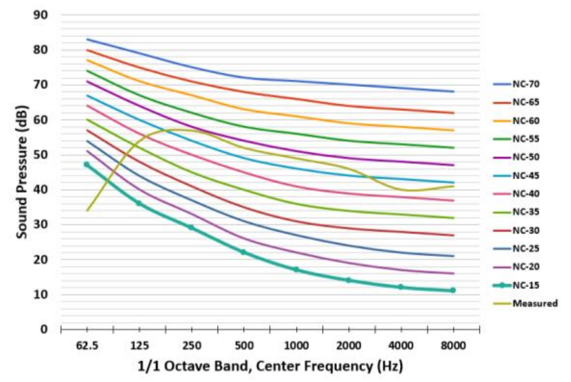
In Table 5.10, it was observed that NC values ranged from 46 to 50 depending on the shading louver's orientation. When shading louvers were oriented at a 90 degree angle (closed position), NC values were the lowest compared to cases with a 0 degree angle (open position) and without shading louvers. Each NC graph was generated as shown in Figure 5.17 and 5.18.

Case 1 (no shading louvers, NC 50)	Case 2 (w/ grilles, solid, 0 degree, NC 49)
	
Case 3 (w/ grilles, solid, 30 degree, NC 49)	**Case 4 (w/ grilles, solid, 60 degree, NC 50)**
	
Case 5 (w/ grilles, solid, 0 degree, NC 47)	**Case 6 (w/ grilles, fabric, 0 degree, NC 50)**
	

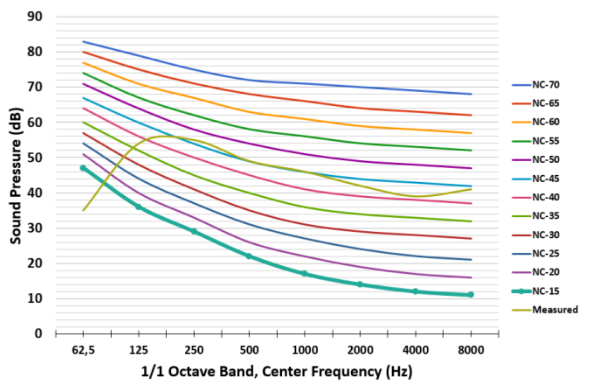
Case 7 (w/ grilles, fabric, 30 degree, NC 49)



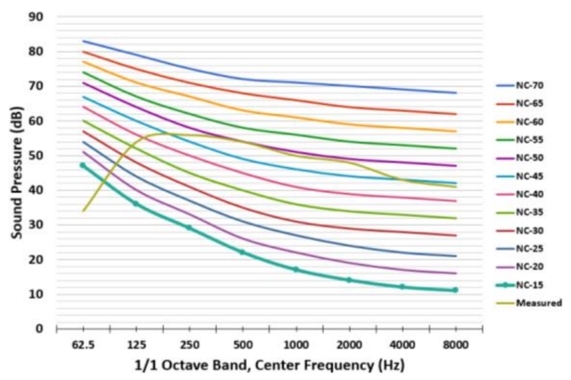
Case 8 (w/ grilles, fabric, 60 degree, NC 48)



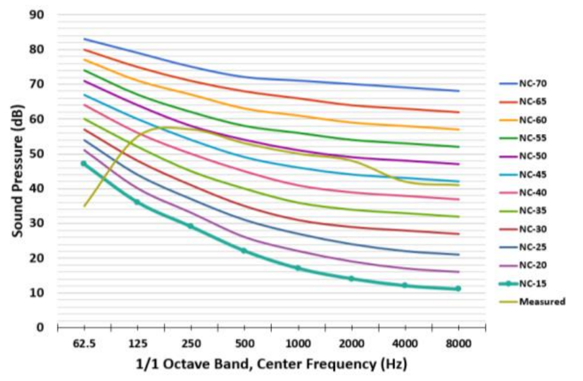
Case 9 (w grilles, fabric, 90 degree, NC 46)



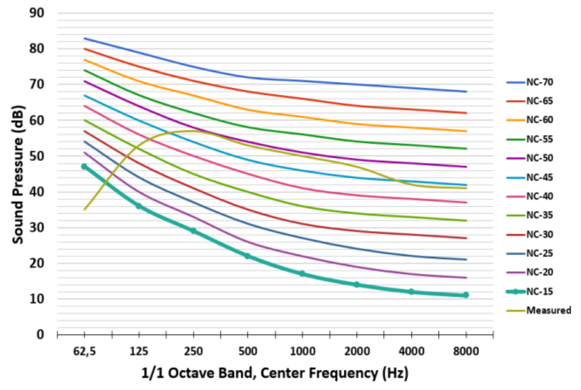
Case 10 (no shading louvers, NC 50)



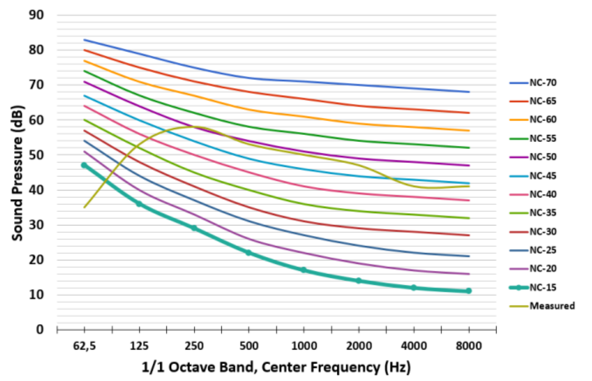
Case 11 (w/o grilles, solid, 0 degree, NC 49)



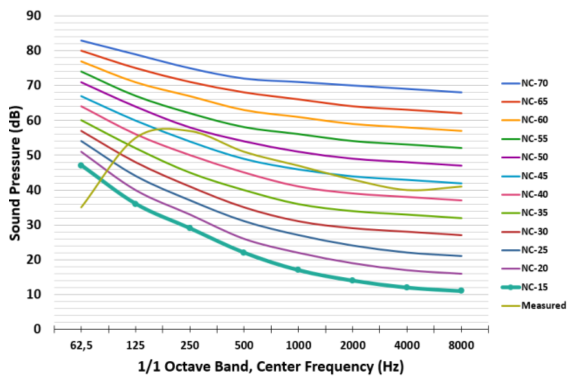
Case 12 (w/o grilles, solid, 30 degree, NC 49)



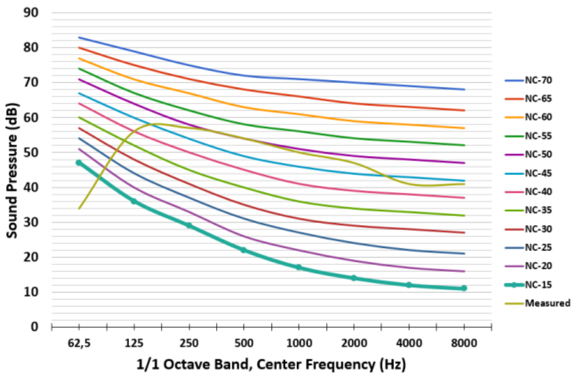
Case 13 (w/o grilles, solid, 60 degree, NC 50)



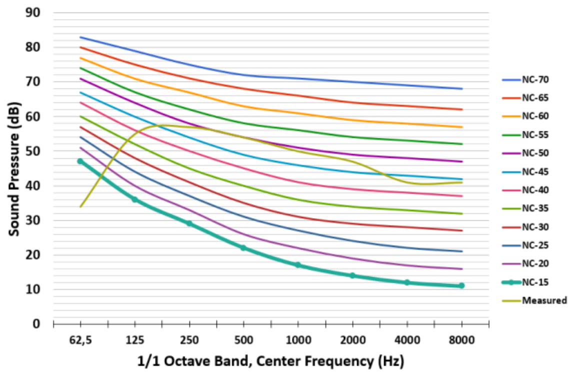
Case 14 (w/o grilles, solid, 90 degree, NC 48)



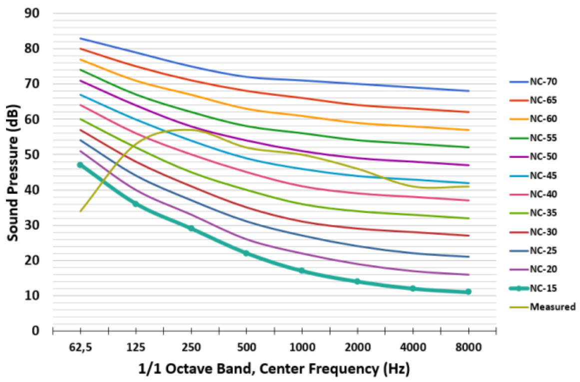
Case 15 (w/o grilles, fabric, 0 degree, NC 50)



Case 16 (w/o grilles, fabric, 30 degree, NC 50)



Case 17 (w/o grilles, fabric, 60 degree, NC 49)



Case 18 (w/o grilles, fabric, 90 degree, NC 47)

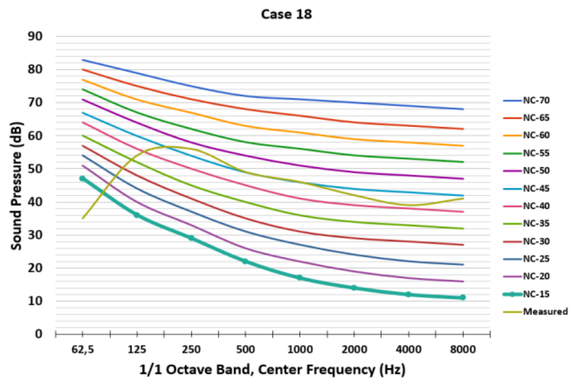
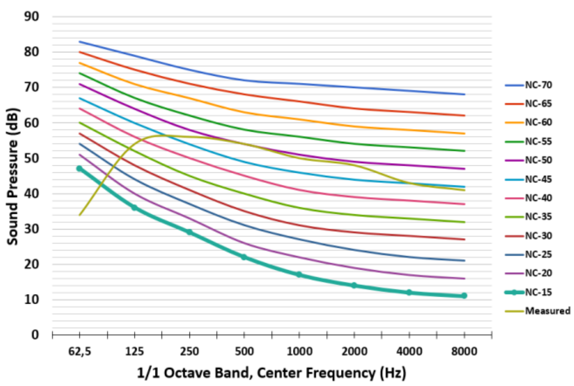
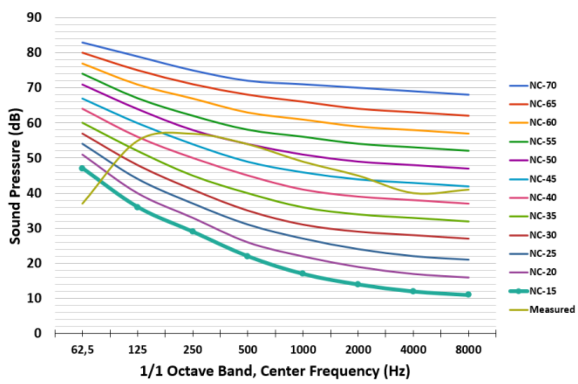


