Title
Shading and Cooling: Impacts of Solar Control and Windows on Indoor Airflow

Author
Hildebrand, Penapa Wankaeo

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Shading and Cooling: Impacts of Solar Control and Windows on Indoor Airflow

by

Penapa Wankaeo Hildebrand

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Committee in charge:

Professor M. Susan Ubbelohde, Chair

Professor Charles C. Benton

Professor Peter C. Bosselmann

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V_{PLAN} = mean spatial velocity ratio in plan, ND

S_{PLAN} = standard deviation of the velocity ratio in plan, ND

V_{SECT} = mean spatial velocity ratio in section, ND

S_{SECT} = standard deviation of the velocity ratios in section, ND

C_{SV} = coefficient of spatial variation, ND

V_i = mean interior velocity location i, m/s

V_{ref} = mean reference velocity location, taken in the unobstructed free stream upwind of the model at 1.1m seated head height (model scale) or above the model floor level, or 5-⅜” above the wind tunnel floor.

CHAPTER 1 INTRODUCTION

Through most of history, natural ventilation was a commonly used passive cooling strategy in building design. Today, in a large part of the developing world, natural ventilation is still a main form of cooling. This is also the case for many buildings intended to be energy conscious. It is common for many buildings today to heavily rely on air conditioning to achieve thermal acceptability, a task the structure itself once performed. Reinforcing what many intuitively already know, research[1] and recent thermal comfort standards[2] agree that increasing airflow improves thermal comfort in warm, humid environments.

In a suitable climate, wind-driven ventilative cooling has the potential to lower dependence on fossil fuels in both new construction and building renovations by minimizing the amount of mechanical cooling energy used. Utilizing exterior shading with windows significantly reduces the need for cooling by lowering solar heat gain, thus increasing the chances that low-energy cooling strategies, like natural ventilation, will work. While the main function of exterior shading is to block direct sun, such projections also directly affect the incoming airflow through open windows, interior daylighting, and the building's form and façade. Thus, exterior shading is likely to obstruct airflow into the building[3]. Screen-like shading systems mounted in front of operable windows are particularly susceptible to this effect.

Given the desire to shade and ventilate naturally, what is the affect of screen shading systems on the indoor airflow in the occupied zone? What combination of window and shade minimizes obstruction to, or perhaps even enhances, airflow?

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[1] Givoni 1962, Chand 1974, Arens 1986.

[2] ASHRAE 55-2010, section 5.2.3.

[3] Sobin 1981. Aynsley 1979. Smith 1970.

This thesis examines these questions via wind tunnel tests of a low-rise classroom-like building model with interchangeable shades and windows. This first chapter introduces the core issues involved in this study: the tropical climate, tropical vernacular and modern buildings, screen shades in contemporary architecture, and classroom buildings.

1.1 THE TROPICAL CONTEXT

Before the mid-20th Century, buildings in the tropical climates of this study did not use air conditioning to cool their interiors. In contrast with the naturally ventilated vernacular, contemporary tropical commercial and institutional buildings have become taller, mechanically cooled and glazed. Today, air conditioning is used throughout commercial, institutional and some school and residential buildings in much of the tropics. These buildings are often conditioned to the same thermal comfort standards as those used in temperate climates and thus consume an enormous amount of electricity in the process. Such thermal conditions have become commonplace in automobiles, shops and other transient spaces.

In addition to requiring more electrical power today, air conditioning seems to "condition" people to require more of it in the future, by lowering our ability to tolerate higher temperatures.[4] The addiction to mechanical cooling seems insatiable. Is there a way to undo some of this dependence on fossil fuels? Cooled air needs sealed spaces; sealed spaces isolate us from the outside world. Over time, this isolation makes the outdoors seem a foreign place. While this dissociation may be desirable for a performance hall, it is arguably less crucial for classrooms, offices, and other daily functions. Might reintroducing natural ventilation indoors restore the awareness that air conditioning took away?

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[4] de Dear and Brager, 2001 and Busch, 1991.

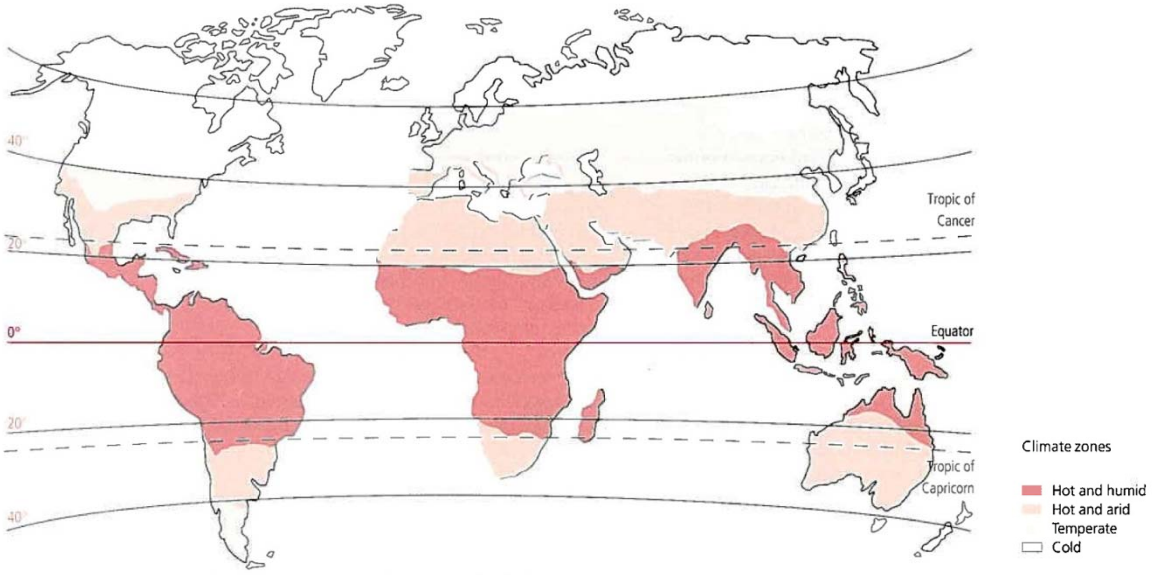

Figure 1. Map of tropical and subtropical zones in the world. (Hindrichs and Daniels. 2007)

The tropical and subtropical regions take up a very significant portion of earth's land mass and population. Because of the angle at which the sun strikes the earth, most areas within the tropics are hot year-round. According to Wikipedia, "Unlike the extra-tropics [or subtropics], where there are strong variations in day length, and hence [seasonal] temperature … tropical temperatures remain relatively constant throughout the year and seasonal variations are dominated by precipitation."[5] There are three types of tropical climates, based on variations in precipitation: the tropical rainforest climate (dominated by low pressure), the tropical monsoon climate, and the tropical wet and dry (or savanna) climate. For the sake of simplifying the study, the climate selected is that of Bangkok, Thailand, at 13.75˚ N latitude. Bangkok's climate is a combination between tropical monsoon and tropical savannah. This climate is generally marked by three seasons, with the start and end of each season varying slightly in the Northern Hemisphere tropics. The summer (or the hottest season) tends to occur around March through June, with high dry bulb temperatures and moderate to high humidity.

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[5] http://en.wikipedia.org/wiki/Tropical_climate

The monsoon season, from about June or July through October, is very warm and humid, with relative humidity frequently approaching 100%, making evaporative cooling nearly impossible. When there is precipitation, temperatures drop slightly, but quickly rise again once the rain stops. Skies during the monsoon period tend to be cloudy and diurnal temperature swings are smaller during this season. The tropical winter season is marked by warm temperatures with lower humidity than the other seasons. Diurnal temperatures tend to vary the most during winter.

1.2 TROPICAL BUILDINGS

One purpose of buildings is to shelter people from the elements: sun, wind and rain. Throughout the centuries, the peoples of the tropics, have built, adjusted, and perfected an architecture that, besides providing adequate shelter from the elements, was shaped to their customs and was sustained by naturally available resources. This is reflected in the distinct features of the vernacular architecture of tropical regions. (In general, the solutions that have prevailed are those that best serve multiple purposes.)

In these regions, traditional houses were often raised from the ground in order to catch the stronger breezes higher up, to reduce moisture migration from the soil, and to provide protection from seasonal flooding. The space underneath the house was used as a shaded outdoor room.

Sometimes it was with high-pitched gables and large eaves that tropical architecture responded to the abundant rains: rain-water flowed quickly off the surface of the roof and this protected the interior from leaks. The deep eaves also kept the drip line further away from the house, protecting often porous walls from rain.

The high roofs also allowed the warm air to rise out, helping keep the interiors cool. The narrow floor plates and the organization of units clustered around a courtyard also made it possible for natural ventilation and day-lighting to be more effective. In these latitudes, outdoor spaces like the courtyard, or terrace, or the galleries and verandahs, were used as additional rooms. Galleries and verandahs provided shade to these outdoor rooms, and also shaded the exterior walls and windows, contributing to keeping the indoors cool.

In the tropics, the sun hits the Earth at a high angle. A strong, bright sun suspended directly above in the sky results in high temperatures. In places like Southeast Asia, the same roofs that give protection from rain also shade the walls and protect from glare. In this vernacular, there is not always a clear distinction between walls and windows. Windows often include screening elements, such as in wood or stone latticework, to block direct sun while bringing in light and air. Features like latticework and shutters suggest that there was also no clear differentiation between shade and window in tropical buildings. Rarely did buildings use glass to separate inside and outside.

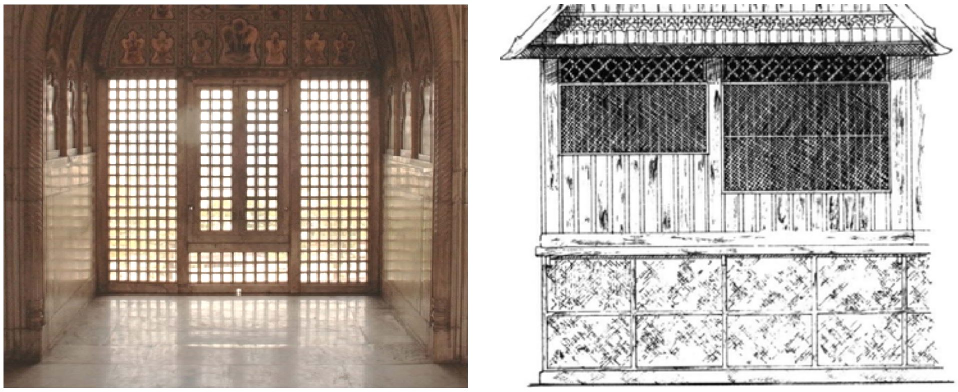

Figure 2. Left: stone lattice Agra Fort, Agra, India. (photo by author) Right: Wooden lattice opening above woven bamboo wall construction in Luang Phabang, Laos. (Somsanuk, 2004)

Figure 3. Left: A rare use of staggered fixed pane glazed windows allow for the passage light and air while blocking rain. Wat Phra Kaeo Museum. (photo by author). Middle: dual action windows with panel sashes that can open like a double casement or like awning windows or "Bahama shutters" at Let's Sea Hua Hin Resort, Thailand. Window sashes, when present in the tropical vernacular, tend to be solid or slatted shutters. (photo by Sittha Sukkasi). Right: Overhangs and solid panel casement windows in Happy Haus in Queensland, Australia[6]

The introduction of glass in the colonial era separated the inside and the outside that had not been so clearly distinct before, as seen in examples of traditional Thai architecture. But colonial architecture also observed its neighboring traditional houses and adapted some of its elements. The walls, now made out of brick, further separated the outside from the inside environment; the thermally massive materials of brick and concrete retain daytime heat well into the evening.

Larger windows that could still be closed with shutters, created a new cool interior space. Verandahs and galleries were also adapted to brick, but they kept functioning as an exterior shaded room that also protected the walls from the sun, lowering the exterior heat loads. The change in materials created a new controlled environment, slower to respond to the exterior conditions than the local architecture.

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[6] Jordana , Sebastian . "Happy Haus / Donovan Hill" 29 Jun 2010. ArchDaily. Accessed 10 Dec 2010. <http://www.archdaily.com/66345>

1.3 SHADE SCREENS IN CONTEMPORARY ARCHITECTURE

Once air conditioning became more common, buildings incorporated more glass, both in larger windows and curtain wall systems, and deeper floor plates, since proximity to windows was no longer required to light and cool. With the introduction of glass separating inside and outside, the difference between window sash and shade clearly emerges. Without sufficient shading protection from the sun, these internal-load dominated buildings quickly overheat and require even more energy to cool. Some architects and engineers acknowledged the all-glass dilemma and incorporated external shading into building designs. Starting in the 1950s, there was an upsurge in research and publications around climate adaptive design and maximizing passive heating and cooling. Publications for architects included *Design with Climate* (Olgyay and Olgyay 1963), *Solar Control and Shading Devices* (Olgyay 1957), and *Tropical Architecture in the Dry and Humid Zones* (Drew and Fry 1964). Before the energy implications of the all-glass building were thought to be important, unprotected glass structures began appearing in tropical climates. They are still being built today, though with more advanced glass technologies.

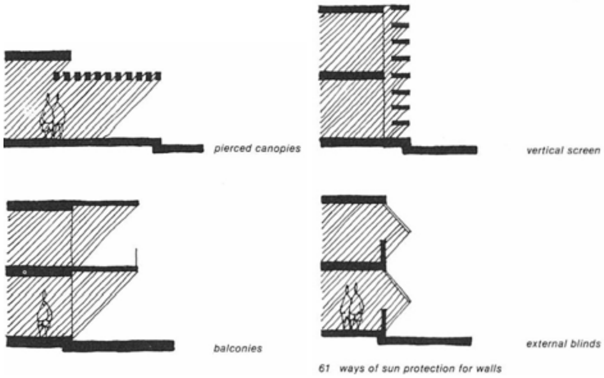

Figure 5. Various types of shading from Frye and Drew.

Figure 4. The IIM Dormitories in Ahmedabad, India (Louis Kahn) were designed to be protected from the sun and permeable to the wind. Images from <*www.flickr.com/photos/jmordhorst/*> and <*www.flickr.com/photos/12474755@N07*>

An increased awareness of energy depletion, fuel price rise, and climate change has brought about an interest in lowering all energy use and building energy use in particular. Low-energy cooling strategies, like natural ventilation, require careful load control and blocking heat gain from the structure, windows and interiors. In tropical buildings, minimizing solar heat gain is done in two main ways: first by insulating exterior walls, (thus restricting the interior surfaces from radiating heat toward the occupied areas), and second by shading openings from direct sun penetration. The first method involves insulative and radiant barriers in the building enclosure; though important for the climate, this is outside the scope of the present study. The second method - shading openings - is achieved by blocking direct sun from entering the occupied space with some sort of interior or exterior shading device.

External shading can block significantly more solar heat[7] and tends to be a more visually prominent part of the architecture, as compared with internal shades. Shielding the building and its occupants from the sun is especially relevant in climates where our bodies easily overheat, as in the tropical, low-latitude environments of interest in this study. In these regions, this means high angled sun from the north and south portions of a building and lower angled sun from the east and west. Forms of external shading include horizontal devices, like overhangs, and vertical devices, like vertical fins or wing-walls,[8] as well as architectural features such as large roofs, loggias and other volumetric forms.

As can be seen, many forms of exterior shading have been employed throughout the centuries. While screen shades have also been utilized historically, such systems have become a

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[7] According to a field test by Lawrence Berkeley National Laboratory, cooling loads were reduced by 77% with exterior Venetian blinds as compared to conventional interior Venetian blinds under the same conditions. Lee, 2009. Innovative Façade Systems for Low-energy Commercial Buildings. *(ask permission)*

[8] *Solar Control and Shading Devices* by Olgyay and Olgyay, 1976 (page 88) is a comprehensive source for exterior shading.

clear visual trend in contemporary architectural design, both in tropical and non-tropical buildings. Examples of screen systems in buildings include the San Francisco Federal Building (Morphosis), the Torre Cube Office tower in Guadalajara (Estudio Carme Pinós), the Tijbaou Cultural Centre in New Caledonia (RPBW), the New York Times Building (RPBW), the De Young Museum (Herrzog & de Meuron Arkitekten), the New Museum in New York (SANAA), the Education Authority in Martinique (Hauvette & Associés), and the Terry Thomas building in Seattle (Weber Thompson). Some of these buildings are shown below. In naturally ventilated spaces, the impact of these screen type shading systems is likely have some affect on airflow, though the full extent of their impacts is unknown, despite their architectural prominence.

Figure 6: Examples of screen shading systems in architecture: (left to right) San Francisco Federal Building (Morphosis), Torre Cube (Estudio Carme Pinos), Tijbalou Cultural Center (Renzo Piano Building Workshop).

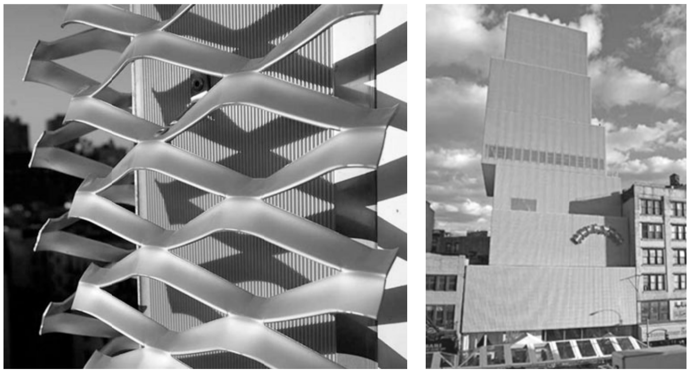

Figure 7. New Museum of Contemporary Art: close-up of expanded metal panel. (SANAA) New York. While the building is not naturally ventilated, it is an example of the use of screens in popular architecture.

Figure 8. Rectorate Office Building. Hauvette & Associés. Cayenne, French Guyana. Images from <http://www.archdaily.com / 21526>

Figure 9. Multiple exterior shading types in Moulmein Rise Residential Building, Singapore by WOHA Architects. *left*: south façade. *middle*: north façade. *right*: view out the north façade. Images from <archnet.org> and <www.akdn.org>

Figure 10. Toulou Collective Housing in Nanhai, Guandong. URBANUS Architecture & Design, Inc.

Figure 11. Examples of low- and mid-rise buildings in the tropical climate of Brisbane, Australia (Donovan Hill). left,W4 Apartments. Right, Cornwall Apartments.

Figure 12. Nishorgo Oirobot Nature Interpretation Centre. Teknaf, Bangladesh. Vitti Sthapati Brindo and Ehsan Khan, 2008.

Figure 13. El Camion Restaurant. Llona+Zamora arquitectos + Fernando Mosquera. Villa el Salvador, Lima, Peru. Images from <*http://www.archdaily.com/94420*>

1.4 CLASSROOMS

The building of interest in this study is the low-rise school building, and specifically the classroom space. Classrooms are good candidates for study; the setting tends to be uniformly and densely occupied with a number of students seated at desks. Except for clothing adjustments, students do not typically have direct control over their thermal comfort in classrooms. Though it is particularly challenging to evenly cool with wind driven ventilation for multiple occupants, the challenges associated with this task may have a role in informing natural ventilation strategies in other nondomestic space types, such as open-plan offices, small retail and clinics in low-rise buildings.

Two main requirements bracketed the scale at which to size the model in this study: indoor air movement studies warrant a larger model for visualizing the interior; taller buildings require smaller models (or a larger wind tunnel) so as not to block more than 5-10% of the wind tunnel cross-sectional area. From the point of view of wind tunnel studies for natural ventilation, low-rise buildings seemed ideal for testing detailed façade components such as exterior shades and windows.

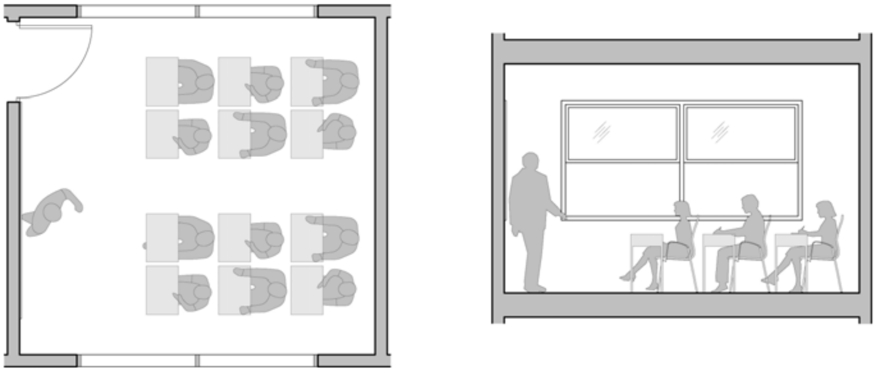

Figure 14. Plan and section of classroom model.

Open-plan spaces (like classrooms or some offices) are particularly desirable from a wind driven ventilation point of view since there are few obstructions. In terms of ventilative (convective) cooling, it is important that furniture obstruct as little as possible in the first twelve inches (30 cm) above the floor. Besides obstructing airflow, furnishings and finishes like seats also add to the thermal insulation at the occupants' bodies; conductive or breathable seat selection can help to remove heat from the body.

Though the tropical vernacular buildings mentioned in the previous section tend to be houses of light wood construction, the historical beginnings of formal education in Thailand existed in the Buddhist temples, which typically had massive (sometimes 30" thick) load bearing walls, shading, and ground contacts[9]. Often the main hall was surrounded on all sides by verandas. Temples were one of the few non-domestic structures where a group of people would regularly gather for prolonged periods of time. Today most classroom buildings are one room deep concrete and masonry construction. It is common for students to not wear shoes in the classroom, further facilitating heat transfer through their socks.

Low-rise school buildings have existed for a long time and are likely to continue to be built and retrofitted in the future. From school houses to school buildings, classrooms have a history of having narrow (1-room deep) plans, as it is common for them to be designed to access light and air. Low-rise buildings in general also offer a number of distinctive properties. Such buildings are common within city

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[9] Sresthaputra, 2003.

centers and they are especially typical at a city’s edges, as they are less costly to build than mid- and high-rise buildings. They are easier and cheaper to renovate, as compared to mid- or high-rise buildings. Though the percentage for tropical regions is unknown, it is likely to be high, since low-rise buildings make up about 77% of the total commercial building stock in the U.S.[10] Examples of one room deep, low-rise classrooms are below. Except for the Royal Oaks School, the others are in tropical climates.