Figure 5.17 NC values based on air vent and vertical shading louver orientation

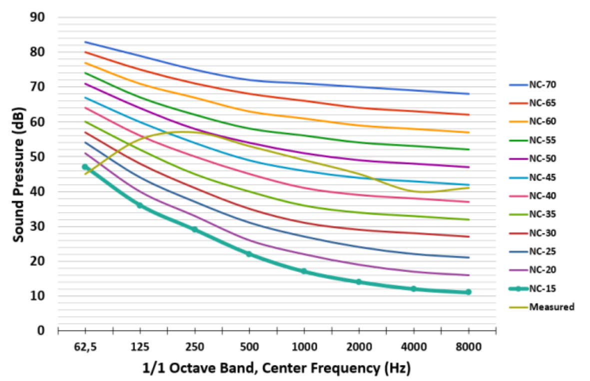
Case 19 (no shading louvers, NC 50)



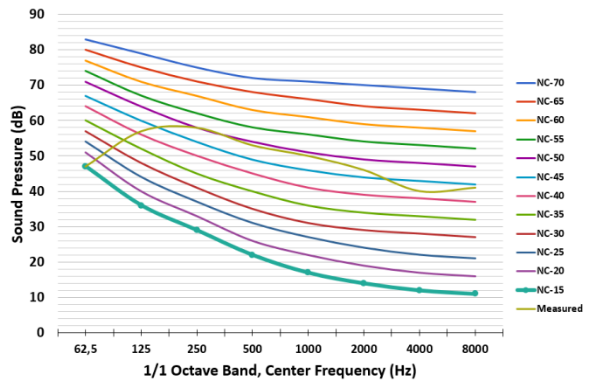
Case 20 (w/ grilles, solid, 0 degree, NC 50)



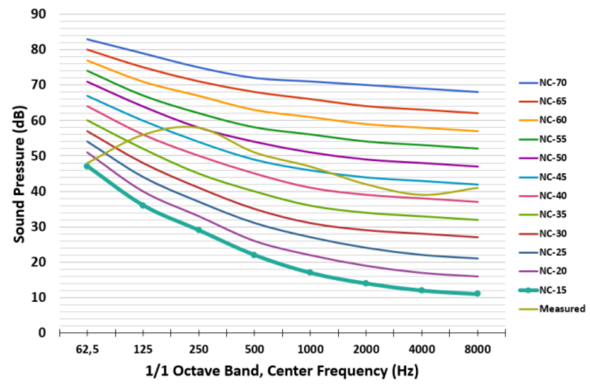
Case 21 (w/ grilles, solid, 30 degree, NC 49)



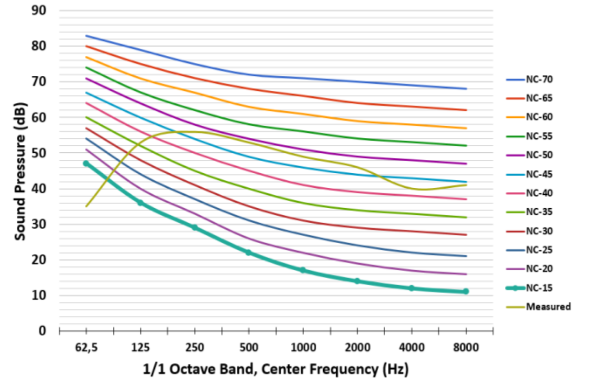
Case 22 (w/ grilles, solid, 60 degree, NC 50)



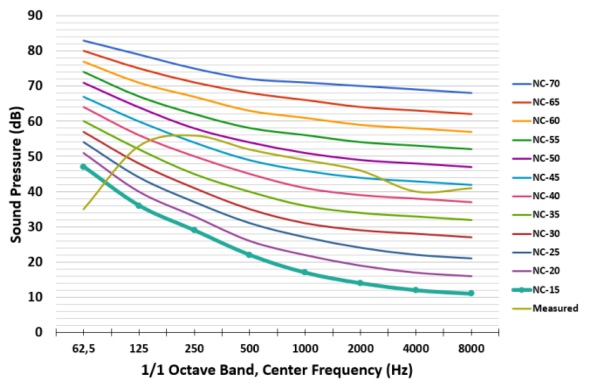
Case 23 (w/ grilles, solid, 90 degree, NC 50)



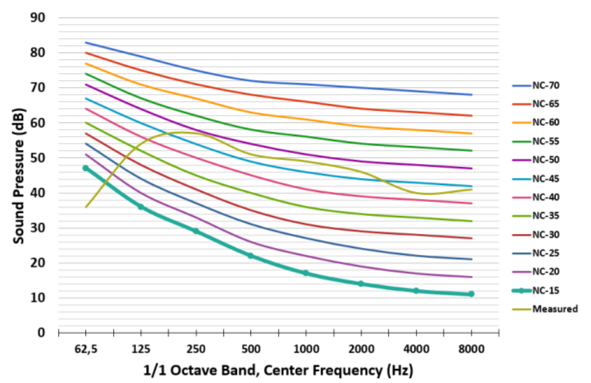
Case 24 (w/ grilles, fabric, 0 degree, NC 49)



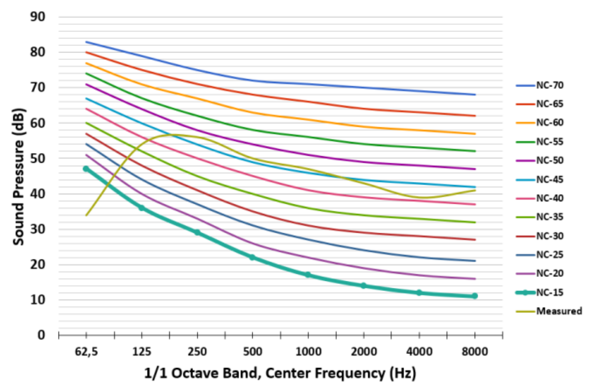
Case 25 (w/ grilles, fabric, 30 degree, NC 49)



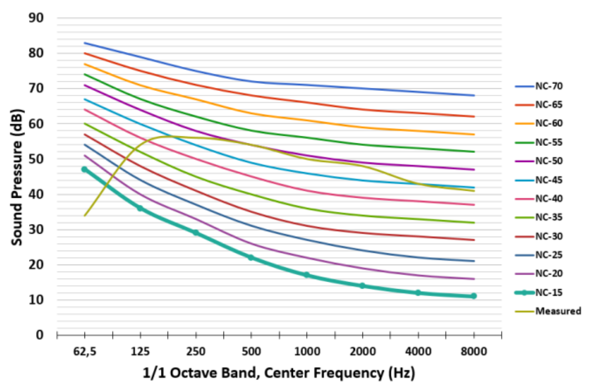
Case 26 (w/ grilles, fabric, 60 degree, NC 48)



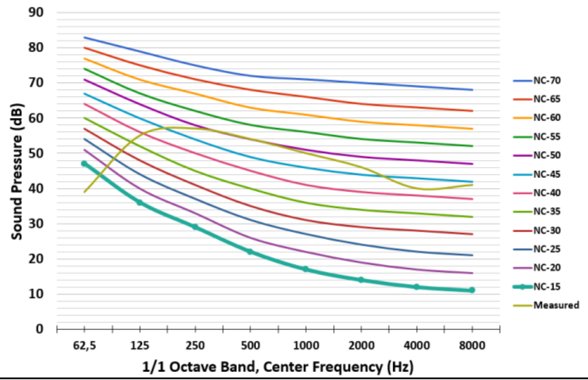
Case 27 (w/ grilles, fabric, 90 degree, NC 50)



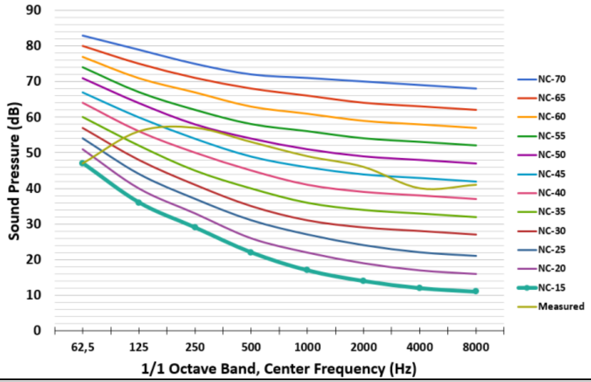
Case 28 (no shading louvers, NC 50)



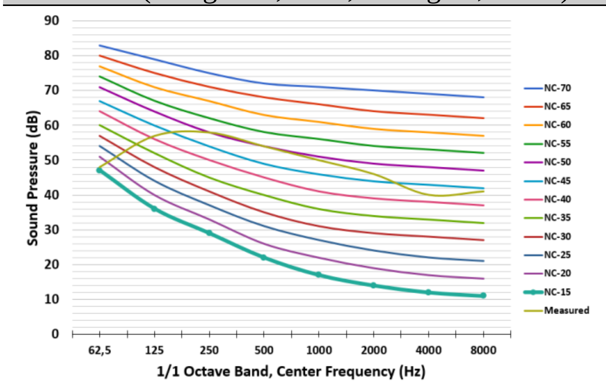
Case 29 (w/o grilles, solid, 0 degree, NC 50)



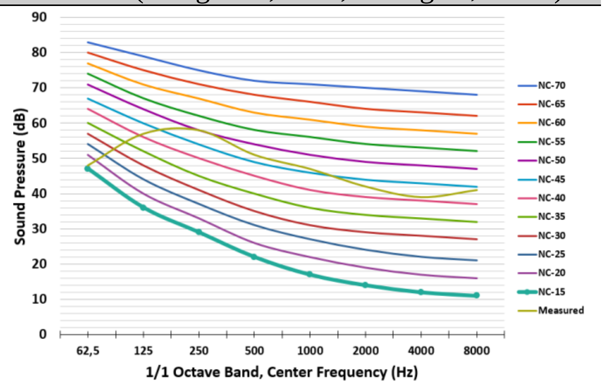
Case 30 (w/o grilles, solid, 30 degree, NC 49)



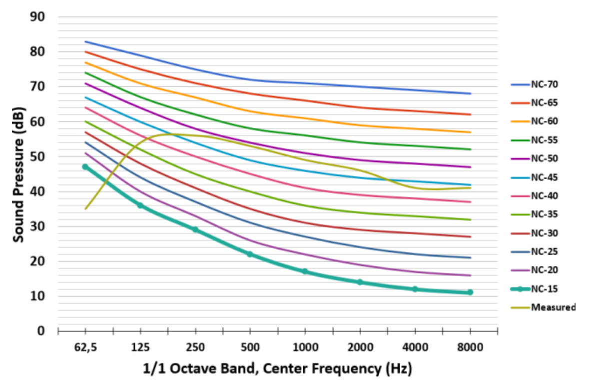
Case 31 (w/o grilles, solid, 60 degree, NC 50)



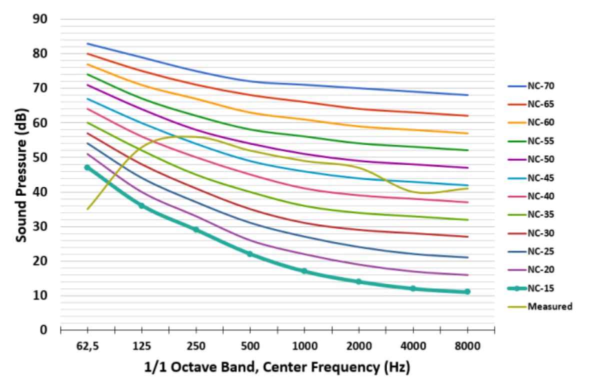
Case 32 (w/o grilles, solid, 90 degree, NC 50)



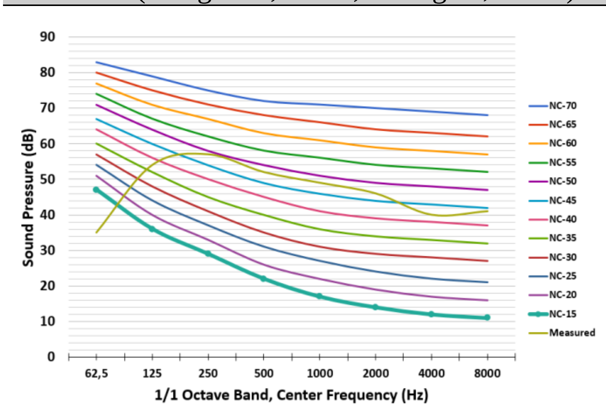
Case 33 (w/o grilles, fabric, 0 degree, NC 49)



Case 34 (w/o grilles, fabric, 30 degree, NC 48)



Case 35 (w/o grilles, fabric, 60 degree, NC 48)



Case 36 (w/o grilles, fabric, 90 degree, NC 47)

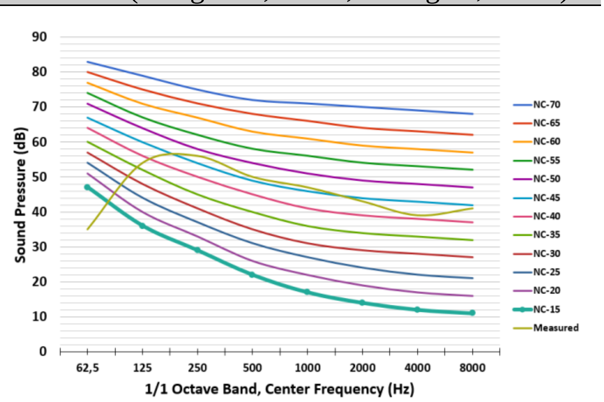


Figure 5. 18 NC values based on air vent and horizontal shading louver orientation

In Cases 5, 9, 14, and 18 with shading louvers tilted at 90 degree angle, each NC value is 47, 46, 48, and 47 respectively compare to cases of NC 50 (e.g., no shading louvers) as shown in Figure 5.19. In Cases 24, 28, 32, and 36 with shading louvers tilted at a 90 degree angle, each NC value is 49, 47, 49, and 47 respectively compared to cases of NC 50 as shown in Figure 5.19 19.

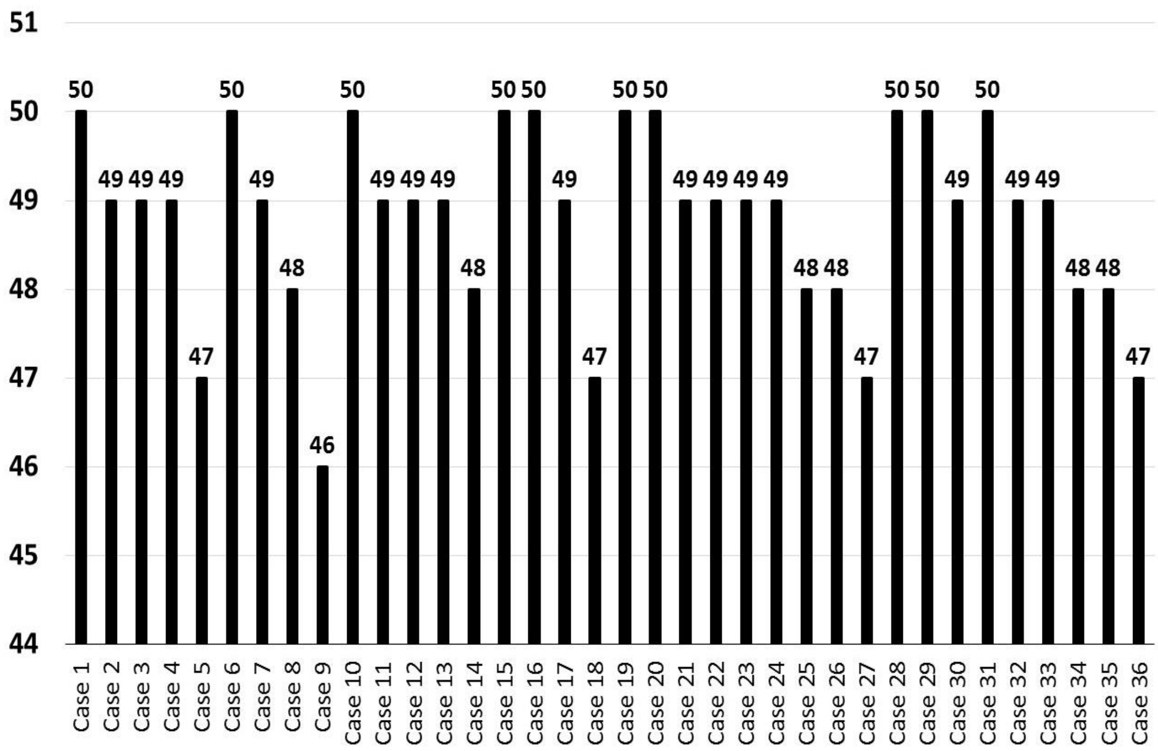
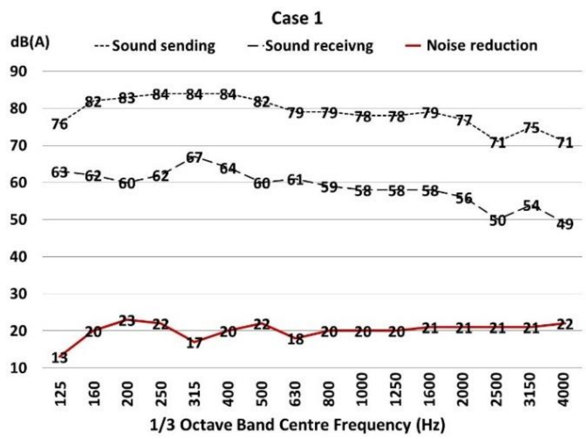


Figure 5.19 NC values by cases

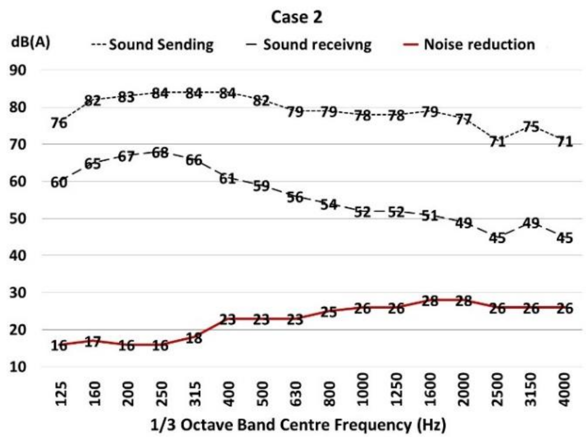
5.3.2 Compact Silencers as Noise Barriers

The experimental data of Phase II resulted in a DSF mock-up achieving noise reduction by 20 up to 37 dB(A), depending on various combinations of ventilation openings when sending sound source with a pink noise spectrum is 89 dB(A) as shown in Figure 5.20. When air vents in each glass of a DFS mock-up were opened, the overall NR value across the entire octave band center frequency was estimated by 20 dB(A) as shown in Case 1, which is the reference case. When compact silencers were applied to an outer and inner glass of a DFS mock-up, the overall NR value across the entire octave band center frequency was achieved by 28 dB(A) as shown in Case 7. When an air vent in an outer glass was closed and a compact silencer was applied to the inner glass during the cold season, the overall NR value across the entire octave band center frequency accounted for 34 dB(A) as shown in Case 11. It was assumed that shading louvers are oriented at a 90 degree angle rather than 0 degree angle, the additional NR value was obtained by 2 to 3 dB(A) as shown in Case 2, 8, and 12.

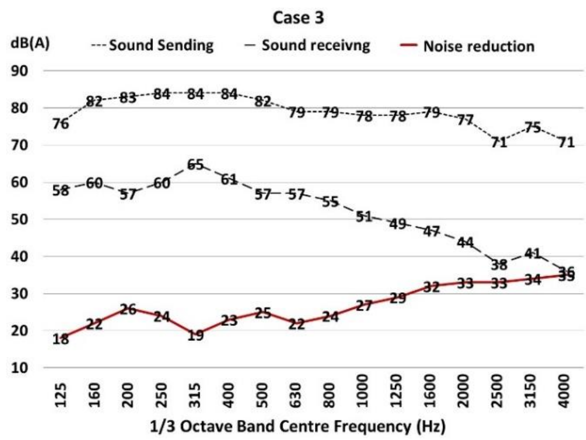
Case 1 (Open, Open, 0 degree, reference case)



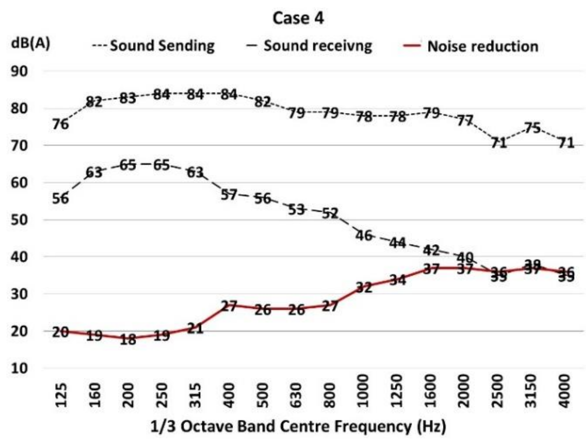
Case 2 (Open, Open, 90 degree)