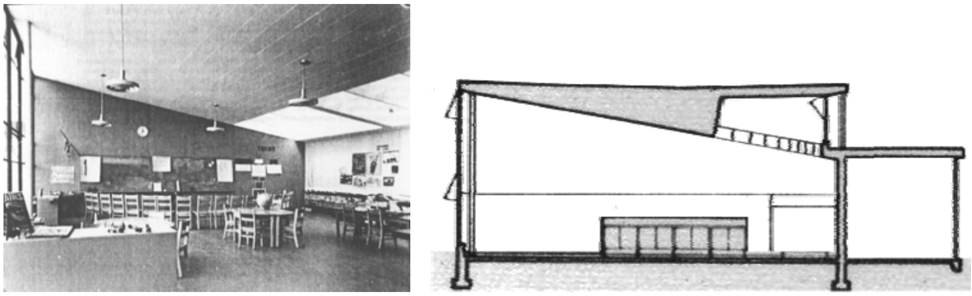

Figure 15. Left: Royal Oaks School, Duarte, California. 34.1˚N latitude. Maynard Lyndon, 1951. (*Lyndon 1993*) Right: Ojai Section. (*Nindra 1998)*

Figure 16. METI Handmade School, Dinajpur, Bangladesh. 25.6˚N latitude. Anna Heringer and Elke Roswag, 2005. (Kurt Hoerbst. *http://www.akdn.org/architecture/project.asp?id=3392 Accessed 5 January 2011*)

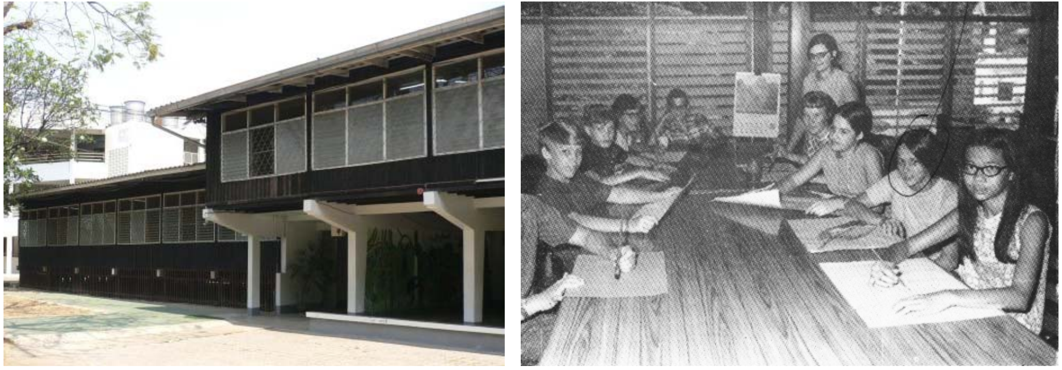

Figure 17. Left: classroom building at Chiang Mai International School, Chiang Mai, Thailand. 18.8˚N latitude. (*Stephens, Kathleen H.*) Right. Classroom interior, showing jalousie windows behind insect screens. (1971 CCC Clarion Call (yearbook, courtesy Cokie Stephens)

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[10] Ed Mazaria is the founder of Architecture 2030, a non-profit organization whose goal it is to “to achieve a dramatic reduction in the climate-change-causing greenhouse gas (GHG) emissions of the Building Sector”

Figure 18. Transitional School, Jacmel, Haiti. 18˚N latitude. John Ryan and Plan International, 2010. (*John Ryan*)

Figure 19. Primary School, Gando, Tenkodogo, Burnika Faso. 11.5˚N Latitude. Diébédo Francis Kéré, 2001. (Francis Kéré *Openarchitecturenetwork.org Accessed 5 January 2011*)

CHAPTER 2 VENTILATION

2.1 THE ROLE OF VENTILATION IN BUILDINGS

In tropical, low-latitude regions, minimizing heat gain allows natural ventilation and other low-energy cooling strategies to work. Natural ventilation provides multiple services: it removes heat accumulation in the building structure (600 CFM)[11]; it cools the space by replacing warm air with cooler air (300 CFM). In addition, the air movement on human skin enhances bodily cooling (300 CFM); and it provides air for breathing (roughly 10 CFM). The type of cooling that is possible is also a function of the amount of wind available and the diurnal temperature ranges (for structural cooling) in a particular site. While the primary purpose of natural ventilation in this study is occupant cooling, the indirect forms cooling outside the scope of this study are important to acknowledge.

STRUCTURAL COOLING. Structural cooling refers to the removal of accumulated heat within the building mass at times when outdoor temperatures are below the comfort zone; it is directly related to the thermal storage capacity of the building and the exposure of thermally massive elements to airflow. Areas beyond the occupied zone – near ceilings, walls and exposed floors – tend to be important for indoor space and structural cooling. Structural cooling is less effective where wide diurnal temperature ranges are not sufficient, as is the case during the tropical monsoon or summer seasons. Though structural cooling is not a primary purpose of natural ventilation in this study, it may have a role in the tropical savannah climate.

SPACE COOLING. Occupied spaces accumulate heat from lighting, people, equipment solar and envelope loads, which increases the ambient air temperature over time. Space cooling refers to

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[11] Brown, G, and University of Oregon.;Northwest Energy Efficiency Alliance.;Seattle City Light. 2004. *Natural ventilation in northwest buildings*. Eugene Or.: University of Oregon. P. 11

the replacement of this warm air with cooler outside air. Balancing low solar gains and daylighting are very much related to the type of shading used, as both direct sun and electric lighting contribute to these thermal loads. Space cooling is an indirect form of occupant cooling and is not a primary purpose of natural ventilation in this study.

BREATHING. It would be difficult to adequately discuss the role of natural ventilation in buildings without first acknowledging its role in our breathing. Respiration is a minor form of bodily cooling and a biological requirement. While the amount of air required for breathing is much less than that for cooling, outside air has other amenities. Unlike recirculated indoor air, outdoor air is more diluted, dynamic in speed and temperature and even carries sound and smell. Outside air is reflective of microclimate, topography, geography and other conditions[12] around the given site. When we go outside for air, we become corporeally aware of our bodies in the surroundings. When outside air comes inside, trances of this connection are likely to follow.

OCCUPANT COOLING. Thermal comfort is elusively complex to quantify. Traditional comfort models (i.e. Fanger) included six quantifiable variables: the two personal variables of clothing level and activity level, and the four environmental variables of air temperature, radiant temperature, air velocity and humidity. Variables harder to quantify that have been shown also influence thermal comfort include climatic adaptation, thermal preference and personal control[13].

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[12] Arens, 1985.

[13] When thermal control occurs through opening and closing windows, the interaction between the user and the building encourages the occupant to be an active participant in the space. This occupant-building interaction visually activates the façade for comfort.

As previously stated, occupant cooling is the primary purpose of natural ventilation in this study. Air movement works to cool the human body in a number of ways: first via the evaporation of sweat from the skin, second by convectively replacing the warmer air near the skin with cooler air and last by replacing warm expired air with cooler inspired air.

There are limitations and caveats to the effectiveness of air movement for thermal comfort: evaporative cooling is less effective when the humidity is higher; convective cooling is not effective when the air temperature is warmer than body temperature; the maximum allowable airspeed at the warm humid end of the comfort zone depends on occupant preference and activity. Findings from recent research and previous studies[14] suggest that in both air-conditioned and naturally ventilated buildings, most occupants prefer to have more air movement and very few want less. How can this finding apply to the design of windows and shades?

While it is possible for natural ventilation to directly cool occupants, this scenario is often more effective for occupants closer to the window than for those who are further away. When the mode of thermal control occurs through the opening and closing of windows, the required interaction between the user and the building encourages the occupant to be an active participant in the space. The architecture becomes visually related to thermal comfort over time via this occupant-building interaction. Provision for occupant control has also been shown to expand the zone of thermal comfort. At the warm, humid end of the comfort zone, the maximum allowable airspeed depends on occupant preference and expectations.[15]

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[14] Arens, E., Turner, S., Zhang, H., & Paliaga, G. 2009.Moving Air for Comfort.

[15] ASHRAE 55-2010, section 5.2.3. This standard also stipulates that the “required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s.” When under local control of the affected occupants, the air

Figure 20. Compound windows with multiple operation types within the same opening. Left and middle, Boyd Educational Center, Glenn Murcutt, 2005. -34.8˚S latitude. Illaroo, NSW, Australia. Image from Dahl, 2010.

2.2 THERMAL COMFORT STANDARDS

Building designers use thermal comfort standards such as *ASHRAE Standard 55-2010*[16], *ISO 7730*[17] and *EN/DIN 15251-2008*[18] to design buildings for human occupation. These standards establish specific criteria for acceptable thermal environments including allowable ranges for air temperature, radiant temperature, humidity and air speeds. In addition to the narrowly defined, laboratory-based results on which they were originally based, the standards have come to incorporate various adaptive models for thermal comfort, which are mostly based on field studies[19]. That is, the standards now recognize that thermal comfort and preferences can differ for people of different climates and habits. ASHRAE-55 was recently modified to expand the allowable range of airspeeds in neutral to warm conditions.[20] This is important to note when discussing whether or not natural ventilation is adequate in providing

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speed may be as high as 1.2 m/s, though it is not explicitly stated. The standard notes that “these figures are conservative for activities above 1.3 mets and for clothing insulation less than 0.5 clo.”

[16] *Thermal Environmental Conditions for Human Occupancy* by the American Society of Heating Refrigeration and Air- conditioning Engineers

[17] *Ergonomics of the Thermal Environment* by the International Standards Association

[18] Indoor environmental Input Parameters for Design and Assessment of Energy Performance of Buildings addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics.

[19] de Dear and Brager 2002. Raja et al 2001. Kwok, 1997. Busch 1992.

[20] ASHRAE 55-2010, section 5.2.3. Elevated Air Speed. This standard also stipulates that the “required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s.” When under local control of the affected occupants, the air speed may be as high as 1.2 m/s with occupant control. The standard notes that “these figures are conservative for activities above 1.3 mets and for clothing insulation less than 0.5 clo.”

comfort at the warmer end of the comfort zone, such as those found in tropical environments. This encourages building designers to use air movement to improve both energy and comfort performance and also opens opportunities for implementing low-energy systems that have cooling capacity limitations. [21] ASHRAE-55's recent modification increases the upper limit of air movement to 1.2 m/s, though the number is not clear for naturally ventilated spaces. Note that the upper limit of relative humidity for naturally conditioned spaces is also not clearly defined for these spaces.

CRITERIA. Given the context of a classroom in this study, airflow characteristics are desirable when the airflow plan (at the seated head height of 1.1 m) has a high velocity with a low spatial variation, or $\boldsymbol{v}_{PLAN}$ and $\boldsymbol{c}_{sv}$ respectively in the wind tunnel test results. More uniformity in airspeed across the airflow plan is considered to be desirable, as a high variation in indoor airspeed can lead to points that are simultaneously too windy (i.e. near the inlet) and points that are too warm (i.e. far from windows) in the same zone. This study assumes that the maximum allowable indoor airspeed is 3 m/s [22] and that occupants have the can reduce air velocity by operating windows or changing seats if speeds are higher than preferred. Thermal acceptability for our purposes is when the SET* adjusted PMV[23] is between slightly cool (-1) and slightly warm (1), which equals a 26% people dissatisfied (PPD). ASHRAE considers a PMV between -0.5 and 0.5 or a PPD of 10% to be acceptable. Air velocities are considered to have

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[21] Zelenay, K., Perepelitza, M, Lehrer, D. 2010.

[22] Based on a discussion with thermal comfort researchers, 3 m/s was considered to be an exuberant number; this number was also the maximum air velocity input allowable for the ASHRAE Thermal Comfort Tool.

[23] "The Standard Effective Temperature (SET) model uses a thermophysiological simulation of the human body … This model enables air velocity effects on thermal comfort to be related across a wide range of air temperature, radiant temperature, and humidity." ASHRAE 55-2010, section 5.2.3.2.

occupant cooling potential when they can offset higher temperatures in the SET* adjusted PMV thermal comfort model.

2.3 OBJECTIVES

It is the hope that this document sheds light on one of the many methods of studying airflow and inspires architects, especially those designing for tropical climates, to consider the design challenges associated with natural ventilation as opportunities rather than simply accepting this to be outside their scope and beyond their control.

As discussed in section 1.2 of the introduction, architects have been increasingly using new types of screens and shading devices that likely affect airflow. While other forms of external shading have been studied in terms of airflow in the past, screen shading systems have not been analyzed in terms of airflow before. The purpose of this study is to assess the impact of a range of shading and window configurations on indoor airflow in order to identify how specific inlet geometries affect the effectiveness of wind-driven cooling in a warm humid climate. While natural ventilation can passively cool occupants and reduce or eliminate the need for mechanical cooling, airflow in buildings is inherently difficult to analyze. Through examining of a number of façade inlet configurations, this study seeks to develop a basis for building façades design principles in terms of natural ventilation. It is the hope that the information presented in this document will encourage designers to consider using natural ventilation in tropical climate projects and help them maximize the potential of natural ventilation in building design.

The impact of inlet façade components - made up of exterior shading devices and windows - on natural ventilation will be assessed in terms of the mean velocity and distribution of the airflow. The main questions asked are:

- What combinations of shading devices and window types create uniformly high airflow across the occupied zone[24]?
- How do exterior shading screens in front of operable windows affect airflow and should they be used if natural ventilation is a goal?
- If the shade screen reduces air velocity, what characteristic of its geometry affects this? How do different types (e.g. perforated panel and thin louvers) of shading devices compare in terms of slowing down or changing the directing of airflow?
- How does the airflow vary with window type?
- Given a combination of shades and windows that effectively promotes air movement, at what times might wind-driven ventilation be acceptable for thermal comfort?
- How might design teams apply this in a project?

2.4 APPROACH

The independent and interdependent effects of the two component types (shades and windows) on airflow are examined using a physical scale model of a classroom in a boundary layer wind tunnel. The desirable airflow characteristics will have a high average velocity ratio with low variation across the airflow plan. This study looks at two types of external screen shades: a perforated panel system and thin exterior louvers; and three types of operable windows: awning, casement and double-hung windows. Some examples of screen shades and window types are shown in Figure 21 and Figure 22. Out of the tested configurations, the most

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[24] ASHRAE 55-2010, 7.2.2: Height Above Floor Measurements. Air temperature and air speed shall be measured at the 0.1, 0.6, and 1.1 m (4, 24, and 43 in.) levels for sedentary occupants at the locations specified in Section 7.2.1. Standing activity measurements shall be made at the 0.1, 1.1, and 1.7 m (4, 43, and 67 in.) levels. These heights correspond to seated and standing ankle, waist and head levels.

promising shading-window combination is selected for a more detailed exploration, where the thermal comfort potential is assessed for the tropical climate of Bangkok, Thailand.

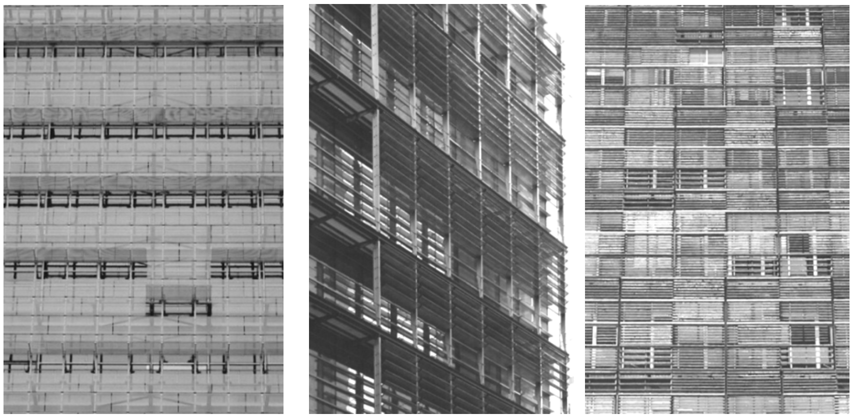

Figure 21. Screen shading systems are prevalent in contemporary architecture. From left to right: perforated panels, thin louvers and wood slats.

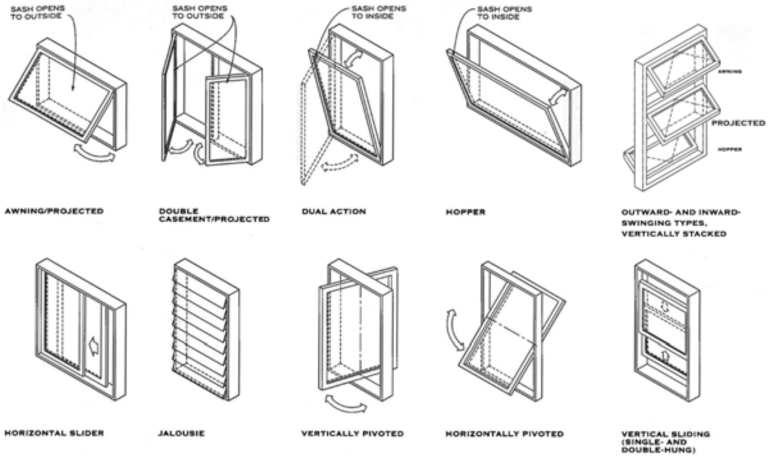

Figure 22: Window Operation Types. (Architectural Graphic Standards 11th ed. p.186) Top left: *awning*, *casement*, dual action, hopper and a combination window, with multiple types in one frame, including, awning, projected and hopper windows. Bottom left: horizontal sliding, jalousie, vertically pivoted, horizontally pivoted, and single- and *double-hung*.

CHAPTER 3 PREVIOUS RESEARCH

Applying the thermal comfort standards mentioned above is not a simple task and architects are typically not involved in the analysis related to comfort standards. Typically, consulting engineers are the ones who employ these standards. Simplified guidelines for architects have attempted to bridge this gap and have historically discussed various forms of mechanical equipment required for heating, cooling and ventilating. In these guidelines, ventilation through windows was treated more as an alternative, non-essential strategy.

3.1 EXISTING DESIGN GUIDELINES

Research on natural ventilation has been conducted at both the academic and professional levels, using both physical and mathematical models. While there has been some effort to consolidate such research into design guides, much this dates back to the 1980s or earlier and is not easily accessible for most practicing professional engineers and architects today.

Existing design guides common in architectural practices do not have specific information on *how* to design windows and shades for airflow. While it is an excellent schematic design guide for architects, G.Z. Brown's *Sun Wind & Light* (SWL) is cursory in its mention of the effects of sun shades and window types on airflow; Brown states that shades can obstruct flow. This is understandable, since this might be of more significance during later stages in design. That said, Brown does cite the Rectorate of the Academy of the Antilles and Guiana (also known as the Education Authority of Martinique), which has fins for directing airflow that “also help with shading the openings.[25]” The references and studies cited in *SWL* are also helpful for further research.

Similarly, *Mechanical and Electrical Equipment for Buildings*[26] provides useful rules of thumb for choosing window types for airflow based on percentage of effective opening area, which is not clearly defined. Figure 23 (left) was cited in *Environmental Control Systems* by Fuller Moore, referencing *Energy-Efficient Florida Home Building* by Vieira and Sheinkopf). Similar windows (but with different effective opening percentages) are also offered by Knaack in *Façades: Principles of Construction* (*Figure 3*, right). The authors above did not describe how these percentages were derived. (Though there were natural ventilation studies at the FSEC at the time, the authors do not reference other sources for this.) While this may suffice for very early design calculations, such omissions give no clue as to when these numbers are reliable for later design phases, when more decisions, like the type and number of openings, must be made.

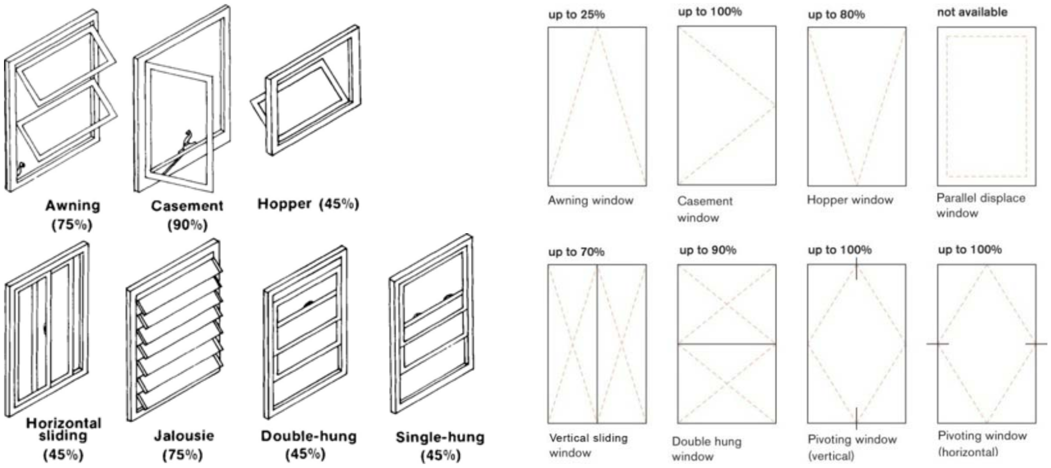

Figure 23: (Left) Effective open area, also called window porosity, of various types of windows from *Energy-Efficient Florida Home Building*, 1988, p.7-3. It is unclear how these percentages were derived. (Right) Note the very different effective open areas from *Façades: principles of construction*, p. 75.

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[25] Brown, Sun Wind and Light p. 184.

[26] Grondzik, Walter T., Alison G. Kwok, and Benjamin Stein. 2009. *Mechanical and electrical equipment for buildings*. Hoboken, N.J.: Wiley.

3.2 REGION-SPECIFIC GUIDELINES

Additional specific, and often obscure, design guidelines for natural ventilation are available from conference proceedings and energy research centers, such as the Florida Solar Energy Center (FSEC). Examples of this include *Cooling with Ventilation*[27] for the southeastern United States, *Ventilation of Wide-Span Schools in the Hot Humid Tropics*[28], *Natural Ventilation in Northwest Buildings*[29]. Except for the last book mentioned, much of this work was done in the late 1970s and early 1980s; while these efforts have much useful information, it is unlikely that architects who do not have access to major libraries can easily find them.

3.3 METHODS OF TESTING WIND-DRIVEN VENTILATION IN BUILDING DESIGN

Though wind driven ventilation in buildings has been used for a long time, methods of estimating its performance have not been around as long. Rules of thumb for architects involve manipulating inlet and outlet areas as a function of the floor area. Rules of thumb are perhaps acceptable for an approximated notion during very early design phases, but do not address the interaction between sun shading and opening areas. For more sophisticated natural ventilation testing, architects usually refer to consultant engineers for design guidance. In turn these mechanical and/or civil engineers use a variety of tools for estimating airflow. These include:

1) The discharge coefficient method
2) bulk airflow models based on pressure coefficients
3) computational fluid dynamics (CFD)

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[27] Chandra et al, 1986. The FSEC has published many design guides and papers. http://www.fsec.ucf.edu/en/index.php

[28] Chand, Ishwar, 1977. UNESCO sponsored research done at Central Building Resesarch Institute, Roorkee, India.

[29] Brown, G, and University of Oregon, 2004.

Researchers employ an even broader range of assessment methods. For the purposes of research, methods of testing indoor wind-driven airflow in buildings include[30]:

- *a)* full and model scale outdoor investigations
- *b)* bulk airflow modeling
- *c)* computational fluid dynamics (CFD)
- *d)* the use of wind discharge coefficient method
- *e)* direct measurement of indoor velocities in a scale model within a boundary layer wind tunnel

The difference between the tool palette of the design engineer and that of the researcher arise largely from the costs involved with wind tunnel testing and the absence of a constructed building (as required in full scale investigations) to test during the design phase. Bulk airflow modeling is not so effective when building geometries are complex or in the case of simple geometries with large openings (as is often the case in hot, humid climates). Of the non-physical tools in the palette, only CFD can provide some guidance to the relative performance of different windows and shades. It should be noted that the kind of CFD used for building design simulations (as opposed to those for aircraft design simulation), rarely models eddies or fluctuations in velocity that are common in natural wind, because doing so would be too expensive[31]. In addition to the challenges of modeling natural wind in CFD, utilizing CFD effectively has a steep learning curve and requires much operational experience before reliable results can be obtained. While each of the evaluative methods has positive features and drawbacks, wind tunnel model testing was selected for the purposes of this study.