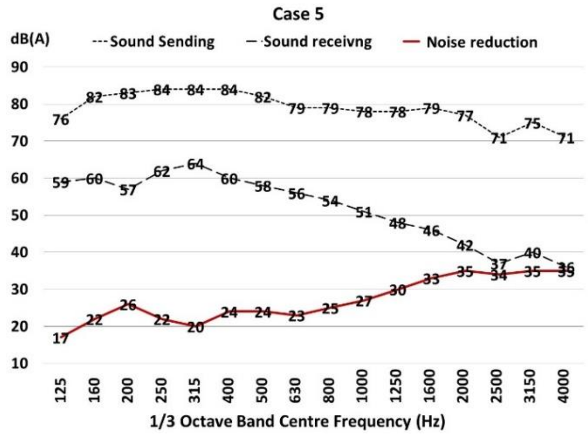
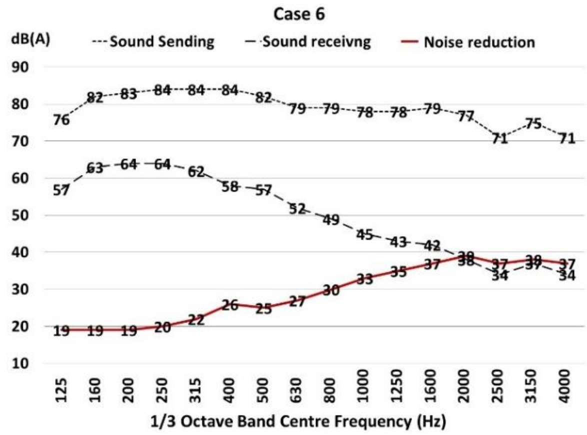
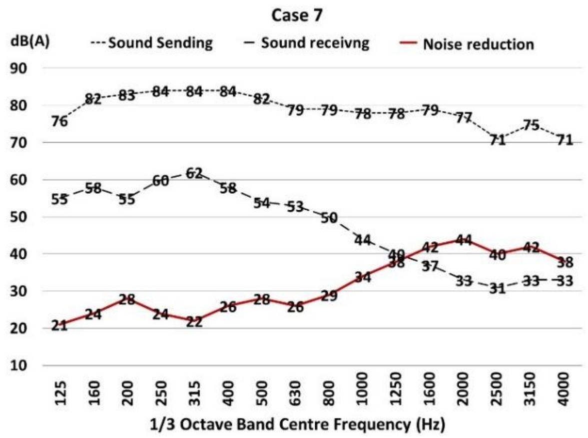
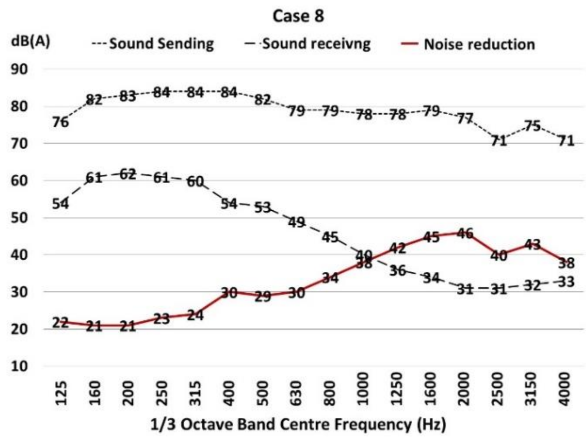
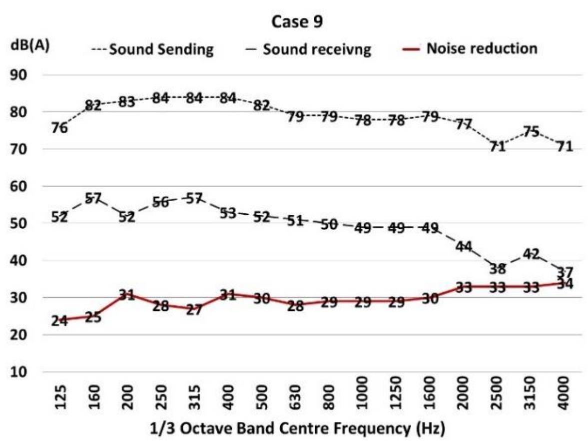
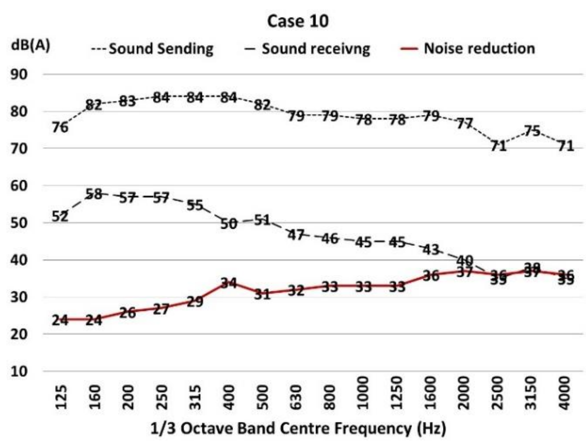


Case 3 (Open, Compact silencer, 0 degree)



Case 4 (Open, Compact silencer, 90 degree)



Case 5 (Compact silencer, Open, 0 degree)	Case 6 (Compact silencer, Open, 90 degree)
	
Case 7 (Both compact silencers, 0 degree)	Case 8 (Both compact silencers, 90 degree)
	
Case 9 (Closed, Open, 0 degree)	Case 10 (Closed, Open, 90 degree)
	

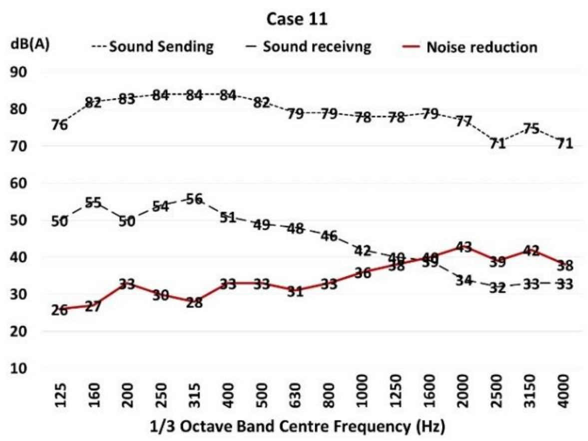
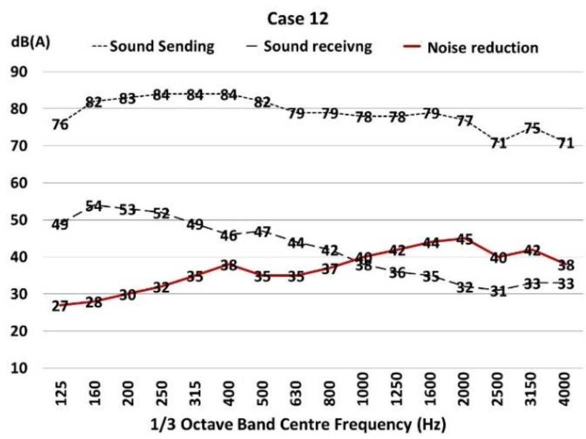
<table>
<tr><th>Case 11 (Closed, Compact silencer, 0 degree)</th><th>Case 12 (Closed, Compact silencer, 90 degree)</th></tr>
<tr><td>
</td><td>
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Figure 5.16 SPL and NR based on air vent and shading louver orientation

It was found that compact silencers applied to each glass of a DSF mock-up achieved an additional noise reduction by 8 dB (A) when compared to vent openings without compact silencers. Most notably, when a compact silencer was applied to either side of a glass, the overall NR values across the entire octave band center frequency ranged between 5 and 7 at 125 Hz dB(A), between 7 and 13 dB(A) at 1000 Hz, and between 12 and 18 dB(A) at 2000 Hz. In addition, when compact silencers were applied to both sides of the inner and outer glass, the overall NR values across the entire octave band center frequency ranged between 8 and 9 at 125 Hz dB (A), between 14 and 18 dB (A) at 1000 Hz, and between 23 and 25 dB (A) at 2000 Hz as shown in Figure 21 and 22. It implies that the application of compact silencers is significantly effective in noise reduction at low-, mid- and high-frequency bands.

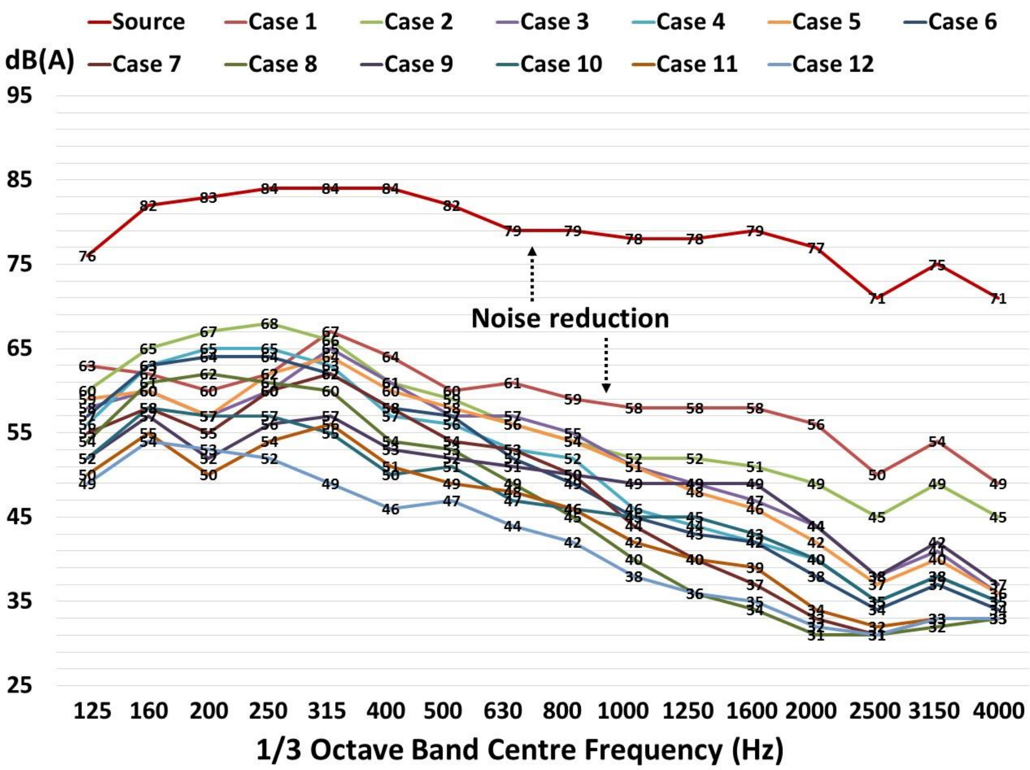


Figure 5.17 SPL and NR measured at the sound sending and sound receiving room

Case	Condition	NR dB(A)	NR values (1/3 octave band center frequency (Hz))															
			125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
Case 1	Open, Open, 0°	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Case 2	Open, Open, 90°	2	3	-3	-7	-6	1	3	1	5	5	6	6	7	7	5	5	4
Case 3	Open, C.S., 0°	5	5	2	3	2	2	3	3	4	4	7	9	11	12	12	13	13
Case 4	Open, C.S., 90°	6	7	-1	-5	-3	4	7	4	8	7	12	14	16	16	15	16	14
Case 5	C.S., Open, 0°	5	4	2	3	0	3	4	2	5	5	7	10	12	14	13	14	13
Case 6	C.S., Open, 90°	7	6	-1	-4	-2	5	6	3	9	10	13	15	16	18	16	17	15
Case 7	C.S., C.S., 0°	8	8	4	5	2	5	6	6	8	9	14	18	21	23	19	21	16
Case 8	C.S., C.S., 90°	10	9	1	-2	1	7	10	7	12	14	18	22	24	25	19	22	16
Case 9	Closed, Open, 0°	10	11	5	8	6	10	11	8	10	9	9	9	9	12	12	12	12
Case 10	Closed, Open, 90°	12	11	4	3	5	12	14	9	14	13	13	13	15	16	15	16	14
Case 11	Closed, C.S., 0°	14	13	7	10	8	11	13	11	13	13	16	18	19	22	18	21	16
Case 12	Closed, C.S., 90°	17	14	8	7	10	18	18	13	17	17	20	22	23	24	19	21	16