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[30] Ernest 1991

[31] The excessive costs include that for technically skilled labor, many hours of work and high-end software. Based on a conversation with David Banks of CPP Wind Engineering and Air Quality Consultants

There were a number of reasons for this: wind tunnel testing has allows for both velocity measurements and flow visualization; exploring the method was relatively accessible; once built, physical models are relatively easy to adjust; most significantly, the Building Science Lab at UC Berkeley has a functional boundary layer wind tunnel as well as researchers with direct experience with this specific wind tunnel.

As can be said of every method, wind tunnel testing has its limitations. In order to fit the testing program into the wind tunnel methods, models cannot obstruct more than 10% of the cross section before results become unreliable. (Some researchers keep their models under 5%.) This limits the size of the test model, causing mid-and high-rise buildings challenging to study. Though originally the idea was to test a room as part of a building mass, it had to be modeled as a one-room box in order to capture the adequate detail required in the shades and windows. In addition to this, the wind tunnel had not been used to collect velocity measurements in about a decade, so more time was required to get the equipment fully functional.

Figure 24.Previous natural ventilation research conducted in the wind tunnel.

Author(s)	Year	Goal	quality affecting indoor airflow	Boundary Layer?	# Angle Tested	# Tests	Tunnel Blockage	Model Scale (dimensions)	metrics	Observations / Conclusions	Notes
Smith, E.G.	1951	comparision of model "flow chamber" and test building.	window details	not likely	?	?	?	1:15		window frame & sash details affect indoor flow pattern	
Holleman, T	1951	Air flow through conventional window openings	windows types: casement, projected, double-hung	not likely	not sure	?	?	some at full scale, some at model scale	smoke		
Givoni	1962	investigate NV challenges in hot climates for occupants and bldgs	inlet/outlet size, cross vent, window location, no. of openings	NO	0, 30, 60, 90		12.8%	(65 x 65 x 50 cm)	5 x 5 v	2 models - 1 room and 2 rooms+corridor in between; tested only square openings	
Chand	1968	Sill Height on Indoor Air Motion	sill height	NO	?		9.9%	1:12 (38x38x25.4 cm)	velocity	0.85% of seated breathing height ideal	using this for my sill height
Chand +	1971	Affect of Louvers on Indoor Air Motion	exterior projections: horizonal overhangs and vertical fins.	NO	0, 15,30, 45,60, 75, 90	7	6.2%	1:15 (30x25x20 cm)	velocity	horizontal overhang above occ. zone requires gap between fin and façade. semibox, L-shape shade effective for airflow	
Chand +	1975	manipulating air flow w/ window accessories (valence)	valence (air deflector) size, location	NO	0?		5.7%	1:15 (28x24x20 cm)	velocity	valences have potential to deflect higher flow down to occupied zone	directs flow downwards; retrofit option
Aynsley	1979	wind-generated natural ventilation of housing for comfort in tropical climates	architectural features: elevated on stilts, eaves, projecting end walls + balconies.	YES	0, 30, 45	18	2.4%	1:150	pressure meas. only	elevated single story model with extended eaves and end-walls performed best	
Sobin	1981	window design that corresponds to air velocity + thermal comfort	in-outlet size, shape & location, wall thickness, window accessories, room depth	YES	0, 45, 90, 315, 270	138, 244	11% max	1:12 (33x33x20.3 cm)	5 x 5 v 4 x 5 v (sect)	1) Givoni's 1962 studies used horizontal windows (no sq or vertical opngs used).	highest av indoor air speed, inlet outlet:inlet = 1.25
Ernest	1992	Prediction of Indoor Air Motion for Occupant Cooling in NV Bldgs	bldg mass, roof shape, obstructions, external bldg projections, interior partitions, window size, window location	YES	0, 15, 30, 45, 60, 75, 90		0.8%	1:30 (25x25x10 cm interior)	4 x 5 v	5 bldg geometries, 20 points - based on equal area coverage for each probe. 4 probes through WT floor, moved 5 times	

3.4 ACADEMIC RESEARCH AND PARAMETRIC WIND TUNNEL VENTILATION STUDIES

For this study, a survey of previous research was conducted in an effort to identify the significant parameters affecting indoor airflow. Bowen (1981) consolidated the general findings of various wind tunnel studies prior to 1981 into a conference paper[32]. Wind tunnel studies on natural ventilation in buildings were begun in the 1950s, at Texas Engineering Experiment Station (Smith, 1951 and Holleman 1951) and continued into the early 1990s. Various building parameters affecting indoor air motion were investigated within this body of work.

BOUNDARY LAYER / SITE DENSITY. Boundary layer describes layers of wind near the ground which are always turbulent due to roughness in the surface of the earth. The wind speed is zero at ground level; the amount it increases with height depends on the type of terrain and is called a boundary layer profile. The presence of neighboring buildings reduces wind speeds. In the wind tunnel, the boundary layer roughness is generated by using wood blocks. Ernest tested the effects of three boundary layers (terrains corresponding to flat farmland, villages and suburbs) on a low-rise building model and found virtually no differences in pressure coefficients [33]. He also noted a previous study (Akins and Cermak 1976), wherein the affect of different boundary conditions had much more of an effect on high-rise buildings.

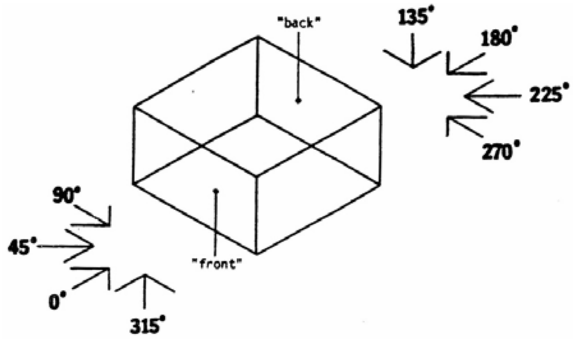

Figure 25. Sobin's diagram describing various incident wind angles he tested.

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[32] Bowen 1981.

[33] Ernest 1991. p.40-41

WIND DIRECTION. Givoni (1962) found that average indoor air velocity was higher for the incident wind angles of 45° than for 0° (Figure 25). Sobin tested multiple window proportions and found this only to be true for horizontal windows, while square windows performed better at 0°. In his 1977 studies, Chand concluded that wind direction cannot be studied independently of other variables.

BUILDING MASSING. In his report on the ventilation of tropical school buildings, Chand (1977) compared various building floor plan shapes; he found wind shadows could be minimized with L-shaped (or re-entrant cornered) plans. In a similar manner, Aynsley (1979) studied six types of free-standing houses for hot humid climates in the context of Queenland, Australia. He concluded that both elevated and ground-level houses with extended verandas and end-walls (types 4 and 2 respectively in Figure 27) could provide the highest cooling potential in the test set. These architectural features, not surprisingly, are also common to Australia's hot humid tropics. Through CFD tests*,* Tantasavasdi et al (2001) came to a similar conclusion. He found houses elevated on stilts, rather than on ground level, to be more effective for natural ventilation in the Bangkok suburban climate.

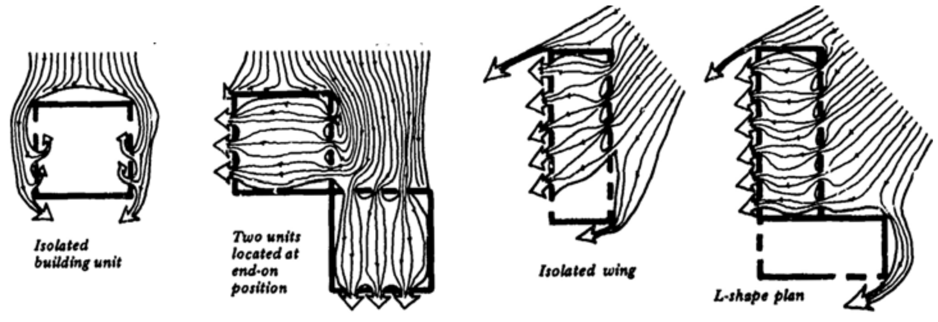


Figure 26. Chand (1976) studied concluded that wind shadows could be remedied with re-entrant corners.

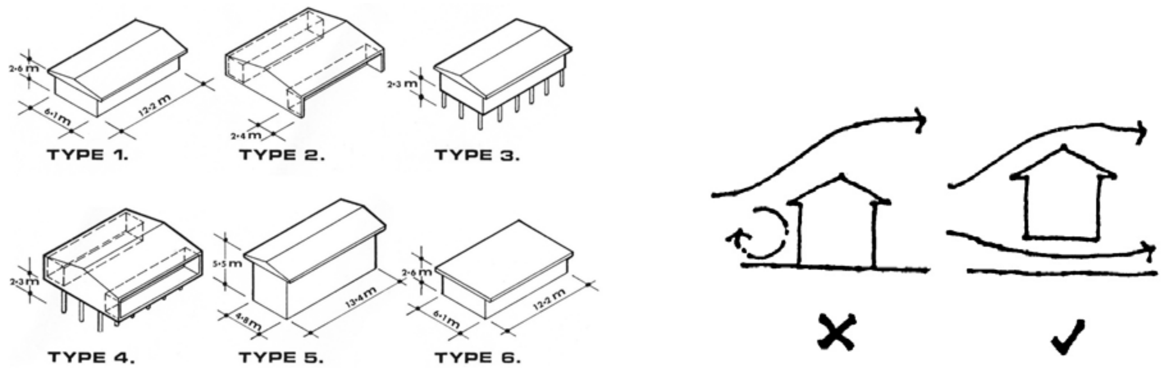
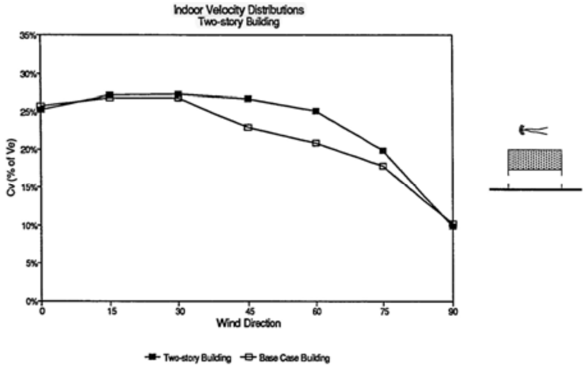


Figure 27: (Left) House types tested by Aynsley (1979). Types 2 and 4 (with eaves and end-walls, with and without stilts) showed the most cooling potential. (Right) Design strategy based on findings from CFD simulations (Tantasavasdi et al, 2001)

At a more basic level of massing, Ernest (1991) tested the addition of mass onto his baseline building. He added on supplementary blocks above and beside the baseline model, although not simultaneously in both places, as would be the case in a midrise building. When adding a block to increase the height of the building, he found a 5% increase in average interior air velocity at some angles (between 30° and 75°). There was little difference at 0°, 15° and 30° angles of incidence. When a block was added to one side of the building, he found less than a 5% increase at some angles. (The interior air velocity was very close to the single block except between 30-75°, where there was less than a 5% increase.) When two blocks were added to the right and left side of the baseline, the average air velocities decreased slightly, as compared with the single block.



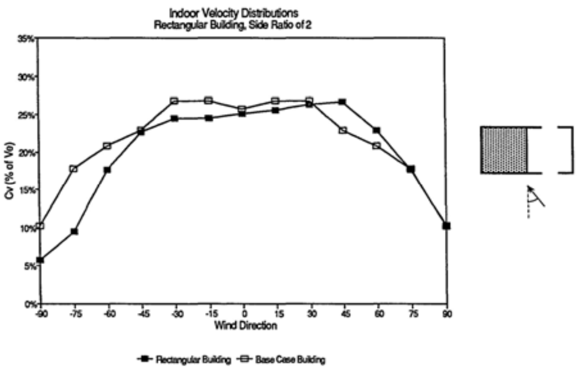


Figure 28 (left). Added height increased average velocity slightly in baseline building at incident angles between 30˚-75˚. Figure 29 (right). Added width in plan decreased air velocity except when at oblique angles between 30˚-70˚

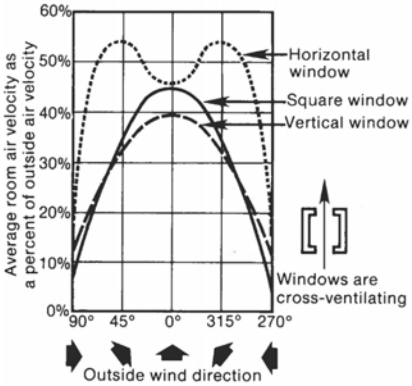


Figure 30. The impact of window shape on air velocity. (Sobin 1981, modified by Chandra 1986.)

ROOM DEPTH and PROPORTIONS. Both Sobin (1983) and Chand (1966 and 1977) tested the affects of room depth proportions on indoor airflow. In his study on ventilation in tropical schools, Chand (1977) concluded increase in the span depth of a building reduces the achievable wind speeds at all points inside the building and that this reduction was more pronounced below sill level, such as for students seated on the floor. Sobin's (1983) data similarly suggested that the airflow in shallow and deep rooms is largely dependent on window geometry. In a room with vertical, floor-to-ceiling inlet and outlet openings, the air velocities significantly decreased in the deeper room further away from the window. For the horizontal windows in Sobin's studies, however, room depth did not greatly affect the average indoor air velocities in plan or section; in plan the average air velocity actually increased 4% while it decreased 5% in section between the shallower and deeper rooms.

OPENING SIZE, SHAPE and LOCATION. Sobin (1983) did an extensive study of various opening shapes, sizes and geometries. He concluded that window opening shape was the "single most important window design parameter in determining the efficacy of wind-driven ventilative cooling."[34] His findings suggest that horizontal windows produce more room airflow at a wider range of angles than square or vertical windows (Figure 30). Chand (1968) found that the height

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[34] Sobin, 1981.

of the window sill had a significant effect in the air movement in the “living zone” between 0.6 and 1.2m; a sill height of 0.9m or 85% of the desk (working plane) height was ideal for achieving maximum air motion in the breathing zone.

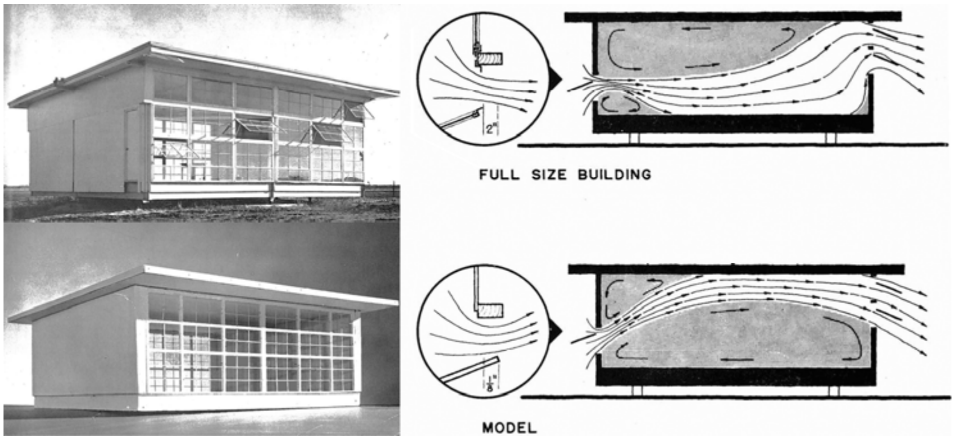
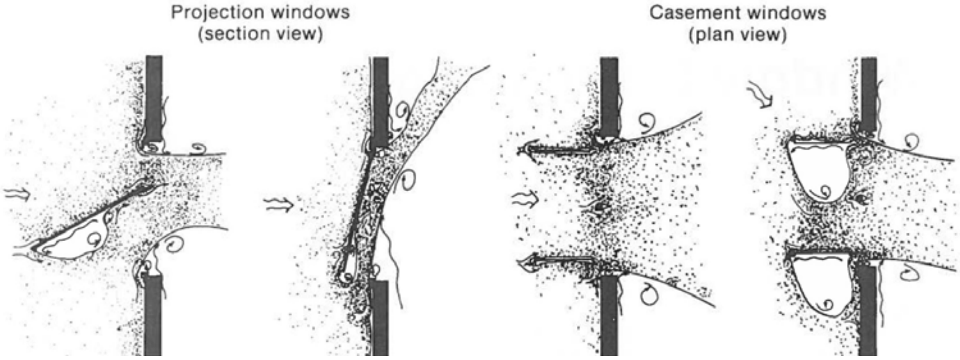


Figure 31. Smith, 1951. The building model showed only a small difference in detail compared to the test facility, causing the flow pattern to be very different from that in the actual building. The discrepancy resulted from a difference in sash and frame detail.


Projection windows (section view)

Casement windows (plan view)

Figure 32. Drawings of full-scale and model studies of different window operation types. Chandra 1986, preprinted from Holleman 1951.

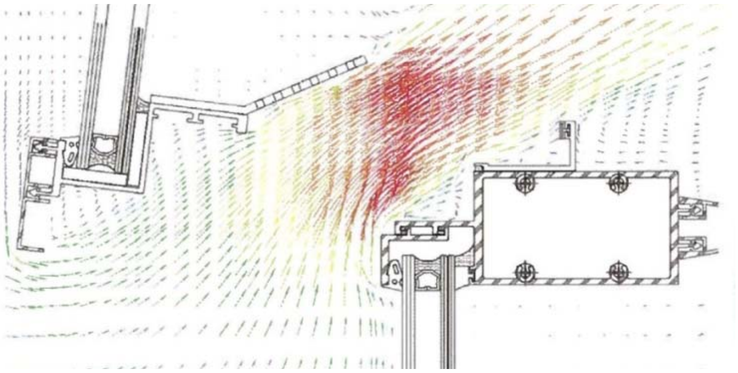


Figure 33. CFD test of an extrusion detail at the bottom of an awning window for flow redirection into the occupied zone.

WINDOW GEOMETRY and DETAILS. Many past wind tunnel ventilation studies were done on thin-walled, one-room models with a single inlet and a single outlet, a basic geometry that might be found in school rooms and residential structures. With few exceptions, only rough openings were modeled – that is, without a window a frame or moveable sash. Often walls and sill were not modeled with realistic thicknesses. As a significant part of the geometry, these details have potential to enhance or obstruct airflow to the occupied zone, as shown in early studies (Figure 31 and Figure 32) as well as in a CFD-tested design of the window frame detail at the SF Federal building below).[35]

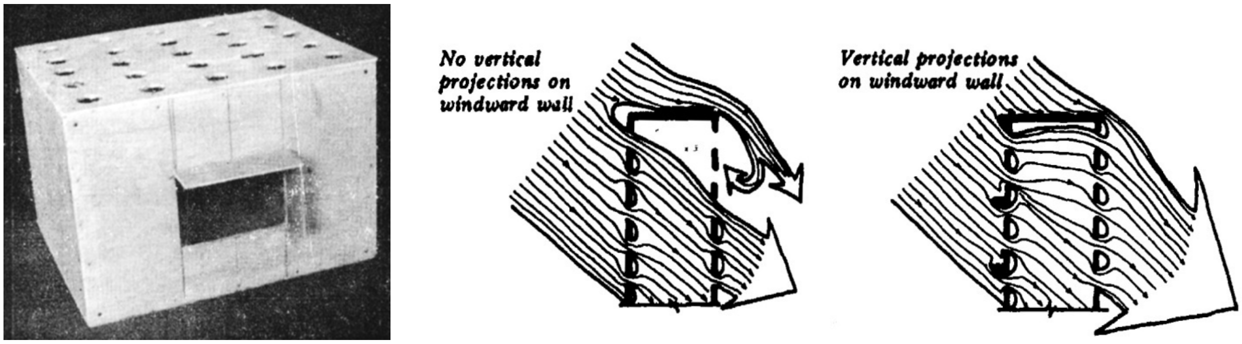
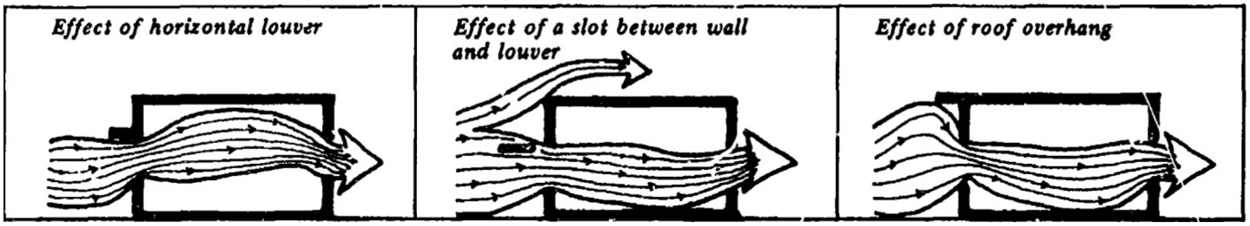


Figure 34. Left: semibox type projection tested by Chand. Middle & right: Effect of Vertical Projections on the Windward Wall. Below. Effect of Louvers (or horizontal shade). Chand, 1976.



EXTERIOR PROJECTIONS and SHADING DEVICES. In his extensive studies, Sobin (1983) was concerned with window system selection on the basis of the "potential for passive ventilative cooling."[36] Both Sobin and Chand (1971, 1975, and 1977) tested multiple fenestration features, including various forms of shading devices of different geometries. Chand and Krishak (1971) studied the impacts of horizontal and projections on indoor air movement. The study found that "semibox type" projections (Figure 34 right), made up of an overhang and a vertical fin, were most effective promoting air motion in the occupied zone for all angles of incidence

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[35] Carter, Brian. 2008. *GSA/Morphosis/Arup: San Francisco Federal building*. Buffalo, NY: School of Architecture and Planning, University of Buffalo, The State University of New York. *(insert image into document)*

[36] Sobin, 1981 p.195

between 0˚ and 90˚. Chandra (1983) studied the effects of wing-walls on enhancing natural ventilation.

Tests on the effect of shading devices on indoor airflow have been addressed through means other than wind tunnel tests. In the examples found, the methods involved measuring the pressure difference across full-scale louvers in a pressurized tests chamber and comparing results with mathematical models. Tsangrassoulis et al (1997) tested moveable vertical and horizontal louvers on an outdoor test cell with single sided ventilation for the purpose of improving a network flow-based method of testing airflow through shading. Pitts and Georgiadis (1994) tested Venetian blind angles and window-opening degrees in a wind tunnel. No mention was made of the particular type of windows used in the test. They observed that thin louvers at the partially closed angle of 45° showed little flow reduction and could enhance air flow through partially opened windows. When set at 85°, however, the blinds significantly blocked airflow. The findings in the three studies above are limited to the region immediately behind the louvers. This information is helpful, but limited in applicability in the context of tropical climates where much more flow is needed to achieve thermal comfort.

A large concentration of wind tunnel based natural ventilation studies is concerned with how to cool by convection in hot humid and hot dry climates (Chand, Givoni 1962). It is from these tropical regions that much of this research originates. Ishwar Chand worked in India and Thailand; Richard Aynsley resided in Papua New Guinea and Queensland; Baruch Givoni spent a significant amount of time in Haifa, Israel; Harris Sobin did his wind tunnel studies at the Centre for Tropical Architecture at the Architectural Association, in London and taught and practiced in Arizona.

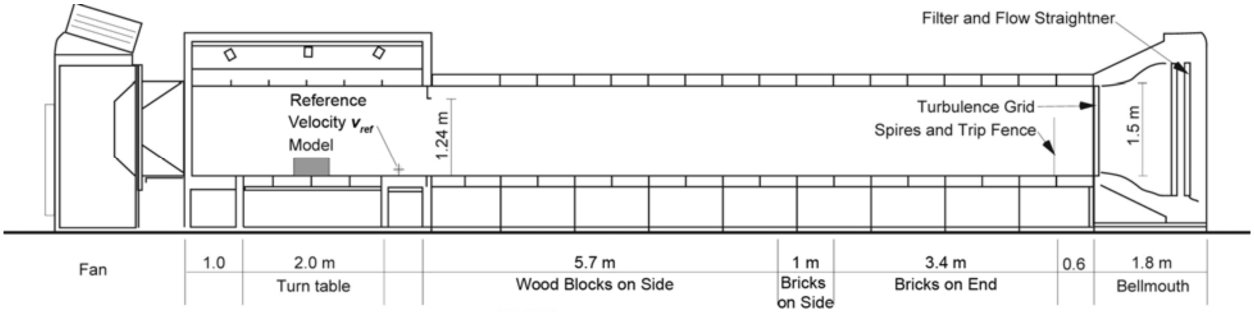
The goal of wind driven ventilation in hot, humid climates is to provide adequate air movement primarily for bodily cooling. It is particularly in the non-residential buildings in such climates that the findings for such research can potentially have an impact.

CHAPTER 4 METHODS

This chapter covers the methods involved with the testing of a scale model and its components in a boundary layer wind tunnel. Each configuration involved taking interior air velocity measurements inside the model at three angles of incidence: 0˚, 45˚, and 90˚. Testing began with configurations of individual components first and then moved on to combinations of components later. Air velocities are spatially described through iso-velocity contour maps in plan and section. Flow patterns are then described in airflow plans and sections drawn from smoke studies observed first hand and captured on video.

4.1 BOUNDARY LAYER WIND TUNNEL

Velocity measurements and smoke studies were carried out in the boundary layer wind tunnel (BLWT) housed in UC Berkeley’s Building Science Laboratory. The wind tunnel is an open circuit design with interior cross sectional dimensions of 1.5 m high by 2.1 m wide and an overall length of 19.5 m. The first 12.8 m of the wind tunnel, from the bellmouth inlet, is the flow processing area and contains a combination of turbulence generating blocks across the floor to simulate characteristics of flow approaching the building model. Immediately following the boundary elements is a 3.7m long test section in which scale models are tested on a 2m diameter turntable. The turntable is used to study the incident wind angles of 0˚, 45˚ and 90˚ moving counterclockwise in plan.



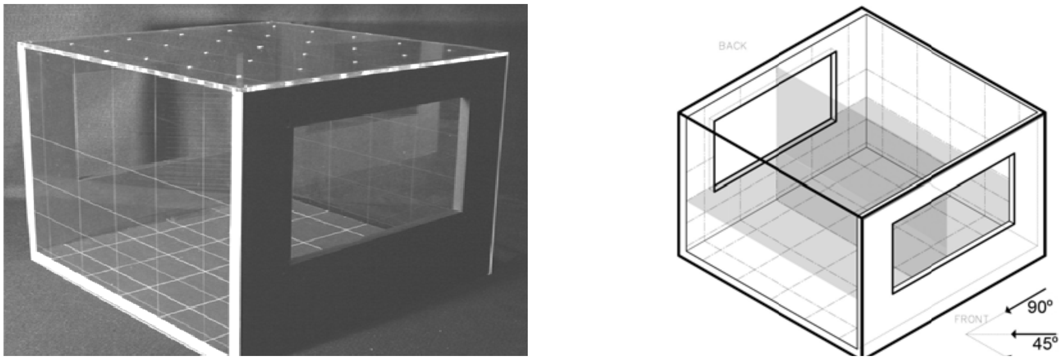


Figure 35. Base model with rough openings, photograph and drawing.

4.2 MODEL DESCRIPTION

The model, at the scale of 1½" = 1'-0" IP units (or 1:8), represents a single classroom within a low-rise building. In order to work within the methods of the BLWT, the classroom was modeled as single room. The model has reconfigurable windows and exterior shading for the purposes of measuring and visualizing airflow. The occupancy type and methods induced limits (described earlier) while seemingly abstract, a single-room space is not far from what one can expect in tropical climates, as shown in the introduction. The model consists of four walls, a ceiling and a floor. The two walls with window openings were designed as rough openings so as to receive interchangeable windows types and exterior shades. While it is possible to adjust the opening amounts for each of the windows, the window configurations were always tested as fully open. The exterior shades were offset 3'-0" model scale from the exterior wall. The other two walls were made of clear acrylic and scored at the measurement heights corresponding to the various heights of the occupied zone. The clear acrylic ceiling of the model has 3/8" (9.5 mm) holes corresponding to the points of velocity measurements. A rubber washer created a seal in the gap between the probe and the acrylic hole. Unused holes were taped shut during the measurements.

This test is Reynolds number independent, as the model parts have sharp edges and the smallest dimensions exceed those allowable. At this scale, openings can be no smaller than 1/8” (or 3mm) actual size before the Reynolds number becomes problematic. The perforations had to be enlarged in order to not have holes smaller than 1/8”. The actual perforations scaled to model size would have resulted in 1/16” diameter holes, which is too small for dynamic similarity. The smallest dimension in the model was for the holes in the perforated panel shade, which are 5/32” in diameter. (See Figure 37 for a visual comparison.)

4.3 VELOCITY MEASUREMENTS

Velocity measurements were taken with a TSI Model 1266 hotwire anemometer. The hot-wire sensor at the tip of the anemometer is most accurate at measuring airflow normal to the wire[37], which in this case means locations in horizontal planes parallel to the wind tunnel floor.

Velocity measurement points were taken in two planes. A horizontal 5 x 5 grid[38] of points 37” (or 1.1 m) above the model floor, corresponding to seated head height, was established to characterize air flow across the room plan, creating an “airflow plan.” A vertical grid of points was also taken at 4”, 24”, and 67” (0.1, 0.6, and 1.7m respectively) along the centerline of the model from inlet to outlet openings, creating an “airflow section”[39]. It is expected that the components will be tested at 0°, 45° and 90° relative to the incident wind, with 0° being head-on from inlet-to-outlet and 45° and 90° turned in the counterclockwise direction from above. With twenty-five points in plan and twenty in section (and 5 that overlap

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[37] Cermak, 1984 [find page]

[38] The 5 x 5 horizontal grid in the occupied zone corresponds to the work of Givoni, Sobin and Chand. Sobin also used a 5x5 grid of points in section.

[39] Sobin used this term to describe these measurement planes.

both), forty different points were measured inside the model for each setup at each angle of incidence.

Airflow in the BLWT, like natural wind, exhibits much fluctuation in velocity. In natural wind, especially in urban conditions, there is yet a higher degree of fluctuation, as larger eddies are possible. To minimize the effects of fluctuation during the velocity measurements, each point was measured 900 times over one minute. The mean wind velocity during that minute was calculated by a customized data acquisition program in LabView 8. The mean velocity at each point ($\mathbf{v}_i$) is then divided by the reference velocity ($\boldsymbol{v_{ref}}$), taken from an unobstructed location the approach flow, in order to obtain velocity ratios. In this case, the reference velocity was taken from a point more than three times the model height and at the same elevation as the plan measurements in the unobstructed stream between the model and turbulence blocks. Velocity ratios are dimensionless values that alone have not meaning; it is only when they are used with wind and data that they begin to suggest in actual air velocities and thus significance for a specific case.

There are many factors that are difficult to control in the wind tunnel. It is Important to identify what is more controlled and what is less controlled. In this case, having a boundary profile was deemed more important than having an appropriately scaled boundary layer profile, since little difference existed between velocity and pressure measurements at different boundary layer scales for previous low-rise building studies[40].

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[40] Ernest, 1991. p.40-41

4.4 FLOW VISUALIZATION

Flow visualization was observed with “smoke” created with an ultrasonic fogger[41] attached to a compressed air hose and later a theatrical smoke machine. Video footage and photographs was captured from these studies in order to observe interior flow direction. Though Images alone are not very descriptive as the fog does not photograph well, video footage was helpful in reviewing what was empirically observed in space. (It was important to physically change viewing angles at times.) Fog is denser than air and this was satisfactory for observations within in the occupied zone. For observing flow in the upper portions of the room, smoke had to be introduced for instantaneous observations. Often, the fog would dissipate quickly; this required filling the model with smoke with the fan off and switching it back on again once the model was filled.

Figure 36. Images taken from flow visualization using ultrasonic fog. (Left) Model with awning window in near still air conditions at 45°. The wood blocks used that contribute to the boundary layer are visible in the background. (Right) Flow visualization of thin louvers and rough opening at 0°.

4.5 SELECTION of SHADING DEVICES & WINDOW TYPES

Of the exterior shading strategies discussed in Chapter 1, the perforated screen and louver screen are frequently visible in contemporary high performance buildings. As there can be a

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[41] This particular boundary layer wind tunnel within a shared office space, so the type of smoke used had to be safe for human breathing. Titanium tetrachloride, the more common type used, is toxic to breathe.

wide variation in shading devices, those selected for testing were designed and constructed to have a porosity of 53%. While the perforated panel was modeled after the San Francisco Federal Building (SFFB), the louver screen was not modeled after a particular building example, though are visually related to the Terry Thomas building and New 42nd Street Studios. Combinations of shading devices and window types were also selected on the basis of their use in high profile green architecture, such as those previously noted. The perforated panel system based on the SFFB, was made with perforations scaled up for wind tunnel modeling, as mentioned in section 4.2. The thin louvered screen is made up of 4" x ½" louvers tilted 22.5° downward and spaced 3 ¾" and 7 ½" on-center (for view and to equalize porosity with the perforated panel). The dimensions of the louvers are comparable to that of commercially available exterior Venetian blinds.

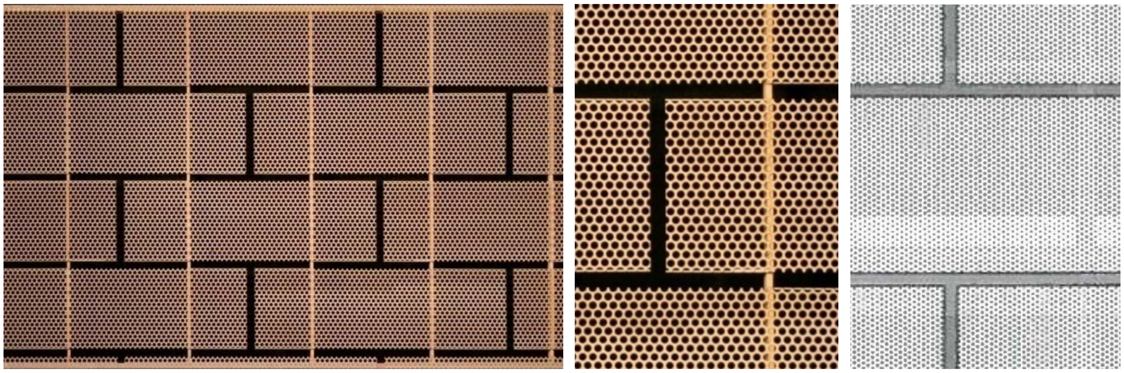


Figure 37. Perforated panel screen. Left: view of perforated screen as constructed. Middle: detail view of actual screen tested with larger holes, but equal porosity. Right: screen as drawn in elevation (Murray 2009).

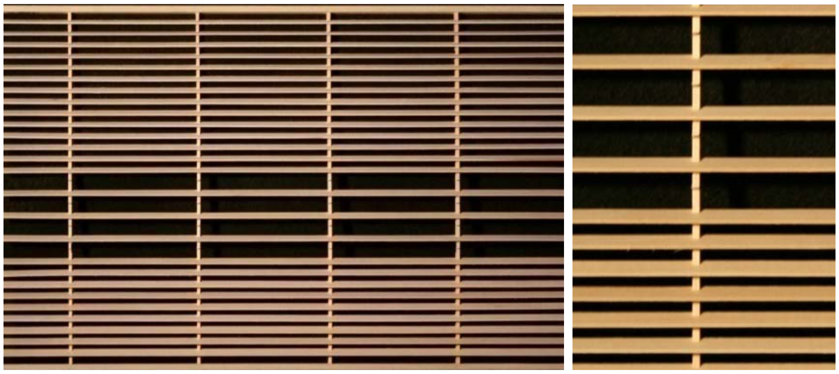
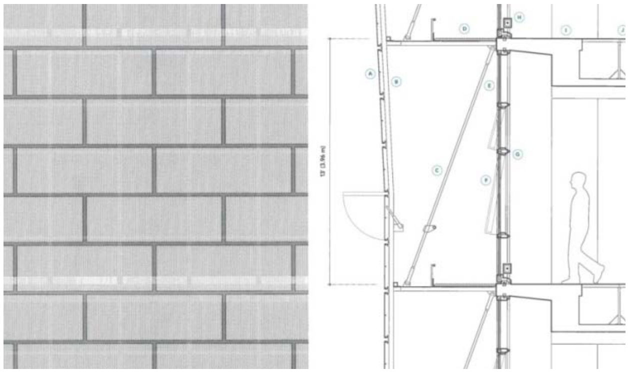


Figure 38. Thin louver screen. Left: General view of thin louver screen as constructed. Right: detail view of actual louver screen tested.



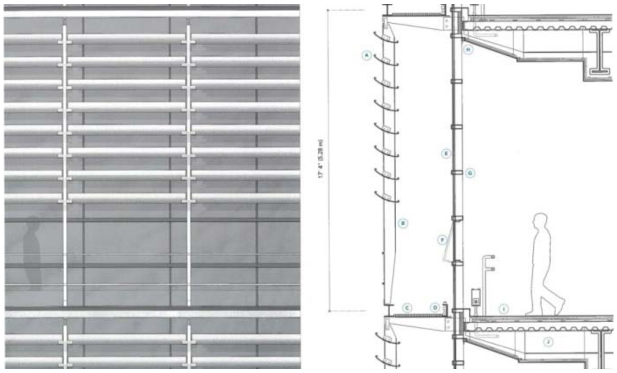


Figure 39. Left: the San Francisco Federal Building has awning windows behinds a perforated panel screen. (Murray 2009). **Figure 40. Right: The New 42nd Street Studios, New York. Platt Byard Dovel White, 2000. Elevation and section.** (Murray 2009)

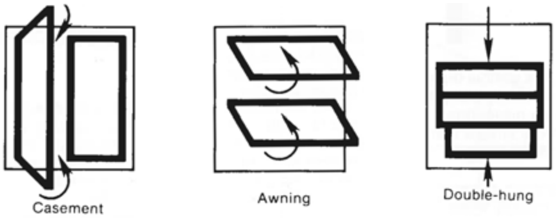


Figure 41. (Left) Terry Thomas Building has awning windows behinds exterior venetian blinds. Image from <www.weberthompson.com>. **Figure 42. (Right) Window opening types tested.** (Chandra 1986)

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CHAPTER 5 RESULTS

This section includes results from the wind tunnel studies described earlier as well as an exploratory thermal comfort exercise using the wind tunnel results. The first section describes the measured and observed air velocity results from three sets of wind tunnel studies. The first set establishes the effects of the base model with and without various outlet windows on indoor airflow. The first set also helps to characterize the effect of two outlet conditions prior to selecting outlet condition for all the following tests. The second set studies the effects of individual façade components on the base model; these include the inlet window test and the shade test. The third and final set shows the results of the combined effects of the multiple, previously tested components.

The velocity results from the most effective combined configuration - with respect to the highest mean air velocity with least variation across the occupied zone in plan ($\boldsymbol{v}_{PLAN}$) - are then used to examine when - both seasonally and time of day - wind-driven cooling might be acceptable for thermal comfort in a suburban Bangkok classroom. In this exploratory thermal comfort exercise, the indoor temperature floats with the outdoor temperature and the building is assumed to be thermally very light.

5.1 WIND TUNNEL TEST RESULTS

The following results apply only to the specific configuration tested. Each test is characterized by an all-points mean velocity ratio in plan and in section ($\boldsymbol{v}_{PLAN}$ and $\boldsymbol{v}_{SECT}$ respectively), plan and section contour maps describing velocity spread in space, and by the spatial variation in velocity within either plan or section, as noted by the coefficient of spatial variation $\boldsymbol{c}_{sv}$, which is also used by Sobin (1983) and Ernest (1991).

A trend common to all the tests was that the flow stream would expand and decelerate as it moved past the window frame, most clear at 0˚. Eddies would form around the openings inside the windows. The lowest velocity ratios tended to occur below the inlet window. Not surprisingly at a 90˚ incident wind (parallel to the window), v_{PLAN} and v_{SECT} were the lowest as compared to the other angles tested.

With the exception of the awning window, the maximum v_{PLAN} and v_{SECT} tended to occur at the 45˚ oblique incident wind angle all façade configurations tested, as the rough opening shape is horizontal[42]. (For the awning window, though the maximum v_{PLAN} and v_{SECT} occurred at 0˚ incident wind angle.) At 45˚ and 90˚, the angled incident wind direction resulted in a clockwise rotation in the indoor air stream.

Generally, v_{SECT} tended to be greater than v_{PLAN} at 0˚ and 45˚. The exception to this was the double-hung window test, which had consistently higher values for v_{PLAN} at all angles. The dimension of this inlet opening in section was also about half of the other inlet windows tested.

The test results were influenced by the ratio between inlet and outlet size (which vary from about 2:1 or 1:1). It is difficult to separate the effects of inlet window geometry obstructions from the influences of this particular experimental setup (when the outlet area is less than or equal to the inlet area)[43]. It is common in large and especially wide openings to have simultaneous inflow and outflow at the same opening[44], a characteristic of single-sided ventilation.

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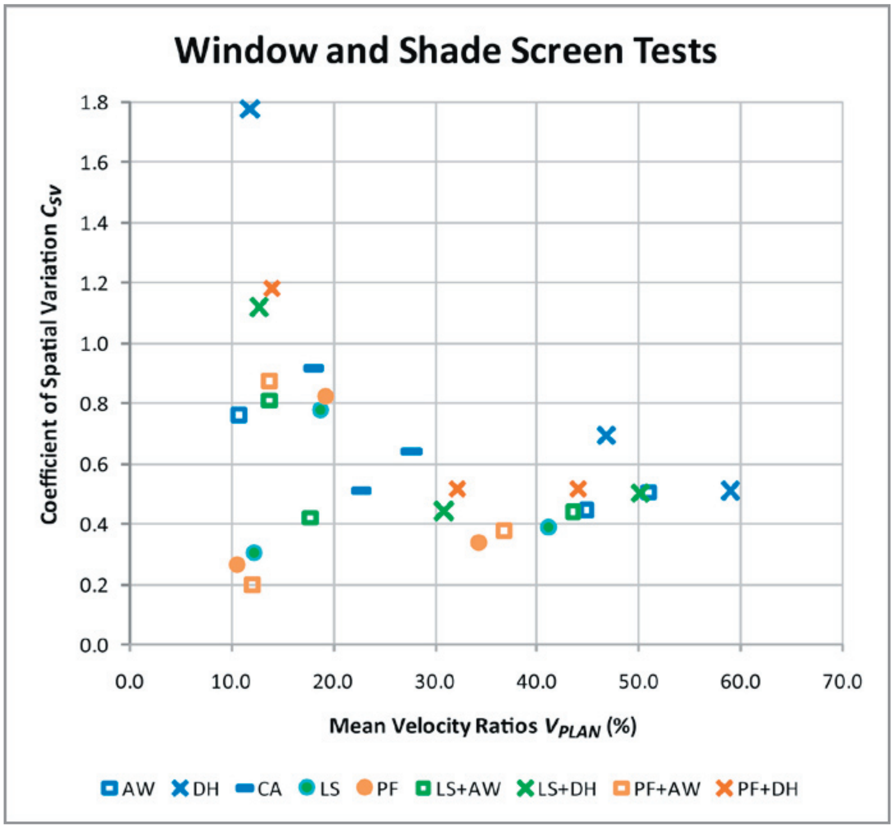
[42] This is consistent with Sobin's findings associated with horizontal windows.

[43] Based on a conversation with David Banks of CPP Wind.

[44] Sobin (1981) also noticed this phenomenon in his study of horizontal windows.

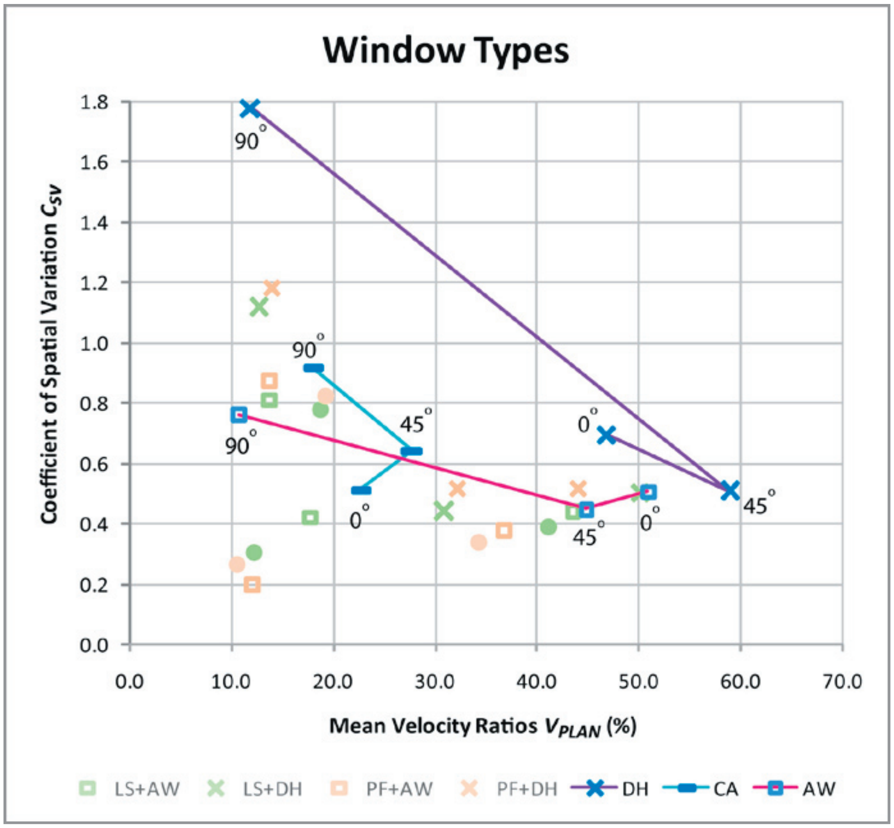
Table 1. Results from tests performed. V_{PLAN} = mean velocity ratio for occupied areas in plan; V_{SECT} = mean velocity ratio for occupied areas in section. Yellow highlight indicates the higher all-points mean velocity, either in plan or section, for a test at a given angle of incidence. Orange highlight and bold text indicate the highest air all-points mean velocity within a configuration at the three angles tested. S_{PLAN} and S_{SECT} are the standard deviation of the velocity ratios in plan and section respectively. *Csv* = coefficient of spatial variation.