NR Index
0
1~4
5~8
9~12
13~16
17~20
> 21

Figure 5.22 NR values across 1/3 octave band center frequency

In summary, Table 5.11 shows the overall NR across the entire octave band center frequency depending on the different combinations of ventilation openings. According to Cases 1 and 2, which are 100% open type ventilation grilles in each glass, a DSF mock-up itself achieved the overall NR across the entire octave band center frequency by 20 and 22 dB(A) when vertical shading louvers are tilted at 0 and 90 degree angle, respectively. In Cases 3 and

4, a compact silencer applied to a vent opening of an inner glass obtained the additional NR values by 4 up to 5 dB (A) when compared to Cases 1 and 2. In Cases 5 and 6, a compact silencer applied to a vent opening of an outer glass can achieve the additional noise reduction by 5 dB (A) when compared to Cases 1 and 2. In Cases 7 and 8, two compact silencers were applied to the vent openings of an outer and inner glass of a DSF mock-up achieved the additional noise reduction by when compared to Cases 1 and 2.

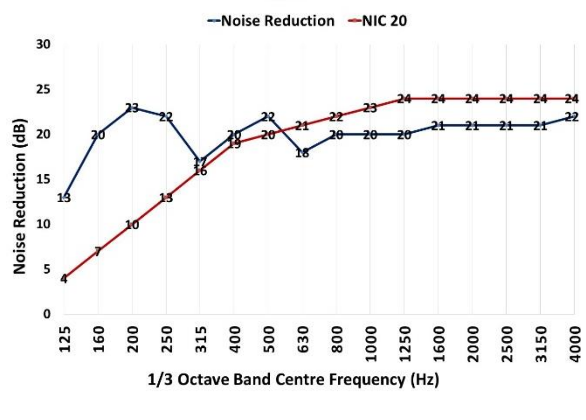
In Cases 9 and 10, with an air vent closed in an outer glass and an opening applied to an inner glass, the additional noise reduction can be achieved by 10 dB(A). In Cases 11 and 12, with an air vent closed in an outer glass and a compact silencer applied to an inner glass, the additional noise reduction can be achieved by 14 and 15 dB(A) respectively.

Table 5.11 NR across 1/3 octave band center frequency

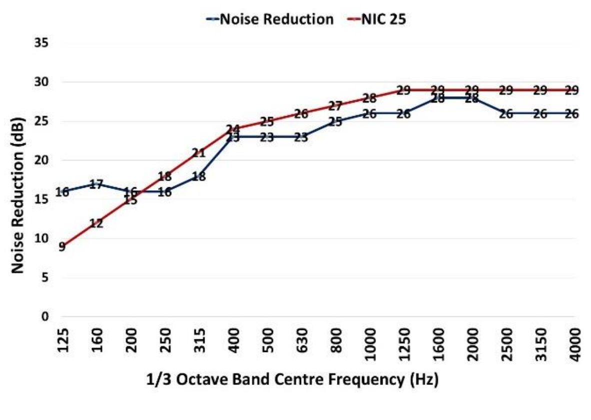
Case	**NR dB(A)**	NR values 1/3 octave band center frequency (Hz)																**NIC**
		125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	
Case 1	**20**	13	20	23	22	17	20	22	18	20	20	20	21	21	21	21	22	**20**
Case 2	**22**	16	17	16	16	18	23	23	23	25	26	26	28	28	26	26	26	**25**
Case 3	**25**	18	22	26	24	19	23	25	22	24	27	29	32	33	33	34	35	**28**
Case 4	**26**	20	19	18	19	21	27	26	26	27	32	34	37	37	36	37	36	**30**
Case 5	**25**	17	22	26	22	20	24	24	23	25	27	30	33	35	34	35	35	**28**
Case 6	**27**	19	19	19	20	22	26	25	27	30	33	35	37	39	37	38	37	**31**
Case 7	**28**	21	24	28	24	22	26	28	26	29	34	38	42	44	40	42	38	**32**
Case 8	**30**	22	21	21	23	24	30	29	30	34	38	42	45	46	40	43	38	**34**
Case 9	**30**	24	25	31	28	27	31	30	28	29	29	29	30	33	33	33	34	**31**
Case 10	**32**	24	24	26	27	29	34	31	32	33	33	33	36	37	36	37	36	**34**
Case 11	**34**	26	27	33	30	28	33	33	31	33	36	38	40	43	39	42	38	**36**
Case 12	**37**	27	28	30	32	35	38	35	35	37	40	42	44	45	40	42	38	**39**

Figure 23 shows the NIC values measured from the NR data of each case. Cases 1 through 4 were designed with open air vents in an outer glass and Cases 5 through 8 were applied with compact silencers in the outer glass, considering ventilation by the stack effect. Cases 9 through 12 were designed with closed air vents, assuming cold outdoor climate conditions. It was shown that the NIC values are the highest in Case 12 and lowest in Case 1 depending on air vent open conditions. The NIC values of cases, which are applied with a compact silencer, are higher than cases with open air vents from 3 to 8 points. Cases with compact silencers show relatively lower NIC values from 3 to 5 points than cases with closed air vents.

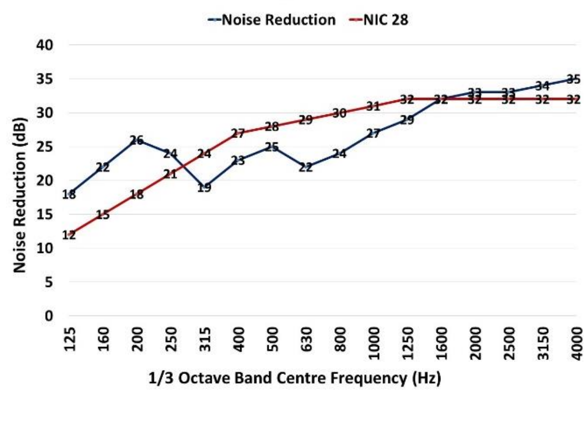
Case 1 (Open, Open, 0 degree, reference case)



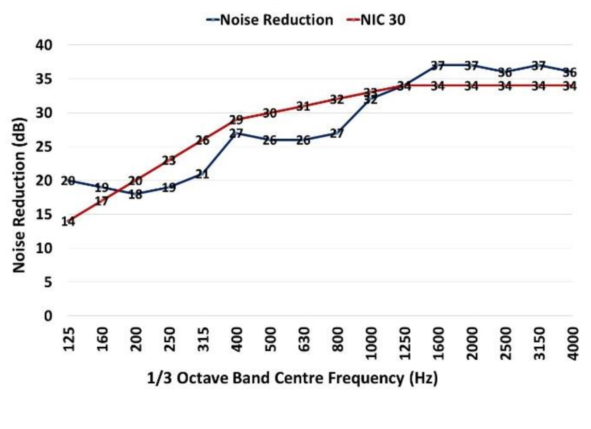
Case 2 (Open, Open, 90 degree)



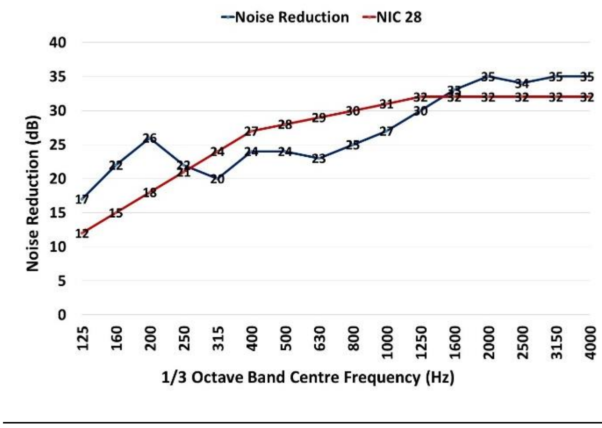
Case 3 (Open, Compact silencer, 0 degree)



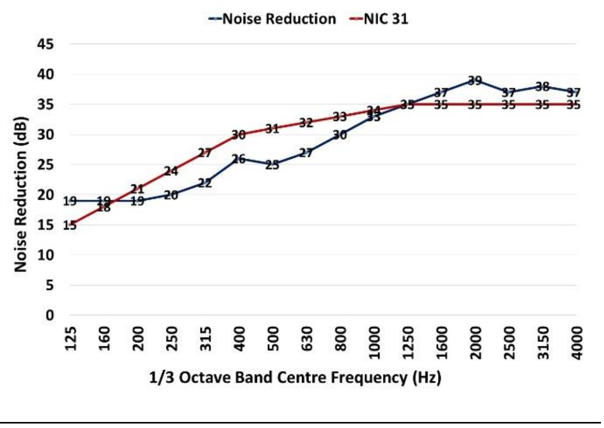
Case 4 (Open, Compact silencer, 90 degree)



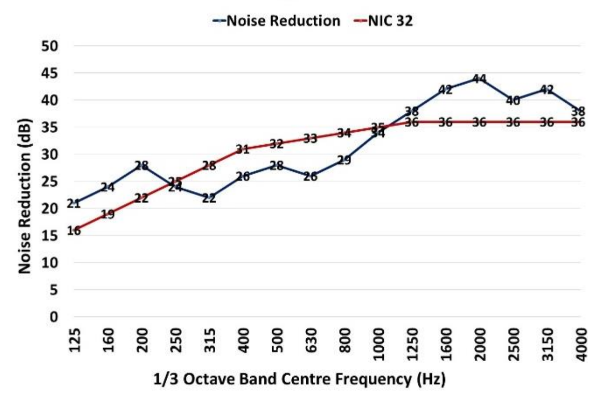
Case 5 (Compact silencer, Open, 0 degree)



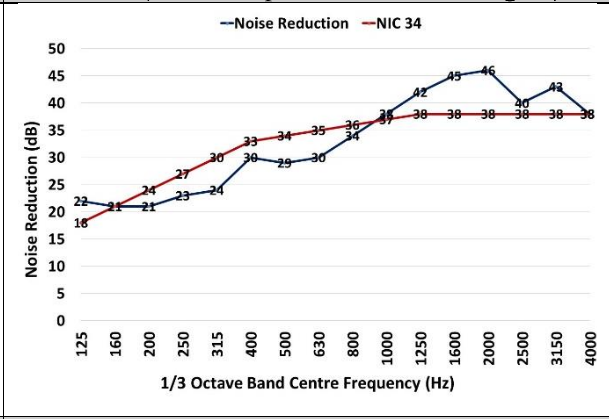
Case 6 (Compact silencer, Open, 90 degree)



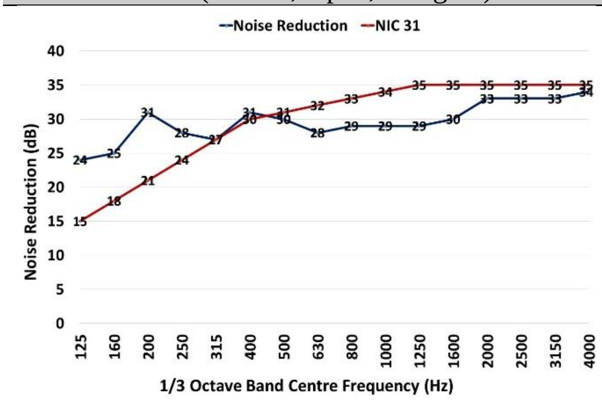
Case 7 (Both compact silencers, 0 degree)



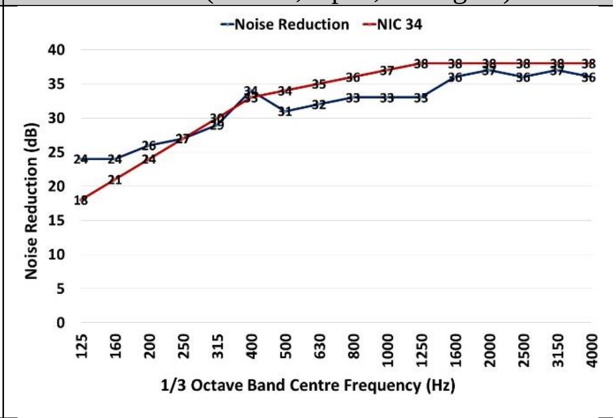
Case 8 (Both compact silencers, 90 degree)



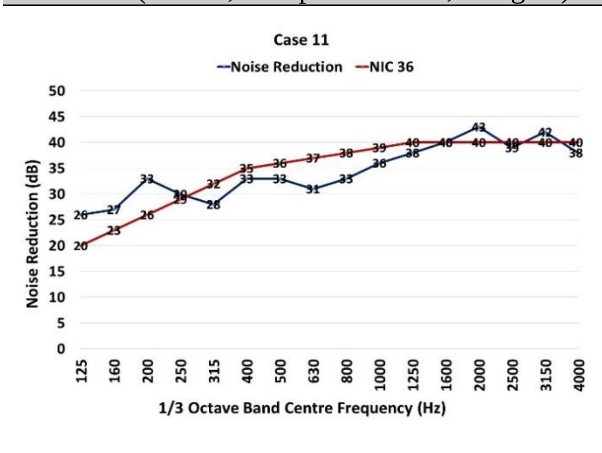
Case 9 (Closed, Open, 0 degree)



Case 10 (Closed, Open, 90 degree)



Case 11 (Closed, Compact silencer, 0 degree)



Case 12 (Closed, Compact silencer, 90 degree)

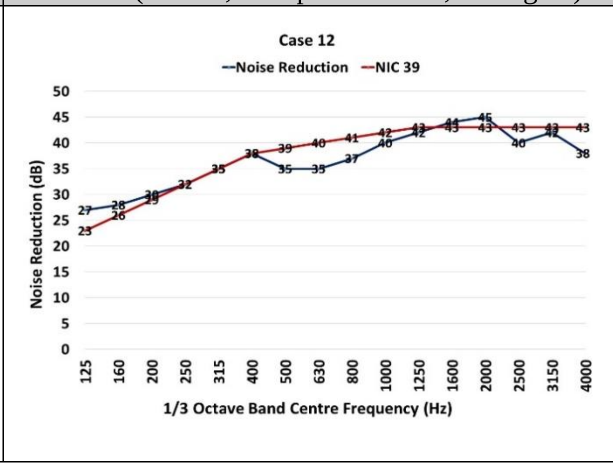


Figure 5.18 NIC based on air vent and shading louver orientation

In summary, Figure 5.24 shows the NIC values of each case. In comparisons among Case 1 (open air vents), Case 5 (compact silencer), and Case 9 (closed air vent), each NIC value is 20, 28, and 31 respectively. Therefore, each NIC difference between two sequential cases is 6 and 3 points, respectively.

In comparison among Case 2 (open air vents), Case 6 (compact silencer), and Case 10 (closed air vent), each NIC is 25, 31, and 34 respectively. Therefore, each NIC difference between two sequential cases is 6 and 3 points, respectively.

In comparison among Case 3 (open air vents), Case 7 (compact silencer), and Case 11 (closed air vent), each NIC is 28, 32, and 36 respectively. Therefore, each NIC difference between two sequential cases is 4 and 4 points, respectively.

In comparison among Case 4 (open air vents), Case 8 (compact silencer), and Case 12 (closed air vent), each NIC is 30, 34, and 39 respectively. Therefore, each NIC difference between two sequential cases is 4 and 5 points, respectively.

It is implied that compact silencers are significantly effective in the NR, particularly when air vents are open in naturally-ventilated buildings. In addition, it was found that compact silencers work efficiently to reduce noise transmission at low-, mid-, and high-frequency band. When noise exposure which is similar to low-frequency band from traffic noise is associated with hypertension, compact silencers can achieve noise reduction by 125 Hz.

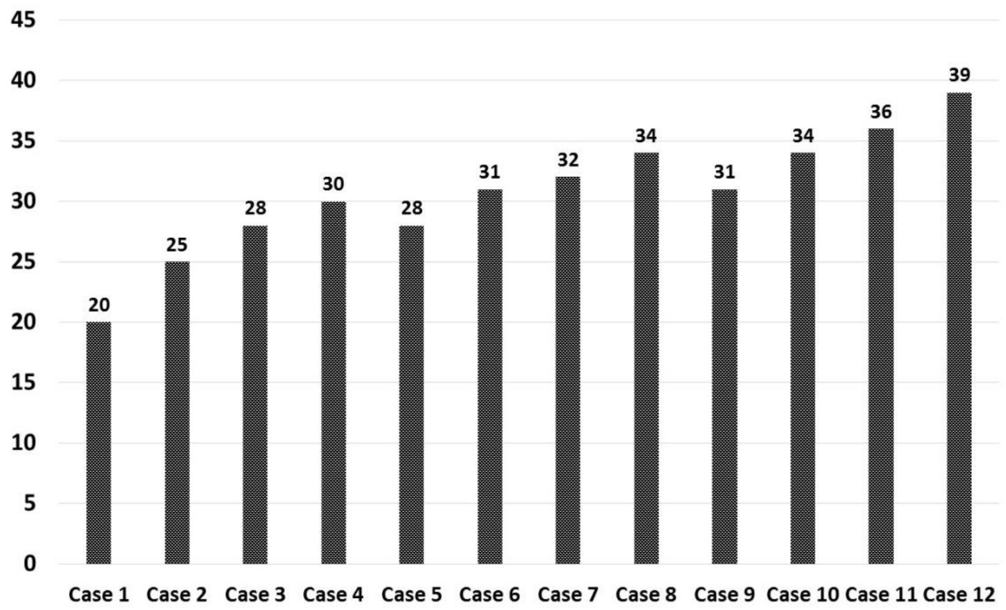


Figure 5.19 NIC values by cases

CHAPTER 6: Conclusions and Future work

6.1 Conclusions

6.1.1 Summary of Phase I

- DSF is fairly effective in overall noise reduction by 33 dB (A) when sending sound source with a pink noise spectrum is 89 dB (A).

- There is noise reduction of 3 to 4 dB (A) when shading louvers are at a 90 degree angle (closed position) compared to 0 degrees (open position).

- There is no significance in noise reduction cases without shading louvers and cases with shading louvers tilted from 0 to 30 degree angles.

- There is no significance in noise reduction by 1 or 2 dB (A) drop between types of vertical and horizontal louvers.

- There is no significance in noise reduction between 40% open grilles and 100% open grilles. However, there is significance in air temperature, air speed, and airflow patterns based on percentage of air vent open surface area, according to the CFD analysis.

- There is no significance in noise reduction by 1 dB (A) drop when 1-milimeter (1/16 inch) polyester fabrics cover solid wooden shading louvers.

- NC values ranges from 46 to 50 depending on the use of shading louvers and orientation of shading louvers. There were no significant differences between cases of “open with grilles” and cases of “open without grilles.” In addition there is no significant difference in NC based on shading louver type.

- It is expected that integrated shading louvers with sound absorbing materials can reduce noise transmission through ventilation openings in naturally-ventilated buildings.

6.1.2 Summary of Phase II

- There is overall noise reduction from 20 up to 32 dB (A) when sending sound source with a pink noise spectrum is 89 dB (A).

- There is slight noise reduction from 2 to 4 dB (A) when shading louvers are at a 90 degree angle (closed position) with 100% open vents in the inner and outer glass.

- Compared to the reference case, overall NR values across the entire octave band center frequency range between 5 to 7 dB (A) when 100% open vents of the inner or outer glass is replaced with a compact silencer.

- Compared to the reference case, overall NR values across the entire octave band center frequency range between 10 and 12 dB (A) depending on shading louver orientation when closed vent in the outer glass and 100% open vent in the inner glass.

- Compared to the reference case, overall NR values across the entire octave band center frequency range between 14 and 17 dB(A) depending on shading louver orientation when closed vent in the outer glass and a compact silencer in the inner glass.

- Compared to the reference case, the overall NR values across the entire octave band center frequency ranged between 5 and 7 at 125 Hz dB (A), between 7 and 13 dB (A) at 1000 Hz, and between 12 and 18 dB (A) at 2000 Hz when a compact silencer was applied to either side of a glass.