Shade	**Inlet Window**	**Outlet Window**	**Test**	**Angle**	***V PLAN***	***S PLAN***	***Csv***	***V SECT***	***S SECT***	***Csv***
none	*none*	*none*	RO + RO	0°	57.5	*24.1*	0.4	73.9	*39.6*	0.5
none	*none*	*none*	RO + RO	45°	69.8	*33.1*	0.5	**79.3**	*39.2*	0.5
none	*none*	*none*	RO + RO	90°	20.9	*13.5*	0.6	19.2	*5.4*	0.3
none	*none*	Double Hung, LO	RO + VS-LO	0°	25.1	*13.0*	0.5	34.2	*16.9*	0.5
none	*none*	Double Hung, LO	RO + VS-LO	45°	33.0	*22.5*	0.7	**34.2**	*26.0*	0.8
none	*none*	Double Hung, LO	RO + VS-LO	90°	17.7	*13.4*	0.8	13.1	*5.2*	0.4
none	*none*	Double Hung, UO	RO + VS-UO	0°	21.9	*12.1*	0.6	32.5	*20.1*	0.6
none	*none*	Double Hung, UO	RO + VS-UO	45°	40.9	*22.0*	0.5	**46.0**	*26.7*	0.6
none	*none*	Double Hung, UO	RO + VS-UO	90°	14.3	*11.9*	0.8	10.4	*7.0*	0.7
none	Awning	Double Hung, UO	AW + VS-UO	0°	50.9	*25.8*	0.5	**77.3**	*44.1*	0.6
none	Awning	Double Hung, UO	AW + VS-UO	45°	44.8	*20.1*	0.4	47.8	*24.9*	0.5
none	Awning	Double Hung, UO	AW + VS-UO	90°	10.7	*8.2*	0.8	9.0	*5.2*	0.6
none	Casement	Double Hung, UO	CA + VS-UO	0°	22.6	*11.6*	0.5	32.4	*17.8*	0.5
none	Casement	Double Hung, UO	CA + VS-UO	45°	27.8	*17.8*	0.6	**42.2**	*20.9*	0.5
none	Casement	Double Hung, UO	CA + VS-UO	90°	18.0	*16.5*	0.9	17.2	*5.8*	0.3
none	Double Hung, LO	Double Hung, UO	VS-LO + VS-UO	0°	46.7	*32.5*	0.7	44.6	*23.3*	0.5
none	Double Hung, LO	Double Hung, UO	VS-LO + VS-UO	45°	**58.9**	*29.9*	0.5	53.9	*27.8*	0.5
none	Double Hung, LO	Double Hung, UO	VS-LO + VS-UO	90°	11.9	*21.2*	1.8	7.2	*5.1*	0.7
Louver Screen	*none*	Double Hung, UO	LS-RO + VS-UO	0°	12.3	*3.8*	0.3	25.6	*14.3*	0.6
Louver Screen	*none*	Double Hung, UO	LS-RO + VS-UO	45°	41.2	*15.9*	0.4	**49.8**	*27.4*	0.6
Louver Screen	*none*	Double Hung, UO	LS-RO + VS-UO	90°	18.7	*14.6*	0.8	13.9	*12.4*	0.9
Perf Panel	*none*	Double Hung, UO	PF-RO + VS-UO	0°	10.6	*2.8*	0.3	21.7	*13.4*	0.6
Perf Panel	*none*	Double Hung, UO	PF-RO + VS-UO	45°	34.3	*11.7*	0.3	**46.4**	*25.5*	0.6
Perf Panel	*none*	Double Hung, UO	PF-RO + VS-UO	90°	19.3	*15.9*	0.8	14.7	*11.2*	0.8
Louver Screen	Awning	Double Hung, UO	LS-AW + VS-UO	0°	17.7	*7.5*	0.4	30.6	*19.3*	0.6
Louver Screen	Awning	Double Hung, UO	LS-AW + VS-UO	45°	43.5	*19.2*	0.4	**46.6**	*24.3*	0.5
Louver Screen	Awning	Double Hung, UO	LS-AW + VS-UO	90°	13.7	*11.1*	0.8	11.3	*8.5*	0.7
Louver Screen	Double Hung, LO	Double Hung, UO	LS-DH-LO + VS-UO	0°	30.9	*13.6*	0.4	39.5	*22.0*	0.6
Louver Screen	Double Hung, LO	Double Hung, UO	LS-DH-LO + VS-UO	45°	50.0	*25.3*	0.5	**54.9**	*27.7*	0.5
Louver Screen	Double Hung, LO	Double Hung, UO	LS-DH-LO + VS-UO	90°	12.6	*14.1*	1.1	7.6	*6.2*	0.8
Perf Panel	Awning *60% complete	Double Hung, UO	PF-AW-LO + VS-UO	0°	12.0	*2.4*	0.2	25.9	*22.2*	0.9
Perf Panel	Awning	Double Hung, UO	PF-AW-LO + VS-UO	45°	36.7	*14.0*	0.4	**45.6**	*24.0*	0.5
Perf Panel	Awning	Double Hung, UO	PF-AW-LO + VS-UO	90°	13.7	*12.0*	0.9	12.0	*9.4*	0.8
Perf Panel	Double Hung, LO	Double Hung, UO	PF-VS-LO + VS-UO	0°	32.2	*16.6*	0.5	33.3	*18.4*	0.6
Perf Panel	Double Hung, LO	Double Hung, UO	PF-VS-LO + VS-UO	45°	44.1	*22.8*	0.5	**50.4**	*25.2*	0.5
Perf Panel	Double Hung, LO	Double Hung, UO	PF-VS-LO + VS-UO	90°	14.0	*16.5*	1.2	8.5	*8.3*	1.0



Distribution of all inlet tests - window, shade and combined - in terms of the mean velocity ratios in plan (Vplan) and the coefficient of spatial variance (Csv) for all angles of incidence tested.

Ideal conditions would have a high VPLAN and a low CSV.



Distribution window tests at each of the incident angles. Other tests are shown greyed out. Note the three different changes in VPLAN at 0°, 45° and 90°.

Ideal conditions would have a high VPLAN and a low CSV.

5.1.1 OUTLET OPENING TESTS

What qualities are desirable in an outlet opening for studying façade inlet conditions? The purpose of the outlet opening test is to characterize the outlet opening in terms of indoor flow in order to determine which outlet window to use with all following façade inlet tests. The outlet opening area affects how air flows through the inlet window; this in turn impacts the characterization of the inlet façade components. Selecting an outlet window that produced conditions of wider applicability was considered to be important; in this case, this meant having a higher and smaller outlet opening area relative to the inlet opening area. (The pattern of flow inside the room was of more interest than the average velocity, as the former better describe flow distribution.) The three options tested were (1) rough opening (base model), (2) double-hung with lower sash open and (3) double-hung with upper sash open.

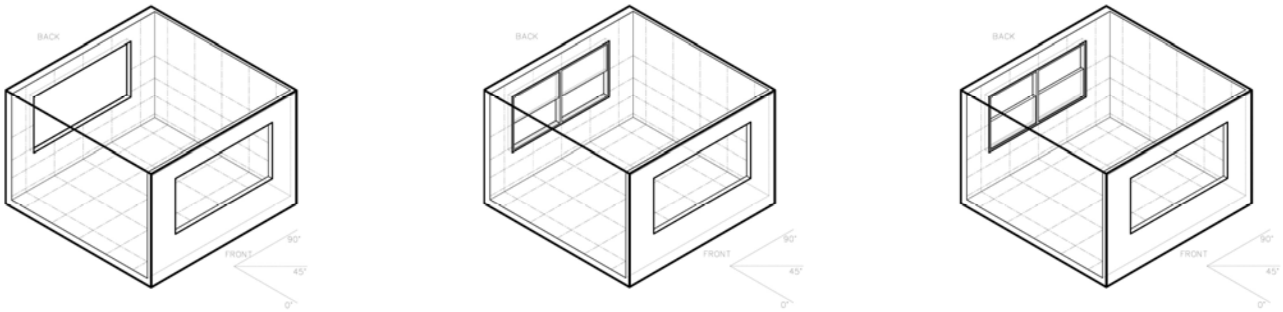
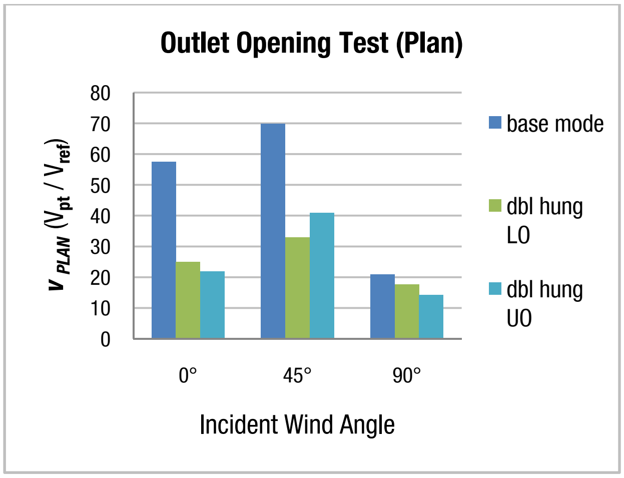
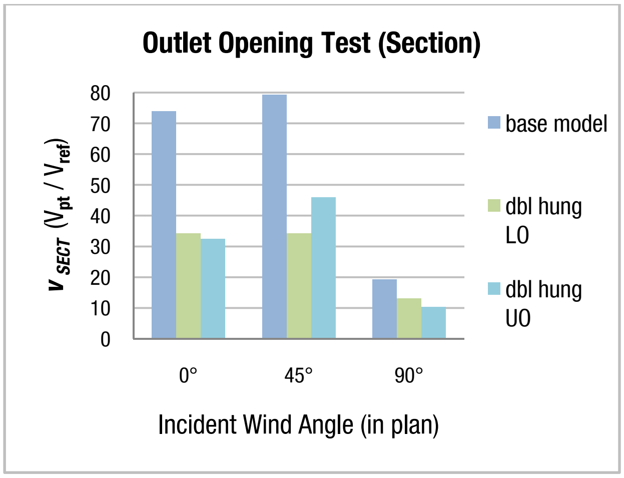


Figure 43. Model configurations for studying the outlet opening. Left: rough openings only. Middle: rough opening at inlet, double hung with lower sash open at outlet. Right: rough opening at inlet, double hung with upper sash open at outlet.

Note that all three tests performed with higher $\boldsymbol{v}_{SECT}$ rather than $\boldsymbol{v}_{PLAN}$ in plan except when the incident wind angle was 90°, when $\boldsymbol{v}_{PLAN}$ was greater. Not surprisingly in this set, the base model (left above) had the highest $\boldsymbol{v}_{PLAN}$ and $\boldsymbol{v}_{SECT}$, with around double the average velocity ratios as the other two tests. Of the two double-hung windows tested at the outlet, the configuration with the lower sash open performed with slightly higher values for $\boldsymbol{v}_{PLAN}$ and $\boldsymbol{v}_{SECT}$ at 0° and 90°, while the values at 45° were lower than its counterpart (the upper sash open).





While the double-hung (upper sash open) test did not have air velocities as high as with the lower sash open, except at 45°, other factors suggested that it might be more widely applicable. Though this condition is not optimal for high air velocities given the 2:1 inlet to outlet ratio,[45] this type of condition is similar to the non-ideal conditions in real buildings, such as those with furniture obstructions, adjacency to circulation or auxiliary spaces and other conditions when two equally large openings are not possible. This condition also causes turbulence to dominate indoor flow. (Obviously, if the outlet window were very large, the indoor airflow would be higher.) Based on this wider applicability, it was determined that this outlet opening condition would be used for all subsequent tests. Figures 43, 44 and 45 describe the velocity distributions of the first set of tests.

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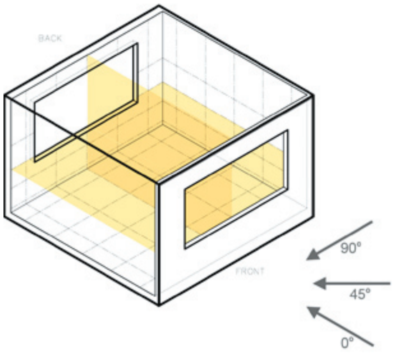
[45] Sobin 1981, Givoni 1962 suggest that air speeds are highest when inlet-to-outlet ratios are between 1:1 and 1:1.5. it is more ideal for inlet and outlet ratios to be closer to 1:1.25 to 1:5, according to Givoni and Sobin respectively. Two of the inlet windows in this study have approximately double the area of the outlet opening.



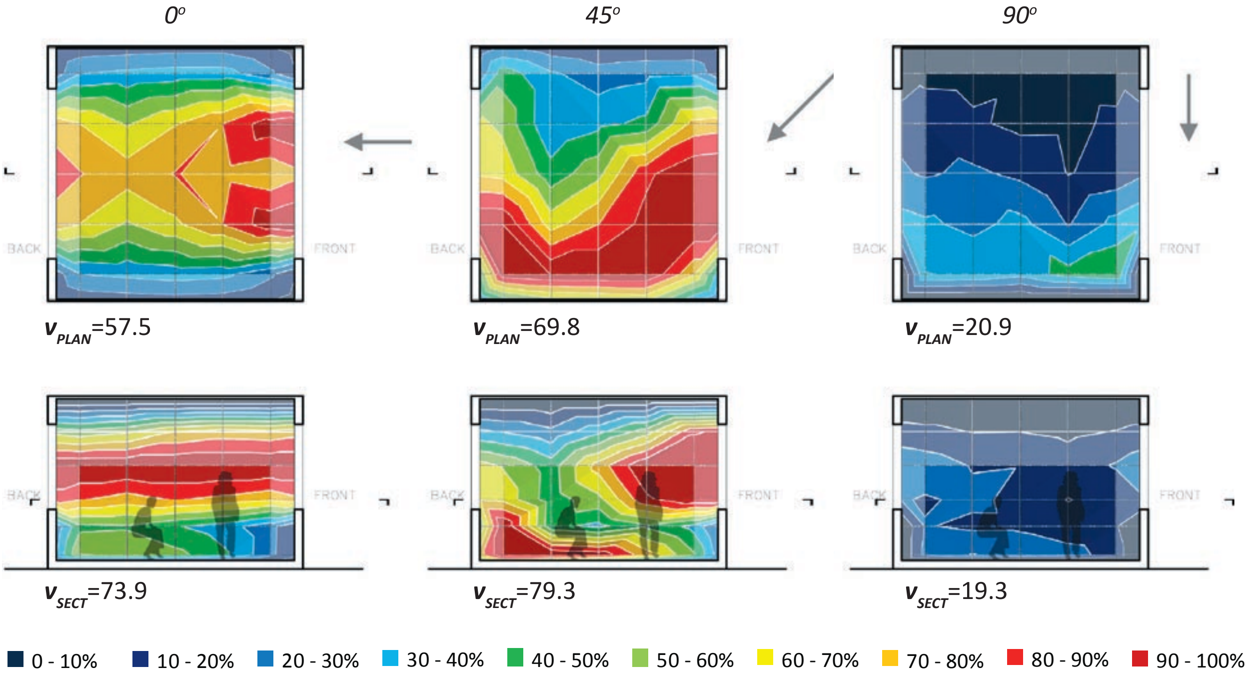
Rough Openings Test

inlet:
rough opening

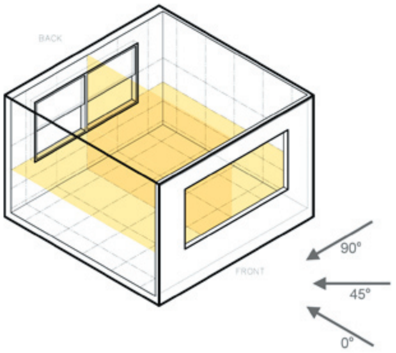
outlet:
rough opening

Figure 44. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.

Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



Outlet Test: Double-hung, Lower Sash Open

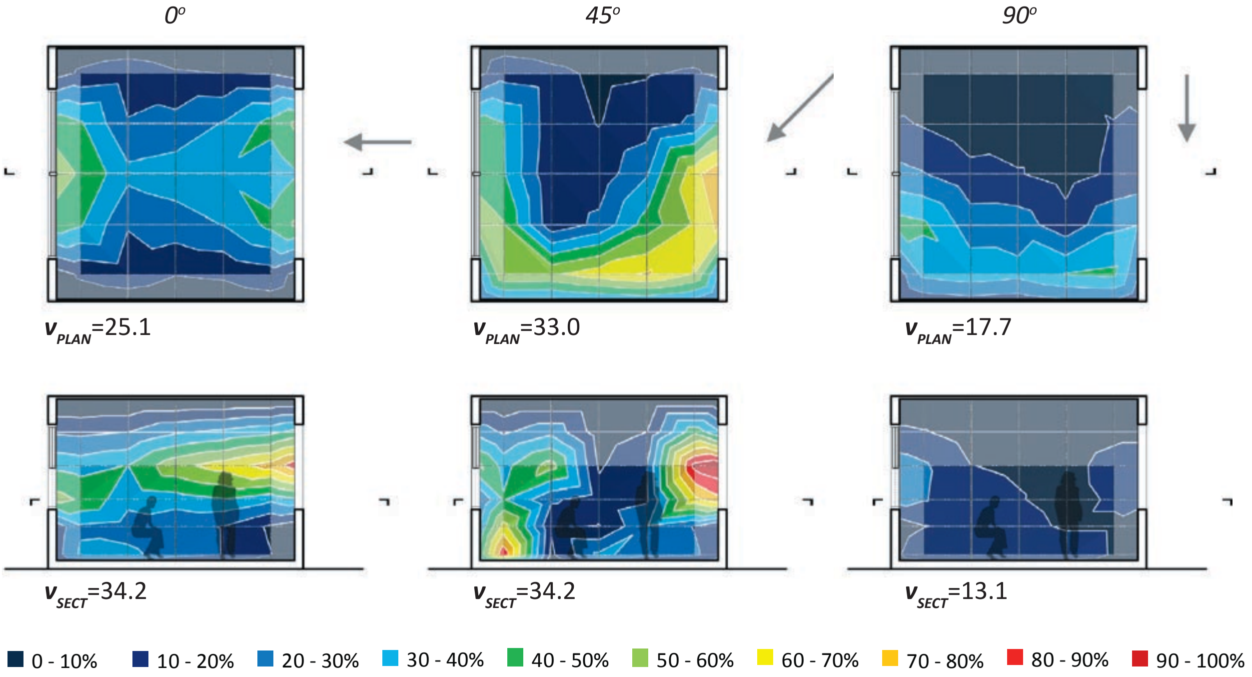


inlet:
rough opening

outlet:
double-hung, lower
sash open

Figure 45. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.

Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



Outlet Test: Double-hung, Upper Sash Open

inlet:
rough opening

outlet:
double-hung, upper
sash open

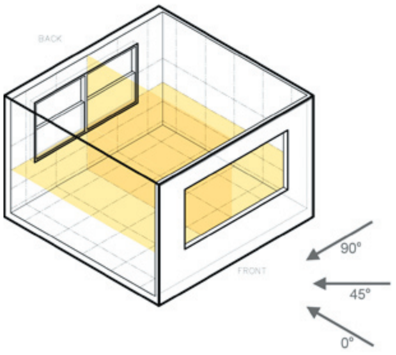
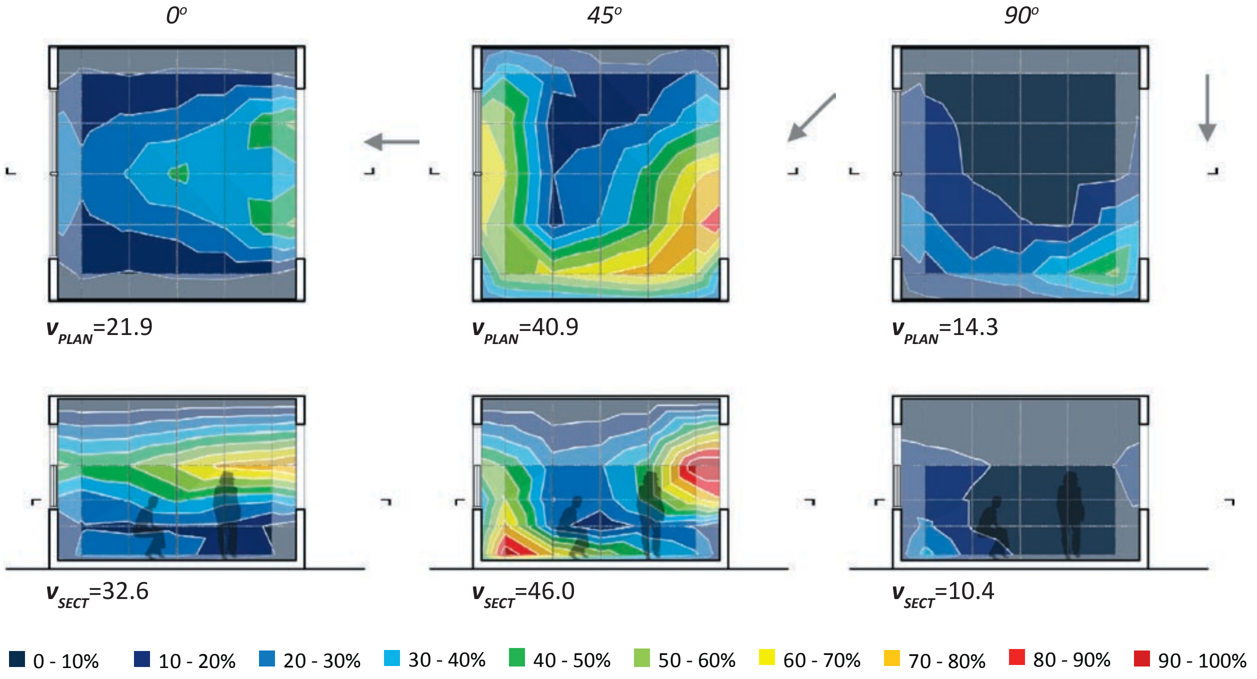
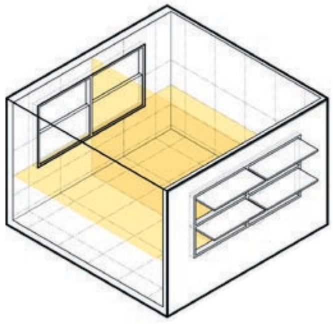


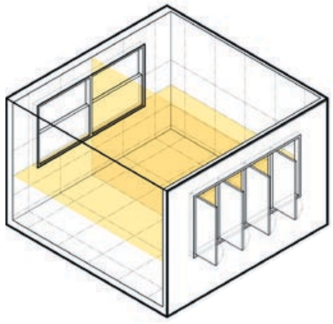
Figure 46. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.