- Compared to the reference case, the overall NR values across the entire octave band center frequency ranged between 8 and 9 at 125 Hz dB (A), between 14 and 18 dB (A) at 1000 Hz, and between 23 and 25 dB (A) at 2000 Hz. when compact silencers were applied to both sides of the inner and outer glass, It implies that the application of compact silencers is significantly effective in noise reduction at low-, mid- and high-frequency bands.

- The NIC values for cases, which are applied with compact silencers, are higher by 3 up to 8 points than cases with no compact silencers.

- It is expected that sound absorbing materials (e.g., compact silencers) to ventilation openings are effective in reducing noise transmission in high noise areas.

6.2 Future Work

6.2.1 Integrated shading louvers with windows for IEQ

Based on the outcomes of a mixed-use study, future work might propose multi-functional shading louvers for thermal, visual, and acoustical performance of building facades. The ultimate objective of this research is to investigate the multi-controls of integrated shading louvers with window openings in naturally-ventilated building facades for improved IEQ and building performance in urban environments.

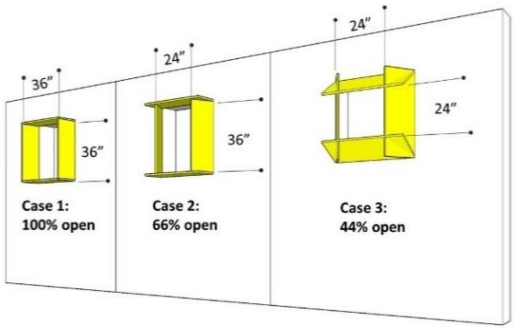
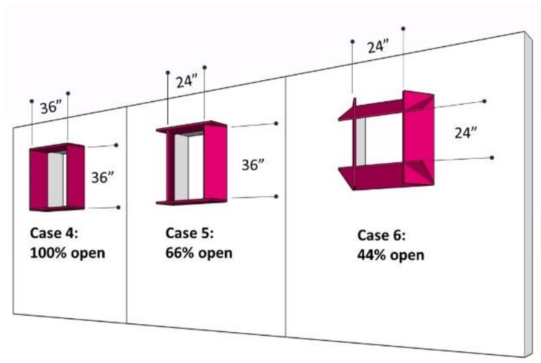
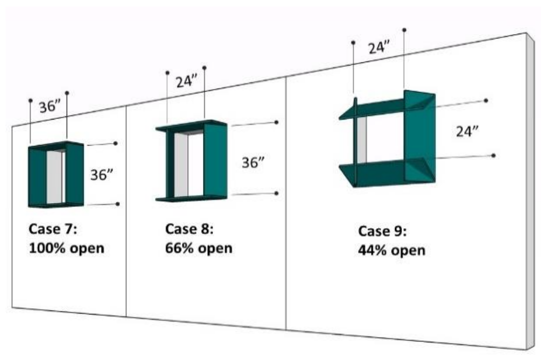
A preliminary simulation study showed the proportional relationship between airflow volume and percentage of air vent open surface area in the DSF cavity. An initial experimental study on a DSF mock-up demonstrated the high potentials of noise transmission loss by the configuration of shading louvers and the application of compact silencers. However, material developments and design applications still need to be investigated to reach successful design solutions to naturally ventilated building facades for improved IEQ and building performance.

The future development of the noise screening shading louvers and ventilation openings is designed to evaluate the concurrent thermal, visual, acoustical, and ventilation performance of shading louvers and ventilation windows. To that end, two types of louvers are proposed: (i) layered shading louvers composed of a perforated aluminum skin and a sound absorbing core and (ii) translucent honeycomb panels. First, two prototypes will be developed, designed, tested, and manufactured for thermal, visual, acoustical, and ventilation performance of shading louvers and ventilation openings. Second, developed noise screening shading louvers and window openings will be upgraded to sensor-operated shading louvers, responding to the outdoor temperature, illuminance levels, and noise levels. The orientation of each shading louver will mimic the diaphragm of a camera lens, which not only controls the amount of airflow and illuminance levels but also screens noise transmission.

The future research project proposes that the design of shading louvers and ventilation openings, previously validated in this research, will have applications in retrofit situations and new buildings; it will transform the current building façade design industries further towards sustainability. Therefore, it is expected that the development of the noise screening shading louvers and ventilation openings will promote natural ventilation performance in high noise urban areas to reduce the use of HVAC systems, which consume 25% to 30% of the energy in a typical commercial building in the U.S.A.

6.2.2 Proposed mock-up settings

Table 6.1 Proposed prototype test cases

<table>
<tr><th>Mock-up setting</th><th colspan="3">Ventilation window opening size: 36”(W) x 36”(H)
Shading louver size per each : 12”(W) x 36”(H)</th></tr>
<tr><td rowspan="3">Reference case:
Solid wood shading louvers</td><td colspan="3">Presentation of ventilation opening area</td></tr>
<tr><td>Case 1: 100%
36”(W) x 36”(H)</td><td>Case 2: 66%
24”(W) x 36”(H)</td><td>Case 3: 44%
24”(W) x 24”(H)</td></tr>
<tr><td colspan="2">
</td><td>
Used Material</td></tr>
<tr><td rowspan="3">Prototype 1:
layered shading louvers composed of a perforated aluminum skin and a sound absorbing core</td><td colspan="3">Presentation of ventilation opening area</td></tr>
<tr><td>Case 4: 100%
36”(W) x 36”(H)</td><td>Case 5: 66%
24”(W) x 36”(H)</td><td>Case 6: 44%
24”(W) x 24”(H)</td></tr>
<tr><td colspan="2">
</td><td>
Used Material</td></tr>
<tr><td rowspan="3">Prototype 2:
translucent honeycomb shading louvers</td><td colspan="3">Presentation of ventilation opening area</td></tr>
<tr><td>Case 7: 100%
36”(W) x 36”(H)</td><td>Case 8: 66%
24”(W) x 36”(H)</td><td>Case 9: 44%
24”(W) x 24”(H)</td></tr>
<tr><td colspan="2">
</td><td>
Used Material</td></tr>
</table>

6.2.3 Expectation

The future research project aims not only to improve human comfort and health, but also to promote the sustainability of naturally-ventilated buildings, where shading louvers and ventilation windows are applied to building facades.

The integrated façade designs using shading louvers and ventilation openings encourage passive design strategies that can minimize the use of HVAC systems which consequently reduce building energy consumption. In contrast to active mechanical systems, passive design strategies are carefully considered for integration with the local climate conditions resulting in building occupant comfort. Natural ventilation is one cost effective and energy saving strategy, where natural ventilation is feasible, operable ventilation windows can offer fresh airflow without the need for energy input. In addition to the multiple advantages of shading louvers to control solar radiation, noise screening shading louvers that allow for natural ventilation will provide a significant benefit to indoor air quality and acoustical comfort for building occupants.

The integrated façade designs using shading louvers and ventilation openings encourage passive design strategies that minimize environmental energy demands and thus lead to reduced carbon dioxide emission. The optimum controls of shading louvers have several environmental benefits such as reducing cooling energy loads during outdoor hot weather conditions and improved daylight harvesting during potentially sunny days. In addition to the thermal and visual performance of shading louvers, integrated photovoltaic systems with shading louvers can not only minimize the use of fossil fuels but also maximize the use of renewable energy.

References

Aksamija, A. (2013). *Sustainable Facades, Design Methods for High-Performance Building Envelopes*. Hoboken, NJ: John Wiley & Sons, Inc.

Ali, S.A. & Tamura, A. (2002). "Road traffic noise mitigation strategies in Greater Cairo, Egypt." *Applied Acoustic*, 63: 1257-65.

Ali, S.A. & Tamura, A. (2003). "Road traffic noise Levels, restrictions and annoyance in Greater Cairo, Egypt." *Applied Acoustics,* 64: 815-23.

Babisch, W. (2006). *Transportation noise and cardiovascular risk. Review and Synthesis of Epidemiological Studies*. Germany Federal Environmental Agency. Retrieved from http://www.bruit.fr/images/stories/pdf/babisch_transportation_noise_cardiovascular_risk.pdf

Baldinelli, G. (2009). "Double skin façades for warm climate regions: analysis of a solution with an integrated movable shading system." Energy and Buildings, 44: 1107-1118.

Berglund, B., Lindvall, T., & Schwela, D.H. (1999). *Guidelines for Community Noise*. World Health Organization report.

Burmistrova, O. (2012). "*Methods for measuring the sound insulation of facades*." The Bachelor's Thesis. Civil and Construction Engineering, Saimaa University of Applied

Sciences. Retrieved from file:///C:/Users/j776l379/Downloads/ BURMISTROVA_ OLGA%20(1).pdf

Carmody, J., Selkowitz, S., Lee, S. E., Arasteh, D. & Willmert, T. (2004). *Window Systems for High-Performance Buildings*. W.W. Norton & company, Inc., The regents of the University of Minesota.

Chan, A., Chow, T., Fong K., & Lin, Z. (2009). "Investigation on energy performance of double skin façade in Hong Kong." *Energy and Buildings*, 40: 1135-42.

China EPA (Environmental Protection Agency, (1995). *Conspectus of Environmental Protection in the 21st Centry in China*. Beijing: China Environmental Science Press.

De Salisa, M., Oldham, D., & Sharples, S. (2002). "Noise control strategies for naturally ventilated buildings." *Building and Environment*, 37: 471-484.

Fisk, W., Price P., Faulkner, D., Sullivan, D., & Dibartolomeo, D. (2002). "Worker performance and ventilation: analyses of time series data for a group of call-center workers." *Proceedings of Indoor Air 2002*.

Ghiaus, C. & Allard, F. (2005). *Natural ventilation in the urban environment*. Earthscan, UK and USA.

Godish, T. (2001). *Indoor Environmental Quality*. Boca Raton, FL: Lewis Publishers.

Gratia, E. & Herde, A. D. (2004). "Natural cooling strategies efficiency in an office building with a double-skin façade." *Energy and Buildings*, 36: 1139–52.

Gratia, E. & Herde, A. D. (2007). "The most efficient position of shading devices in a double-skin facade." *Building and Environment*, 39(4), 364-373.

Gratia, E., & Herde, A. (2007). "Guidelines for improving natural daytime ventilation in an office building with a double-skin facade." *Solar Energy*, 81(4), 435-448.