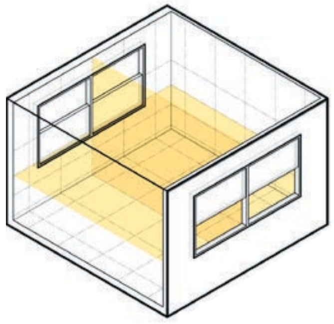
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



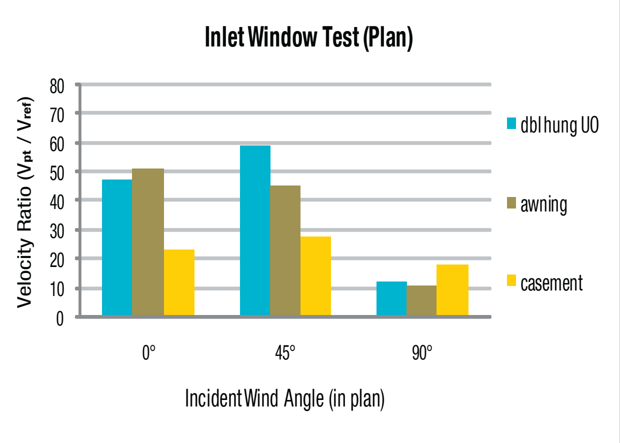
5.1.2 INLET WINDOW TEST

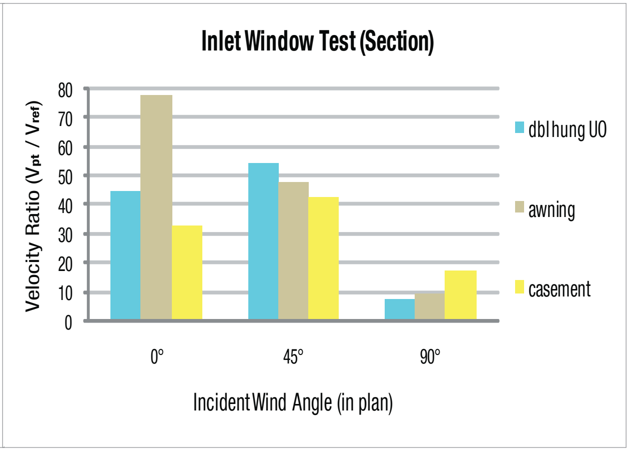






The next tests done were to determine the pattern and average velocity on indoor airflow created by each of the inlet window types. The inlet windows tested here were the awning window, the casement window and the double-hung window (with lower sash open). Each of the three windows performed with maximum v_{PLAN} and v_{SECT} values at different angles of incidence. The awning window had maximum values for v_{PLAN} and v_{SECT} at 0°; the double-hung at 45°; the casement window and at 90°. As the double-hung has about half the opening area as the other windows, its inlet to outlet ratio was 1:1. This resulted in relatively high average speeds. These results agree with Sobin and Givoni's findings that a 1:1 or 1:1.25 ratio results in the maximum average air velocity across the plan.





Distribution awning window tests at each of the incident angles. Other tests are shown greyed out. Note the dramatic difference of **VPLAN** when combined with the shade screen at 0°.

Ideal conditions would have a high **VPLAN** and a low **CSV**.

Distribution double-hung window tests at each of the incident angles. Other tests are shown greyed out. Note the incremental decrease of **VPLAN** when combined with the shade screen at t.

Ideal conditions would have a high **VPLAN** and a low **CSV**.

5.1.2.1 **AWNING WINDOW TEST**

In the awning window test, the window sash acts as a blade that directs and accelerates flow immediately above and below it. This window configuration had its highest average velocity ratio in section when normal (0˚) to the incident wind. This might be due to the long continuous opening width and window sash depth reducing at angles oblique to the façade.

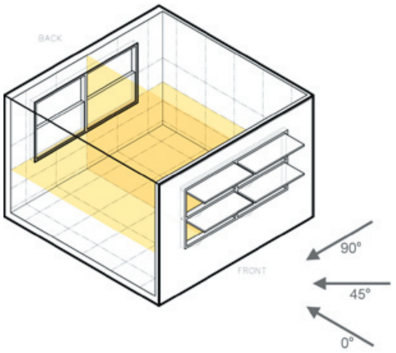
Once past the inlet awning window, the flow splits into a jet at standing head height and above with major and minor eddies within the occupied zone. The major secondary eddy is a result of the sashes blocking the lower half of the outlet window. At 45˚ incident wind, conditions are similar but swirl around the room while decelerating; a distinct "wind shadow" with velocity ratios of 10% or less begins to form on one side. At 90˚, a large, very slow eddy forms in the room; the wind shadow becomes grows larger and the $\boldsymbol{v}_{PLAN}$ (average velocity at the airflow plan) is at about 9%.

While this window was tested as fully open, in real buildings it is typically partially open, in which case the breeze would be directed toward the ceiling. The direction of flow is dependent on the degree of opening. The sash size also plays a role in the open sash angle. Depending on where and how high it is placed, this type of window might be more appropriate for space or structural cooling, rather than people cooling.

Awning Window Test

inlet:
awning window

outlet:
double-hung, upper
sash open



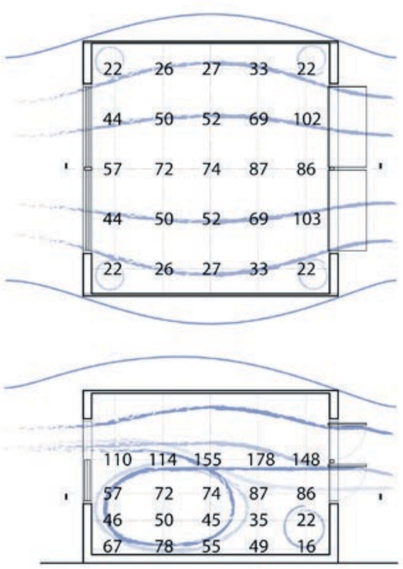
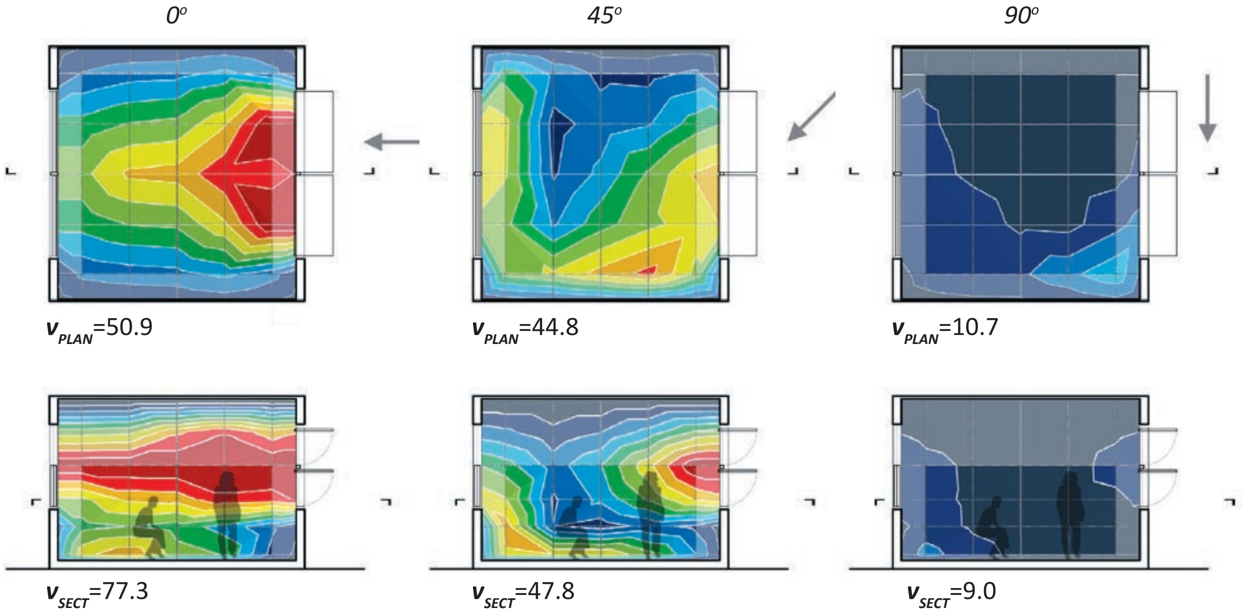


Figure 47. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



■ 0 - 10% ■ 10 - 20% ■ 20 - 30% ■ 30 - 40% ■ 40 - 50% ■ 50 - 60% ■ 60 - 70% ■ 70 - 80% ■ 80 - 90% ■ 90 - 100%

5.1.2.2 **CASEMENT WINDOW TEST**

Relative to the other windows tested, the casement window exhibited the most similarity in average velocity ratios ($\boldsymbol{v}_{PLAN}$) at the three different incident angles. The casement window is the only asymmetrical window configuration amongst the window tests. In the plan at 0˚, the higher air speed (or green triangle in Figure 44 left) behind the casement window has no counterpart on the other side, suggesting that the series of projecting vertical sashes obstruct flow much more flow than did the awning window sashes; this is most clear at 0˚ and 45˚. (The awning windows are 2 by 2, while the casement windows are 1 by 4.) At 45˚ and 90˚, the casement windows redirect and distribute the flow more evenly as compared to the other windows at the same angle, as noted in the absence of a distinct "wind shadow" at these incident angles.

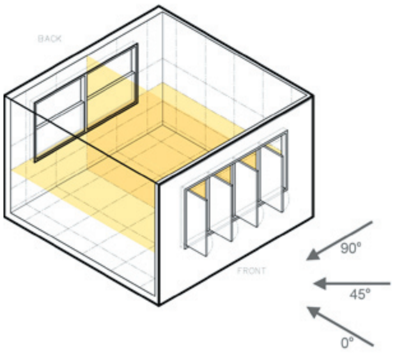
As the flow moves past the windows, it separates into two main groups. Most of the lower level wind (below 1.7 m) seems form a well-dispersed collection of major and minor eddies in the occupied zone. Above that, the some of the flow streams skip over the major eddy and exit, while some still collide and dissipate into the space. The higher level flow (above standing head height) runs smoothly along the ceiling and jets out.

As the upper portion of flow did not seem to stick to the ceiling much, this window may be more appropriate for occupant and space cooling than structural cooling. With the highest value for $\boldsymbol{v}_{PLAN}$ at only 27.8%, this configuration would be less appropriate in locations with little to no wind. This test likely may have higher velocity ratios with wider sashes and clear openings and thus fewer drag elements.

Casement Window Test

inlet:
casement window

outlet:
double-hung, upper
sash open



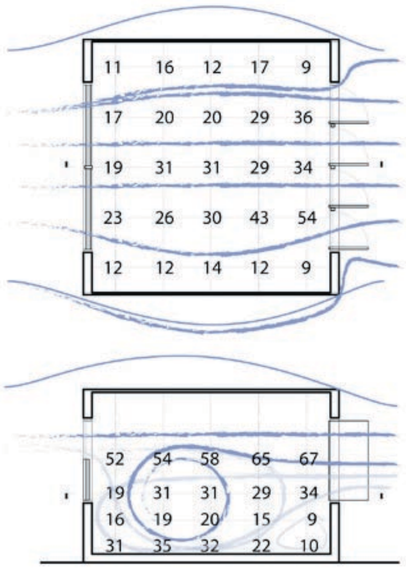
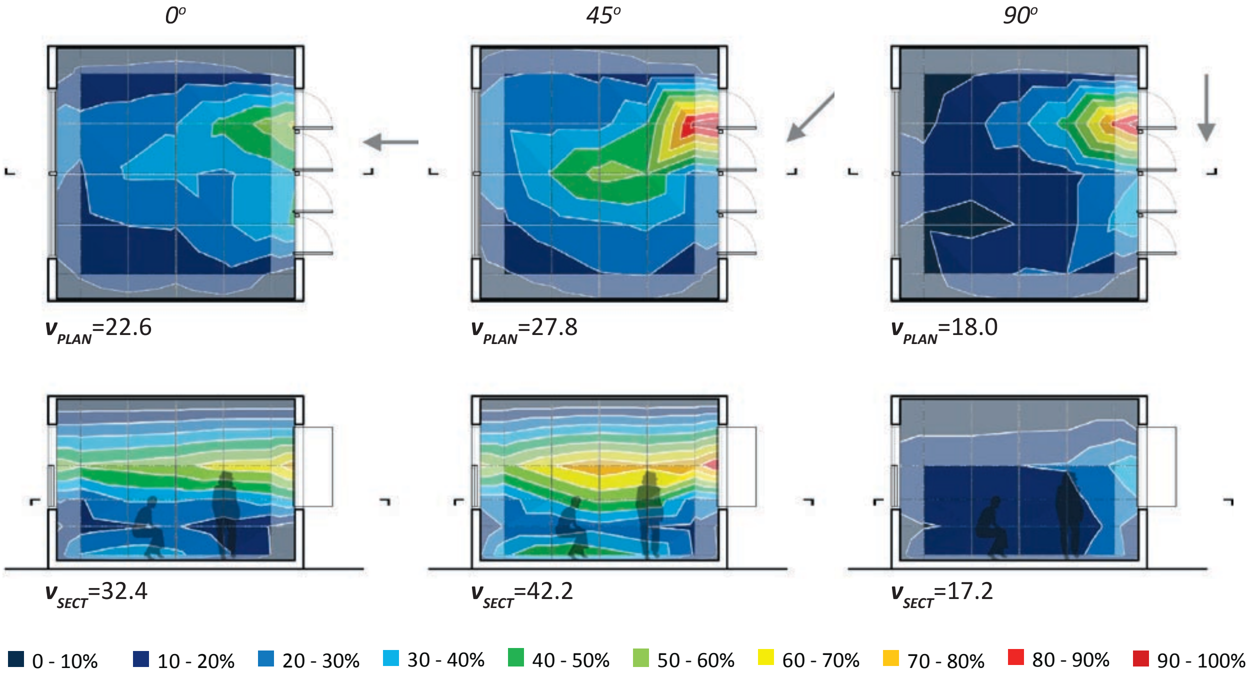


Figure 48. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



5.1.2.3 **DOUBLE-HUNG WINDOW TEST** (WITH LOWER SASH OPEN)

A number of factors make this test distinctly different from the other window tests: 1) the inlet and outlet ratio are 1:1, (while the other two are about 1:2,) 2) the inlet and outlet are offset in section from one another, and 3) the absence of a direct jet from inlet to outlet and the shape of the resultant flow was unique to this test.

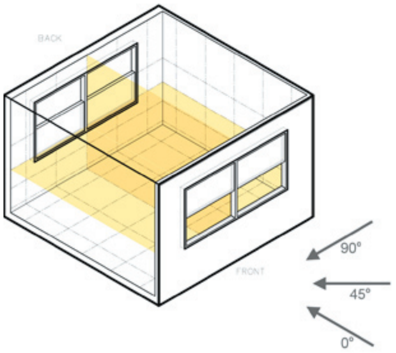
The predominant flow consisted of a horizontal "blanket" of air that moved down into the occupied zone and then up the outlet wall and out. A large eddy forms over this low-level stream. At 45˚, this test had its highest velocity ratios. These high ratios are created by a large, three-dimensional clockwise eddy in plan. The approximate center of this whirlwind or large eddy is indicated by the region with the lowest $\boldsymbol{v}_{PLAN}$ (or the dark blue slit). At 90˚, the wind shadow common to other tests at this angle emerges.

This window appears to have good merit for people cooling. Since double-hung windows can also open from the top down, it also should be further explored for space and structural cooling. As sliding a window utilizes the jambs, sill and head of the opening to direct flow, the design of these elements may also aid flow distribution.

Double-hung Window Test

inlet:
double-hung, lower
sash open

outlet:
double-hung, upper
sash open



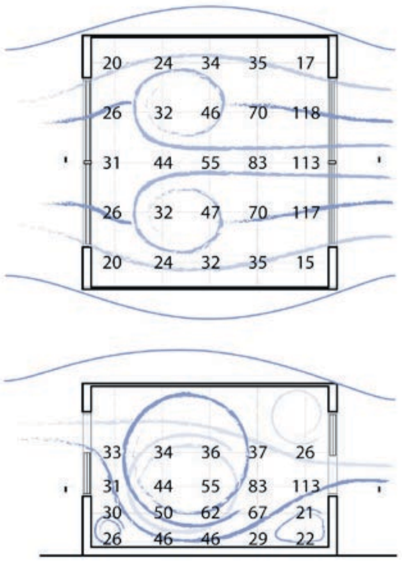
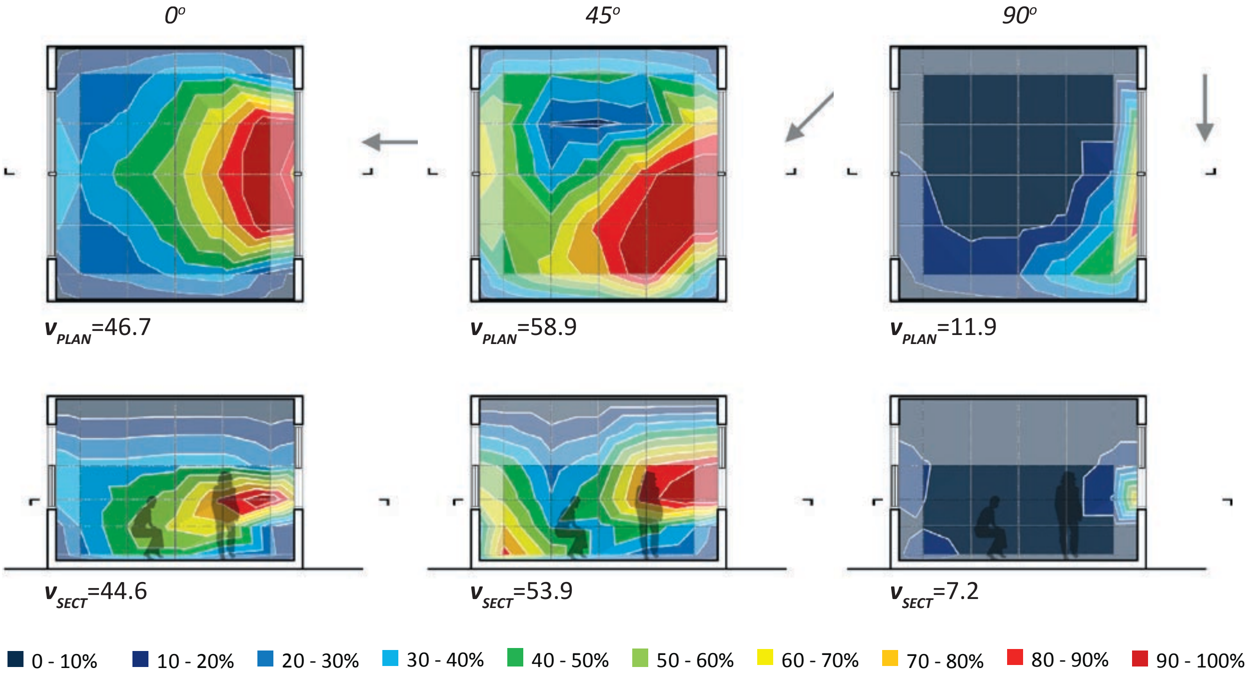
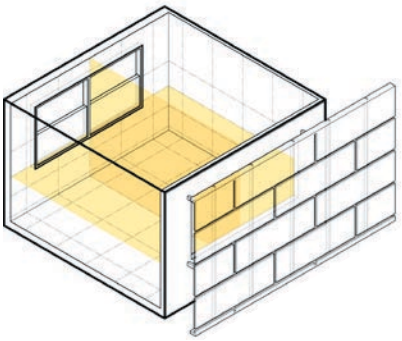
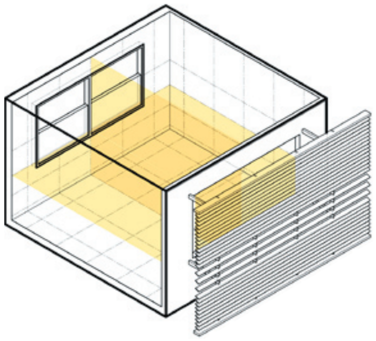


Figure 49.*Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.

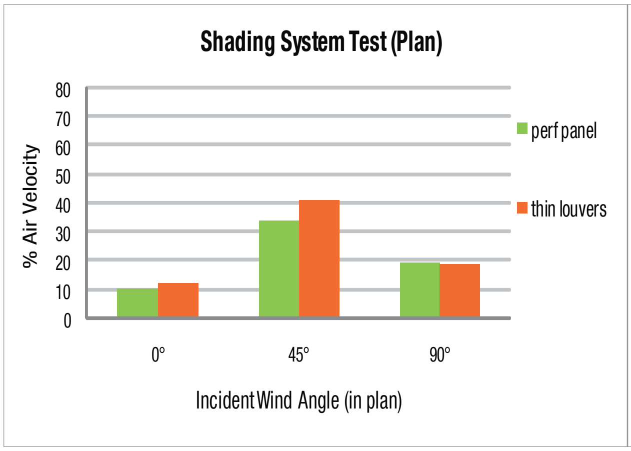


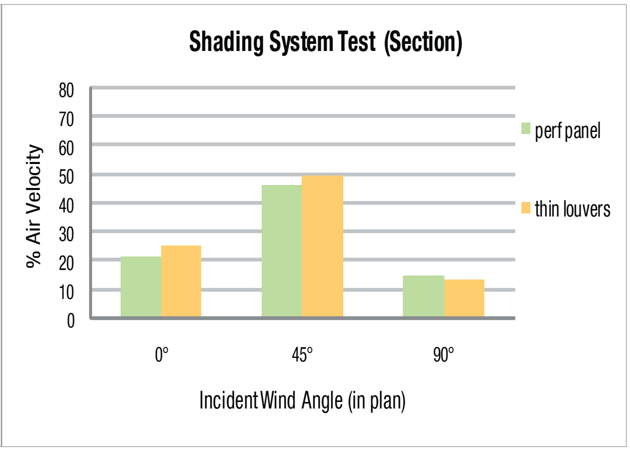
5.1.3 SHADE SCREEN TESTS





The purpose of this test was to study the different velocity and patterns associated with the two screen-like exterior shades described in Section 4.5: the perforated panel and the thin louver screen. To get a sense of the isolated impact of each shade, no window was used at the inlet opening during these tests. The (rough opening) inlet to outlet ratio is about 2:1 It was expected that the perforated panel would constrict flow more than the thin louvers since it has more surface perpendicular to oncoming flow; the results support this, though the difference in terms of velocity ratios was not as great as expected; the ratios were within 6% of one another. The extent of the screen edge seemed to affect the flow shape, as shown in the asymmetrical contours for both screen shades at 0˚.

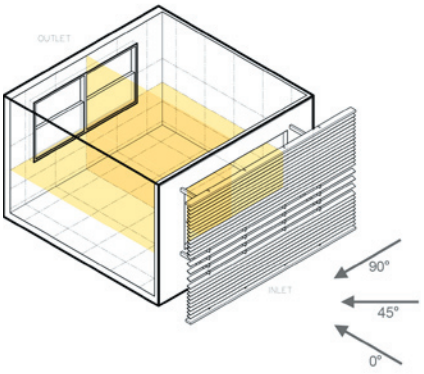




5.1.3.1 **THIN LOUVER SCREEN TEST**

In most respects the louver screen tests did not seem very different from the perforated panel, except that the amount of drag was slightly less and the flow spread was not as narrow as in the perforated panel at 0˚ and flow was directed upwards. As the case with the perforated panel, all three incident wind angles tested possessed low velocity regions with ratios of 20% or less.

The louver screen diffuses and directs the oncoming air upwards at the angle of its tilt. Once inside, the lower layer of the air sinks back down, creating an eddy under the outlet window, while the upper layer of air rolls over this eddy and through the outlet.



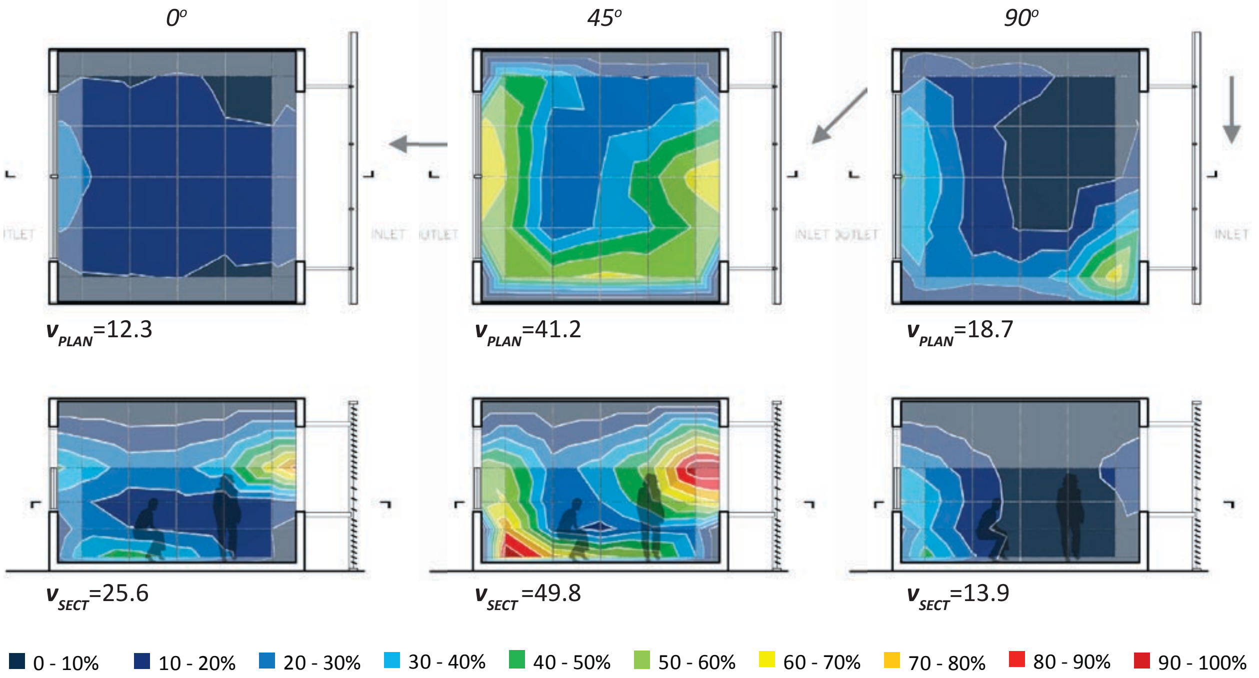
Louver Screen Test

inlet:
exterior venetian blind
over rough opening

outlet:
double-hung, upper
sash open

Figure 51.*Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.

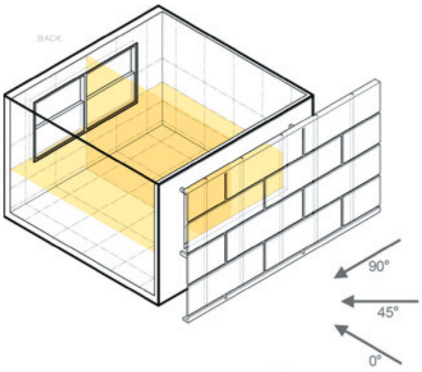
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



5.1.3.2 **PERFORATED PANEL TEST**

The perforated panel system slowed oncoming airflow significantly. At 0˚ incident wind, this configuration seemed constrict and straighten the general pattern of flow dispersion inside as well as decelerate the speed dramatically; this is more visible at seated head height (1.1m) than at standing head height (1.7m). All three incident wind angles tested possessed regions of low velocity ratios of 20% or less.

Once the flow passes the perforated screen, the smoke quickly dissipated, suggesting that this combination creates high turbulence with small eddies. The flow in the form of small eddies pushes across the room toward the outlet. Some of this flow collides with the outlet wall and forms a gentle eddy below the outlet opening. Though the flow path is not distinct, the upper half of the flow pushes across the room at standing head height and higher and exits the outlet window.



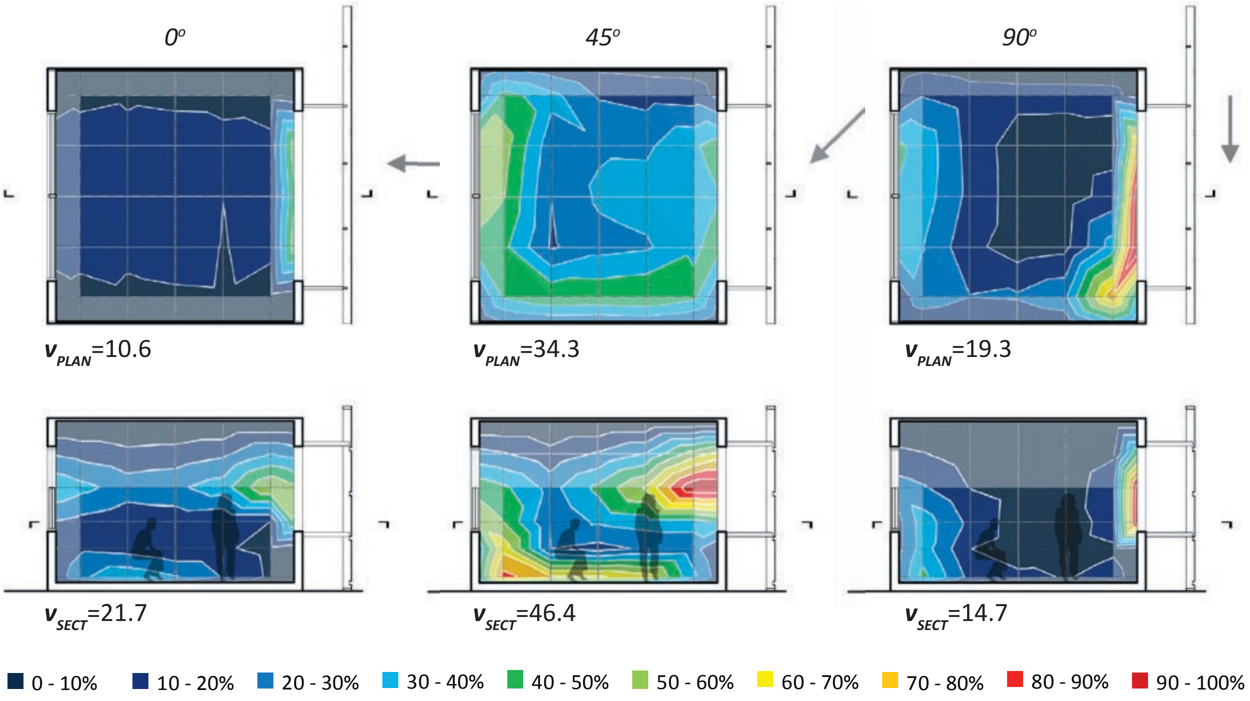
Perforated Panel Test

inlet:
perforated panel over
rough opening

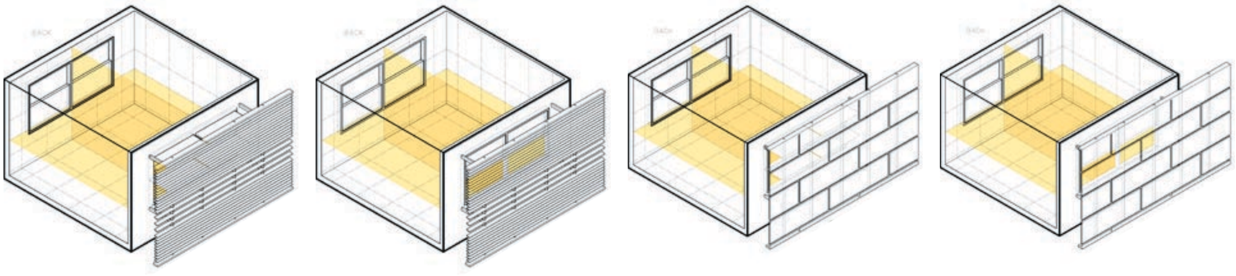
outlet:
double-hung, upper
sash open

Figure 50.*Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.

Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



5.1.4 SHADE AND WINDOW COMBINED TESTS



When combined together, window type, rather than screen type, seemed to have more of an effect on flow shape, likely due to the greater its geometric variety in this study. Though the velocity ratios of the two screen types were not dramatically different when tested without windows, the difference became more apparent when tested with windows. Even though the awning window as tested independently had a high $\boldsymbol{v}_{PLAN}$ and $\boldsymbol{v}_{SECT}$ compared to its counterparts, this effect diminished significantly (from about 51% to 18%, at 0°) with an exterior screen is placed in front of it. In contrast, the performance of the double hung window diminished only slightly (from about 47% to 32%) when obstructed by screen shades. This may be due to the difference in the way (less turbulent) larger eddies and (more turbulent) smaller eddies move across the plane of the awning window's sash. Larger eddies and jets seem to "stick" to smooth surfaces (i.e. the awing window sash) much more so than the smaller, more turbulent eddies do. Unfortunately, the casement window was not tested in combination with shades due to sensor failure.

5.1.4.1 **LOUVER SCREEN WITH AWNING WINDOW**

At the 0˚ incident angle, the shape and magnitude of flow speed was significantly diminished (from 51% to 18%) with the louver screen in front of the awning window (relative to the awning window alone).

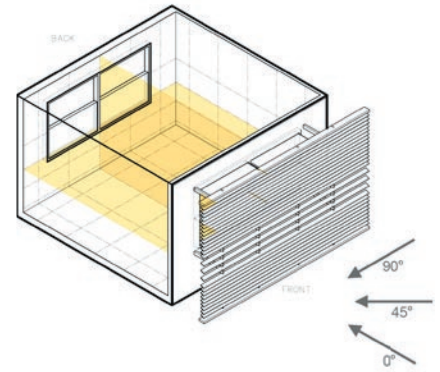
Both the velocity measurements in section and the smoke studies indicate that the louvers seem to direct flow upwards into the space, which explains why the velocity ratios in plan (at 0˚) are so low and dramatically different to the awning windows alone. At the 45˚ incident angle, the flow seems nearly the same as that without the louvered screen, with $\boldsymbol{v}_{SECT}$ less than 2% lower than the awning window alone. At 90˚, the flow seems to actually increase slightly (up to 3%) with the addition of the louver screen. This may be because the louver screen does not wrap around the corners of the model and the plane of the louver screen itself somewhat directs and assists flow.

With the higher velocity ratios at 1.7 m and 0.1 m above the floor, this configuration does not seem ideal for occupant cooling at the 1.1 m seated head height breathing zone.

Louver Screen + Awning Window

inlet:
ext. venetian blinds +
awning window

outlet:
double-hung, upper
sash open



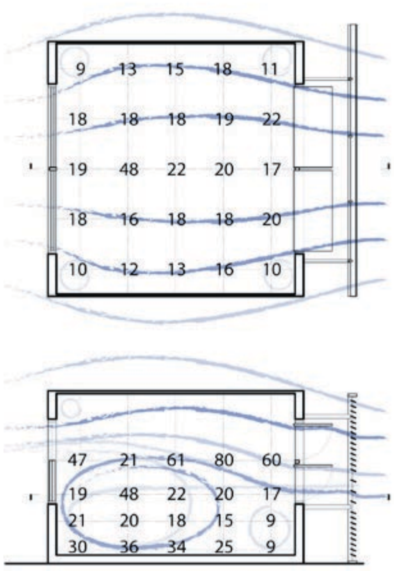
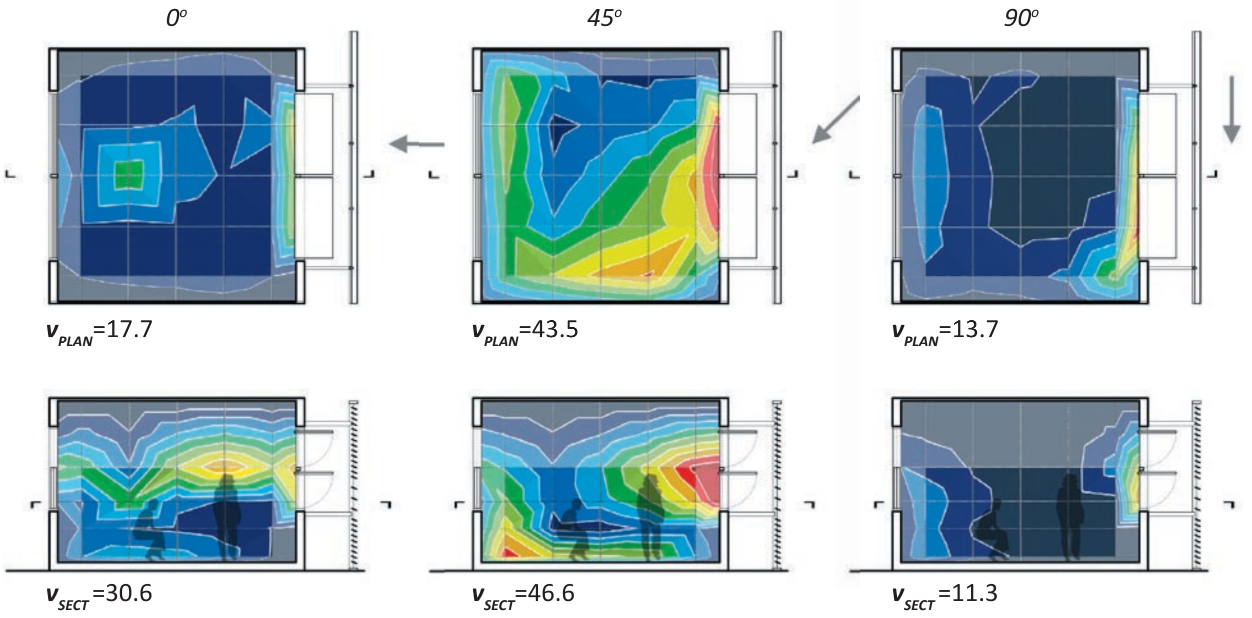


Figure 52. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



■ 0 - 10% 🟦 10 - 20% 🟦 20 - 30% 🟦 30 - 40% 🟩 40 - 50% 🟩 50 - 60% 🟨 60 - 70% 🟧 70 - 80% 🟥 80 - 90% 🟥 90 - 100%

5.1.4.2 **LOUVER SCREEN WITH DOUBLE-HUNG WINDOW** (LOWER SASH OPEN)

As mentioned earlier, the shape of the flow stream for this window is different than that of the other windows. The addition of a shade seems to dramatically alter the shape of the airflow, most notably at 0˚. The thin louvers seem to direct the flow up as it enters the space, covering both seated head height and higher. The double-hung window alone had more air velocity at standing head height and lower into the occupied zone. The asymmetry of the flow at 0˚ suggests that this flow was impacted by the edges of the louvered shade screen. At 45˚ & 90˚, the shape of the flow seemed to be a lower-velocity version of the double-hung window alone.

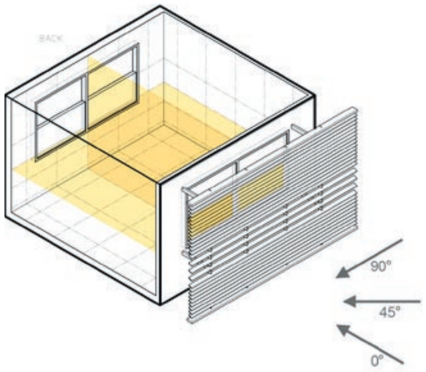
As the flow passes the louver screen, much of it is projected upwards past the window into the space and begins to fall. As it descends, Some of this upward flow exits the back window, while some forms a large eddy adjacent to the outlet wall. As the louver screen diffuses the air in addition to directing it, the added turbulence creates a fluctuating stream into the space; in addition to the flow path initially described, at times this stream shoots up to the ceiling and forms a minor eddy above head height, other times this flow jets across and forms another minor eddy below sill height.

With the higher velocity ratios at 1.7 m and 1.1 m above the floor, This configuration may be appropriate for occupant cooling at the 1.1 m seated head height breathing zone.

Louver Screen + Double-hung Window

inlet:
ext. venetian blind +
double-hung, lower
sash open

outlet:
double-hung, upper
sash open



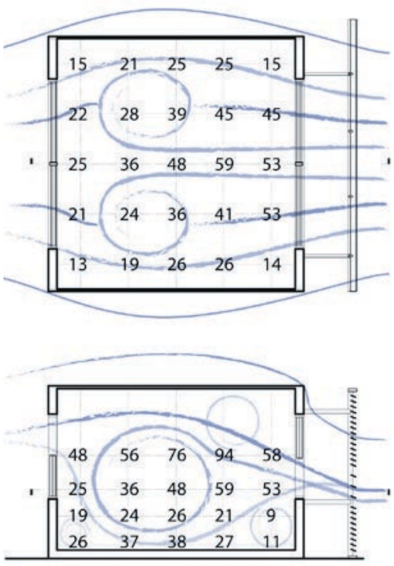
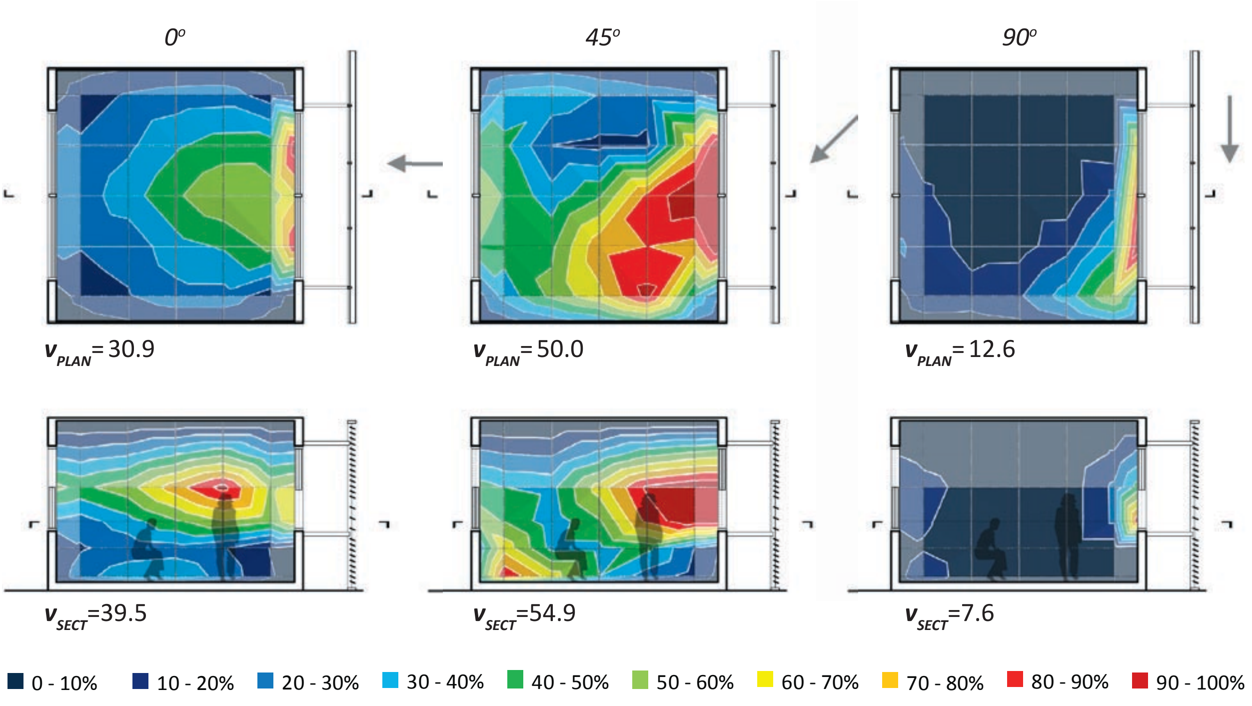


Figure 53. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



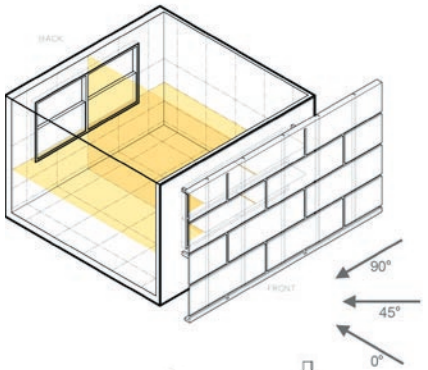
5.1.4.3 **PERFORATED PANEL WITH AWNING WINDOW**

This test at 0˚ has only 60% of the velocity ratios due to sensor failure. The data that is available seem to suggest a similar pattern to the louver screen and awning test. Though the velocity ratios are lower, the tests at 45˚ and 90˚ also seem to also be very similar to corresponding louver screen with awning window test. Not surprisingly, the perforated panel significantly reduced and narrowed the shape of indoor flow as compared with the awning window alone. At 45˚ incident angle, the flow seems very similar to its counterpart without the shade screen, but slower and more evenly distributed velocity ratios. (The maximum velocity ratio in plan was 60-70% with the mean $\boldsymbol{v}_{PLAN}$ around 37%.)

Once the flow passes the perforated screen and awning window, the smoke quickly dissipated, suggesting that this combination creates high turbulence with small eddies; this turbulent flow then creates larger, slower patterns in the space. The flow travelling through the upper windows seems to cross the ceiling, through the outlet, and produces eddies at the outlet wall. The flow through the lower inlet windows is also very turbulent; some of it forms into eddies between the 0.6 and 1.7 lines, while some flows over the eddies either exits the outlet window or and falls down the outlet wall, recombining with the larger eddy there.

Based on the data that exists, it is assumed that this test would be similar to its louver screen counterpart, but with less momentum as the flow moves toward the outlet. With the higher velocity ratios at 1.7 m and 0.1 m above the floor, this configuration is less appropriate for occupant cooling at the 1.1 m seated head height breathing zone.