Harris, P. (2005). *A literature review of Double skin facades for office buildings*. Department of Construction and Architecture. Lund University. Retrieved from http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Bok-EBD-R3-G5_alt_2_Harris.pdf

Harris, P. (2006). *A literature review of Double skin facades for office buildings*. Department of Construction and Architecture. Lund University. Retrieved from http://www.ecbcs.org/docs/Annex_43_Task34Double_Skin_Facades_A_Literature Review.pdf

Hasse, et al. (2007). "Double-skin facades for Hong Kong." *The journal of Surveying and Built Environment*. Hong Kong Institute of Surveyor, Vol. 18(2), 17-32. Retrieved from http://w.hkis.org.hk/ufiles/jrnl200712-v18i2_full.pdf#page=22

Heschong L., Wright, R.L., & Okura, S. (2002). "Daylighting impacts on human performance in school". *Journal of Illumination Engineering Society*, 31(2), 101–14.

Hong, T., Kim, J., Lee, J., Koo, C., & Park, H.S. (2013). "Assessment of Seasonal Energy Efficiency Strategies of a Double Skin Façade in a Monsoon Climate Region." *Energies*, 6(9), 4352-4376.

Huh, J.H., Joe, J., Choi, W., & Kwon, H. (2013). "Load characteristics and operation strategies of building integrate with multi-story double skin façade." *Energy and Buildings*, 60: 185-198.

Hygge, S., Boman, E., & Enmarker, I. 2003. "The effects of road traffic noise and meaningful irrelevant speech on different memory systems." *Scandinavian Journal of Psychology*, 44: 13-21.

ISO 140-5. (1998) Acoustics measurement of sound insulation in buildings and of building elements – Part 5: field measurement of airborne sound insulation of façade elements and facades. Retrieved from http://www.bbri.be/antenne_norm/akoestiek/fr/

Joynt, J.L.R. (2005). "A sustainable approach to environmental noise barrier design." Ph.D dissertation, School of Architecture, University of Sheffield, UK.

Kang, J. (2007). *Urban Sound Environment*. London: Taylor and Francis Group.

Khan, N., Su. Y., & Riffat, S (2008). "A review on wind driven ventilation techniques." *Energy and Building*, 40: 1586-1604.

Kim, M., Chang, S.I., Seong, J.C., Holt, J.B., Park, T.H., Ko, J.H., & Croft, J.B. (2012). "Road traffic noise annoyance, sleep disturbance and public health implications." *American Journal of Preventive Medicine*, 43(4), 353-360.

Kim, M..J. & Kim H.G. (2007). "Field measurement of façade sound insulation in residential buildings with balcony windows." *Building and Environment*, 42:1026-1035.

Lagios, K., Niemasz J., & Reinhart, C.F. (2010). "Animated Building Performance simulation (ABPS) - Linking Rhinoceros/Grasshopper with Radiance/DayxSIM." *Proceeding of SimBuild*, New York, U.S.A.

Ljung, R., Sorqvist, P., & Hygge, S. (2009). “Effects of road traffic noise and irrelevant speech on children's reading and mathematical performance.” *Noise and Health*, 11: 194-198.

Lee, J., Je, H., & Byun, J. (2011). “Well-being index of super tall residential buildings in Korea.” *Building and Environment*, 46:1184-1194.

Lee, E., Selkowitz, S., Bazjanac, V., Inkarojrit, V., & Kohler, C. (2002). *Higher performance of commercial building facades.* University of California. Retrieved from https://escholarship.org/uc/item/7d30b3rd

Lee, I.H., Ahn, Y.H., Park, J., & Kim, S.D. (2014). “District Energy Use Patterns and Potential Savings in the Built Environment: Case Study of Two Districts in Seoul, South Korea.” *Asian Journal of Atmospheric Environment*, Vol. 8-1, pp. 48-58.

Marathe, P.D. (2012). “Traffic noise pollution.” *International Journal of Educational Development*, Vol. 9, No. 1: 63-68. Retrieved from http://serialsjournals.com/serialjournalmanager/abstractimage/1345287760.pdf

Mehta, M., Johnson, J., and Rocafort, J. (1998). *Architectural acoustics principles and design.* London: Prentice Hall.

Muzet, A. (2007). “Environmental noise, sleep and health.” *Sleep Medicine Reviews*, 11: 135-142.

Naish, A.D., Tan, C.C.A. & Demirbilek, N. (2012). “Estimating health related costs and savings from balcony acoustic design.” *Applied Acoustics*, 73: 497-507.

Nicol, F., & Wilson, M. (2004). “The effect of street dimensions and traffic density on the noise level and natural ventilation potential in urban canyons.” *Energy and Buildings,* 36(5), 423-434.

Röber, N., Kaminski, U., & Masuch, M. (2007). “Ray acoustics using computer graphics technology.” *Proceeding of the 10th International Conference on Digital Audio Effect*. DAFx-07, Bordeaux, France.

Organization for Economic Cooperation and Development (2014). *OECD Green Growth Studies Compact City Policies: Korea: Towards Sustainable and Inclusive Growth, OECD Green Growth Studies*, OECD Publishing.

Oesterle, E. (2001). *Double-Skin Facades integrated planning*. Munich: Prestel Verlag.

Patterson, R. M. (2008). “Structural Glass Facades: A Unique Building Technology.” Master Thesis. University of Southern California.

Parry, G.A., Pyke, J.R., & Robinson, C., (1993). “The excess attenuation of environmental noise sources through densely planted frost.” *Proceedings of the Institute of Acoustics (IOA),* Bath, UK.

Pedrero, A., Sánchez, J. L., Ulin, V. & Díaz, C. (2012). “Influence of loudspeaker directivity on the measurement uncertainty of the acoustic testing of facades.” *Proceedings of Inter-Noise*. Osaka, Japan, September 4-7, 2011.

Pe´rez-Lombard, L., Ortiz, J., & Pout, C. (2008). “A review on building energy consumption information.” *Energy and Building,* 40: 394-398.

Prajongsan, P. & Sharples, S. (2012). “Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts.” *Building and Environment*, 50: 104-113.

Ryu, I.C., Kim, H.K., Oh, K.R., Yeo I.H. & Eom, S.W. (2012). “A study on the characteristic of traffic noise on urban area in Seoul.” *Report of Seoul Research Institute of Public Health and Environment,* 48:152-164.

Safer, N., Woloszyn, M., & Roux, J.J. (2004). “Three dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin façade equipped with a venetian blind.” *Solar Energy*, 79(1), 193-203.

Santamouris, M. & Georgakis, C. (2006). “Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes.” *Energy and Building*, 38(4), pp.367-376.

Sanders, M. Russel (2006). “Curtain Walls: Not Just Another Pretty Façade.” *The Journal of Architectural Technology*, Hoffman Architects, Inc. Vol. 23, 2006.

Schreckenberg, D., Schuemer-Kohrs, A., Schuemer, R., Griefahn, B., & Moehler, U. (1999). “An interdisciplinary study on railway and road traffic noise: annoyance differences.” *Journal of the Acoustical Society of America*, 105(2), 1219.

Seidman, M.D., & Standring R. T. (2010). “Noise and Quality.” *International Journal of Environmental Research and Public Health,* 7(10), 3730-3738.

Seong, J.D., Park, T.H., Ko, J.H., Chang, S.I., Kim, M., Holt, J.B., & Mehdi, M.R. (2011). “Modelling of road traffic noise and estimated human exposure in Fulton County, Georgia, USA.” *Environmental International,* 37: 2011-1341.

Seppänen, O., & Fisk, W. J. (2002). “Association of ventilation system type with SVS symptoms in office workers.” *Indoor Air*, 12(12), 98-112.

Shield, B., & Dockrell, J. (2003). “The effects of noise on children at school: A review.” *Building Acoustics*, 10:97-116.

Smith, K.R. (1994). *Workshop on the energy-Environment Nexus: Indian Issues and Global Impacts*, Center for the Advanced Study of India, University of Pennsylvania, Philadelphia.

Sørensen, M., Andersen Z.J., Nordsborg, R.B., Becker, T., Tjønneland, A., Overvad, K., & Raaschou-Nielsen, O. (2011). “Long-term exposure to road traffic noise an incident Diabetes: A Cohort study.” Environmental Health Perspective, Vol. 121(2) 217-222.

Stansfeld, S. & Matheson, M. (2003). “Noise pollution: Non-auditory effects on health.” *British Med. Bull*, 68: 243–257.

Stansfeld, S., Berglund, B., Clark, C., Lopez-Barrio, I., Fisher, P., Öhrström, E., Haines, M.M., Head, J., Hygge, S., van Kamp, I., & Berry, B.F. (2005). “Aircraft and road traffic noise and children’s cognition and health: a cross-national study.” *Lancet 365*, 1942-1949.

The United Nation (2014). *Department of Economic and Social Affairs. Population Division*. World Urbanization Prospects 2014. Retrieved from http://esa.un.org/unpd/wup/Country-Profiles/Default.aspx

U.S. Environmental Protection Agency (EPA 1997). *An Office Building Occupant's Guide to Indoor Air Quality*. Retrieved from http://www.epa.gov/iaq/pubs/occupgd.html.

Van Renterghem, T., Hornikx, M., Forssen, J., & Botteldooren, D. (2013). “The potential of building envelope greening to achieve quietness.” *Building and Environment*, 61, 33-44.

Vallet, M., Vernet, I., Champelovier, P., & Maurin, M., (1996). “A road traffic noise index for the night time.” *Proceedings of Inter-Noise,* Liverpool, UK.

Viveiros, E.B. and Gibbs B.M (2003). “An image model for predicting the field performance of acoustic louvers from impulse measurements.” *Applied Acoustics*, Vol.64 (7), pp.713-730.

Waitz, I.A, Bernhard, R.J., & Hanson C.E. (2007). *Challenges and Promises in Mitigating Transportation Noise*. Noise Engineering, National Academy of Engineering. Retrieved from https://www.nae.edu/File.aspx?id=7411

Wargocki, P., Wyon, D., Sundell, J., Clausen, G., & Fanger, P. (2000). “The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity.” *Proceedings of Indoor Air*, 10: 222-236.

World Health Organization. (1999). *Guidelines for Community Noise.* World Health Organization Retrieved from http://whqlibdoc.who.int/hq/1999/a68672.pdf

World Health Organization. (2009). *Night noise guidelines for Europe*. Copenhagen: World Health Organization.

World Health Organization (2011). *Burden of Disease from Environmental Noise*: *Quantification of Healthy Life Years Lost in Europe*. Copenhagen: World Health Organization.

Yano, T., Yamashita, T., & Izumi, K., (1996). “Social survey on community response to railway noise-comparison of responses obtained with different annoyance scales.” *Proceedings of Inter-Noise,* Liverpool, UK.

Yosida, T., Osada, Y., Kawaguchi, T., Hoshiyama, Y., Yoshida, K., & Yamamoto, K. (1997). “Effects of Road Traffic noise on inhabitants of Tokyo.” *Journal of Sound and Vibration*, 205: 517-22.

Zhou, J., Chen, Y.M. & Fang, S.S. (2009). “The ventilated double skin facades in hot-summer and cold-winter zones in China.” *Journal of Hunan University Natural Sciences,* 36: 160–2.