Perforated Panel + Awning Window



inlet:
perforated panel +
awning window

outlet:
double-hung, upper
sash open

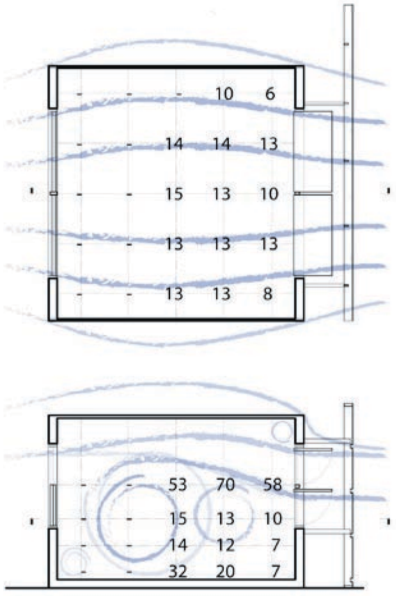
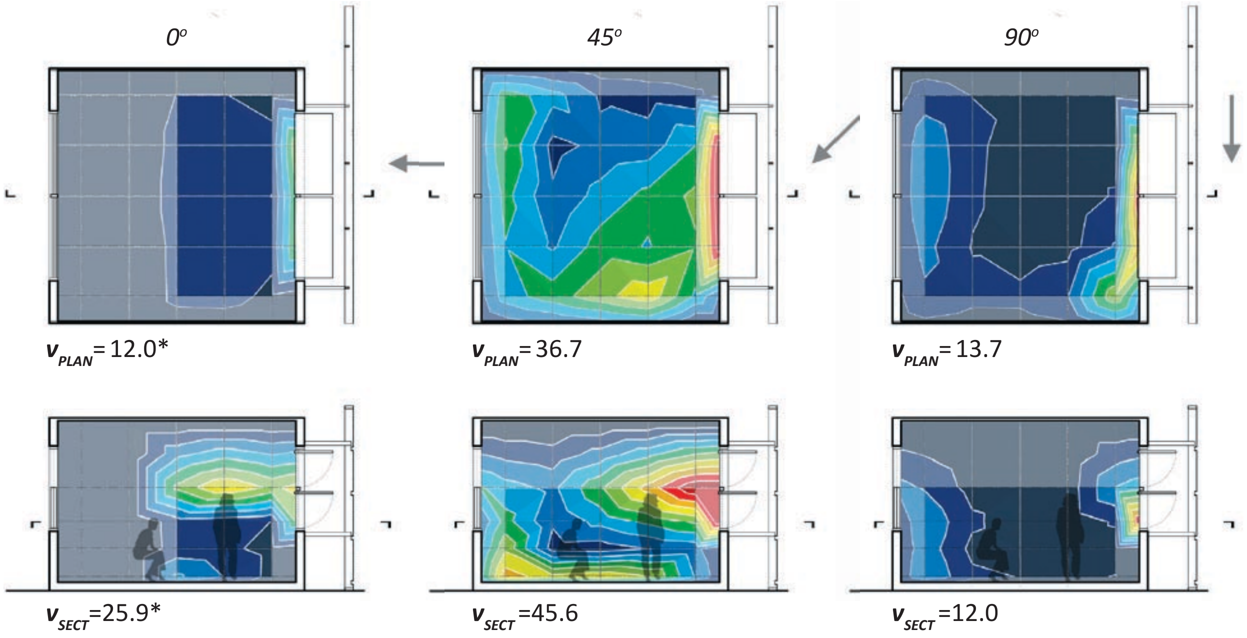


Figure 54. *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



■ 0 - 10% ■ 10 - 20% ■ 20 - 30% ■ 30 - 40% ■ 40 - 50% ■ 50 - 60% ■ 60 - 70% ■ 70 - 80% ■ 80 - 90% ■ 90 - 100%

5.1.4.4 **PERFORATED PANEL WITH DOUBLE-HUNG** (LOWER SASH OPEN)

This test produced results very similar to its thin louver counterpart, though with slightly lower velocity ratios and less variation; $\boldsymbol{v}_{PLAN}$ and $\boldsymbol{v}_{SECT}$ also were slightly lower than the louvered screen counterpart. The iso-velocity plan at 0˚ indicates The edges of the shade seem to impact the flow shape less than in the thin louver and double-hung test, suggesting that the presence of the screen itself has more of an impact than where its edges are. As with the other perforated panel tests once past the screen, this test showed turbulence and flow deceleration.

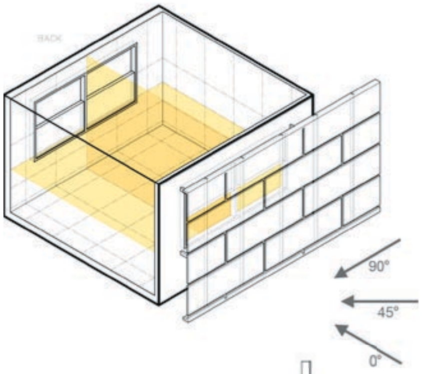
The predominant flow path changed direction a fair amount; from more to less frequent, the turbulent stream would move 1) up toward the ceiling and then curl down toward the outlet wall and window, 2) straight across the space and curl into an eddy mid way, or 3) along the floor and up to the window. Two of the paths observed – up toward the ceiling and across the room - swirled into an eddy before exiting and as paths fluctuated. Each dominant flow path created its own a large, slow eddies in the remainder space.

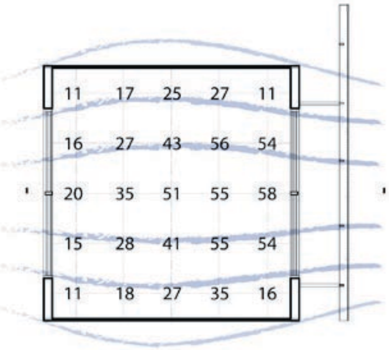
With the higher velocity ratios at 1.7 m and 1.1 m above the floor, This configuration may be appropriate for occupant cooling at the 1.1 m seated head height breathing zone.

Perforated Panel + Double-hung Window

inlet:
perforated panel +
awning window

outlet:
double-hung, upper
sash open





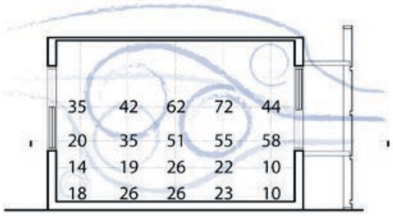
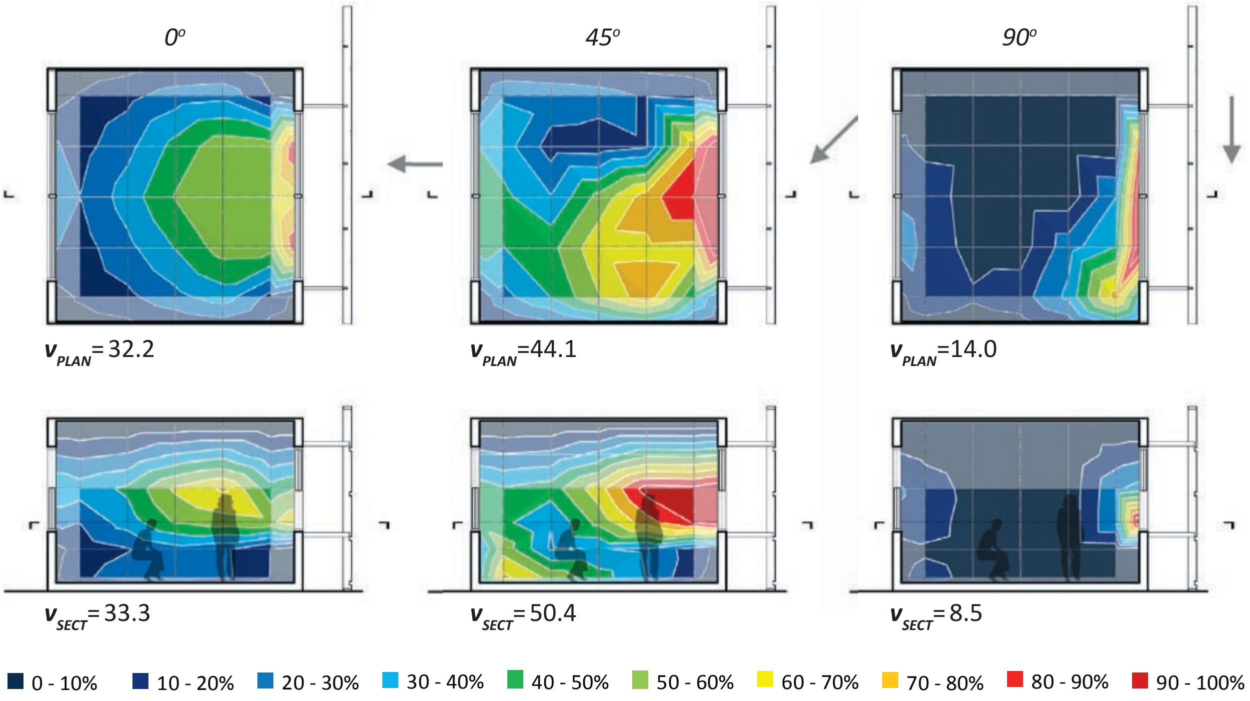


Figure 55. Top: *Top*: three incident wind angles tested indicated in axonometric drawing. The tinted planes indicate the locations of the airflow plan and section.
Left: directional airflow plan and section describing predominant flows, as observed at 0˚ incident wind. Smooth lines represent regions of less turbulence while rough lines indicate regions of more turbulence.
Below: airflow velocity plan and section contour maps at 0˚, 45˚ and 90˚ incident wind. Colors indicate velocity ratios at for each location (v_i/v_{ref}), expressed as a percentage of the unobstructed free stream air velocity (v_{ref}). Lighter tones at the perimeter are inferred velocities outside the measurement zone.



5.2 EXPLORING THE POTENTIAL FOR THERMAL COMFORT

Given a shade and window combination, when might wind-driven air motion have potential to work in suburban Bangkok? How much of the year might such a configuration work? The following exercise estimates the cooling potential of wind-driven ventilation for thermal comfort.

First, Typical Meteorological Year (TMY) Bangkok weather data was studied via *Climate Consultant 5* in order to determine the months where thermal comfort might be possible according to the adaptive model. In a previous study on natural ventilated houses in Bangkok[46], it was estimated that natural ventilation might be possible during the months of November through February. The results of Climate Consultant 5 for this exercise expanded upon this time frame, since according to the built-in adaptive model, there are more occupied hours within the comfort zone for the months of July, August, September or October than there are in January or February, as shown in Table 2 below. (In the case of classrooms, the Thai academic school year has summer vacation from late February or early March through early May; this also coincides with the hottest months.)

Velocity ratios from the wind tunnel data were applied to wind data for Bangkok, Thailand.[47] The urban density (and corresponding terrain roughness) was assumed to be suburban at a height of 5m above ground level, which results in a reduction factor[48] of 0.56. This was applied to the wind speed from the weather data at 10m above ground. With weather tape wind and data inputs, the average velocity for the best-performing combination – a louver

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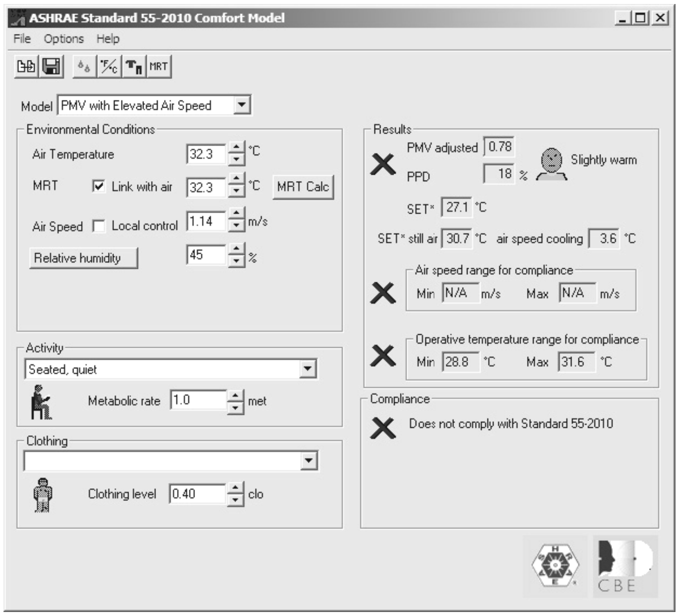
[46] Tantasavasdi, 2001.

[47] Weather data acquired from http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

[48] The following assumptions were made for scaling down local wind data from 10m weather data: The building was assumed to be situated in suburban Bangkok and the classroom was assumed to be on the second story, or 5m above ground level. The reduction factor is the coefficient with which wind data from a 10m high weather tower is scaled down so as to more closely relate to a specific terrain condition and height above ground. This factor was retrieved from Chandra 1986.

screen over double-hung window with upper sash open - was tested for thermal comfort in the Bangkok climate.

In order to simplify the process of studying climate data, each day of a month was divided into 3-hour blocks and averaged over the month, resulting in mean monthly 3-hour weather data. Each 3-hour block was then input into the ASHRAE Thermal Comfort Tool[49]. Note that the hours of the day considered for the study only included those in expected hours of occupancy of 7am and 6pm, as the program is that of a classroom. The clothing insulation value was assumed to be 0.4, 0.6 or 0.9 clo, the latter two for winter mornings[50] and interior temperatures float with outside temperatures. As an exploration, this does not include a true heat balance of the indoor thermal loads and thermal mass. (This condition modeled is more similar to buildings that have light construction.)



Model: PMV with Elevated Air Speed

Environmental Conditions
Air Temperature: 32.3 °C
MRT: ☑ Link with air 32.3 °C
Air Speed: ☐ Local control 1.14 m/s
Relative humidity: 45 %

Activity: Seated, quiet
Metabolic rate: 1.0 met

Clothing
Clothing level: 0.40 clo

Results
PMV adjusted: 0.78
PPD: 18 %
Slightly warm
SET*: 27.1 °C
SET* still air: 30.7 °C air speed cooling: 3.6 °C
Air speed range for compliance: Min N/A m/s Max N/A m/s
Operative temperature range for compliance: Min 28.8 °C Max 31.6 °C

Compliance
Does not comply with Standard 55-2010

Figure 56. Screen shot of the ASHRAE Comfort Tool.

This version of the ASHRAE Thermal Comfort Tool has the potential to account for the cooling impacts of air velocity given (radiant and air) temperature and relative humidity. Within

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[49] ASHRAE Thermal Comfort Tool version 2.0.03, Implemented in accordance with ASHRAE 55-2010 developed by Charlie Huizenga and Marc Fountain.

[50] 0.4 andn 0.6 clo is based on Kwok, 1997, p.89, who studied thermal comfort in Hawaii classrooms.

this tool, the “PMV with Elevated Air Speed” (also called SET* adjusted PMV) was the thermal comfort model selected for this exercise, as it has the most potential for studying the cooling effects of air motion. PMV utilizes a seven-point thermal sensation scale, where 3=hot, 2=warm, 1=slightly warm, 0=neutral, -1=slightly cool, -2=cool, and -3=cold. After each 3-hour block of weather data with adjusted velocities based on the wind tunnel studies was input, the model output a series of Predicted Mean Votes, or PMV. The summarized results of this exercise are shown in Table 2 below. Detailed portions are shown in Appendix A. To reiterate from section 2.2, ASHRAE considers a PMV between -0.5 and 0.5, or 10% people dissatisfied (PPD), to be acceptable. For the purposes of this study, PMV values between -1 to 1, or 26 PPD, are also considered to be acceptable. The results of this exercise for each wind angle are graphed in Figures 57, 58 and 59. For comparison, the same exercise was performed for the fixed air velocities of 0.5 m/s, as graphed in Figure 60.

	Percentage of Occupied Hours within Bangkok Comfort Zone								
	Adaptive Model *(assumes personal adjustment)*	**SET* PMV between -0.5 and 0.5** *(elevated air motion)*				**SET* PMV between -1 and 1** *(elevated air motion)*			
month		0°	45°	90°	0.5 m/s FAN	0°	45°	90°	0.5 m/s FAN
Jan	38%	50%	75%	25%	50%	100%	100%	50%	100%
Feb	37%	50%	75%	25%	50%	100%	100%	50%	75%
Mar	30%	the summer and early monsoon months were not tested				the summer and early monsoon months were not tested			
Apr	23%								
May	29%								
Jun	32%								
Jul	42%	50%	75%	25%	25%	100%	100%	25%	75%
Aug	47%	75%	100%	25%	50%	100%	100%	25%	100%
Sep	46%	75%	75%	25%	50%	100%	100%	25%	75%
Oct	58%	100%	100%	25%	75%	100%	100%	50%	100%
Nov	51%	75%	100%	25%	50%	100%	100%	25%	100%
Dec	53%	100%	75%	50%	75%	100%	100%	50%	100%
total	47%	72%	84%	28%	53%	100%	100%	38%	91%

Table 2. Results of thermal comfort explorations, showing percentage of time comfortable with Adaptive Comfort Ventilation and the SET* adjusted PMV for various speeds of air movement - both naturally ventilated (with shades and windows) and as fan-powered.

THERMAL COMFORT AT THE DIFFERENT INCIDENT WIND ANGLES. At the 0˚ incident wind angle, the PMV (adjusted to SET*) is between -0.5 (slightly cool) to 0.5 (slightly warm) for 72% of the occupied time; for 100% of the occupied time at the same angle of incidence, the PMV values fell between -1 (slightly cool) and 1(slightly warm).

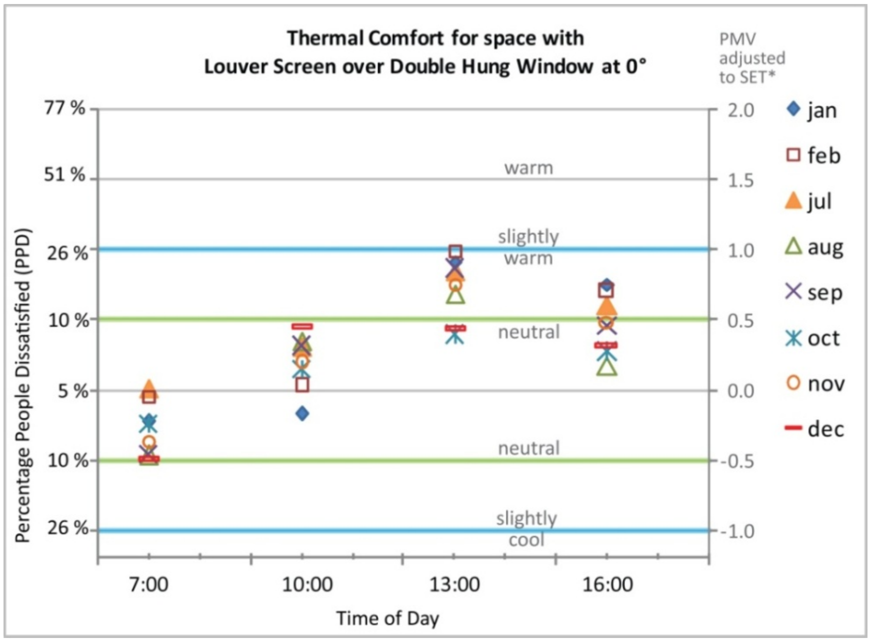


Figure 57. Thermal comfort for room with louver screen over double-hung window at 0˚ incident angle. 72% of the hours were within the range of -0.5 to 0.5, from slightly cool to slightly warm. 100% of the hours were within -1 and 1, from cool to warm.

Values for a 45˚ incident wind angle look even more promising, with PMV between -0.5 and 0.5 for 84% of the time and between -1 and 1 for 100% of the time (Figure 58).

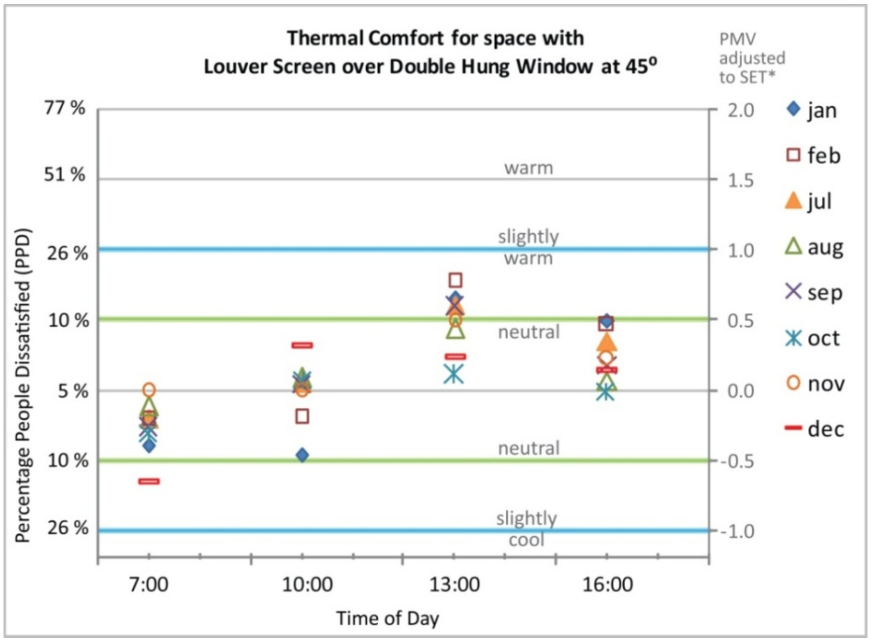


Figure 58. Thermal comfort for space with a louver screen over double-hung window at 45˚. 84% of the hours were within the range of -0.5 to 0.5, from slightly cool to slightly warm. 100% of the hours were within -1 and 1, from cool to warm.

Not surprisingly, at a 90˚ incident wind angle, the percentage of acceptable hours drops significantly to 28% of the occupied hours; even when comfort parameters are expanded to PMV between -1 and 1, the acceptable hours only reach 38%.

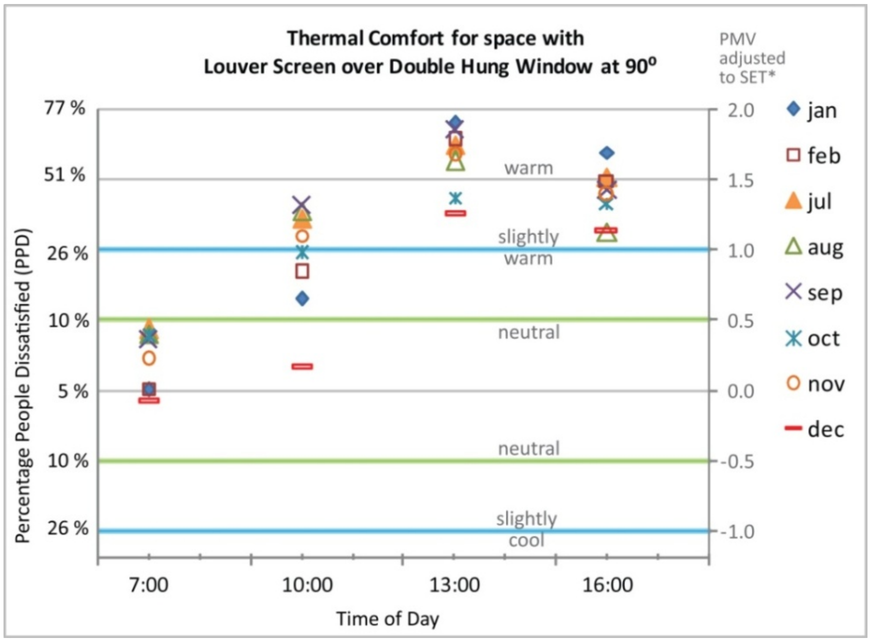


Figure 59. Thermal comfort for space with a louver screen over double-hung window at 90˚. 28% of the hours were within the range of -0.5 to 0.5, from slightly cool to slightly warm. Only 38% of the hours were within -1 and 1, from cool to warm.

For the 0.5 m/s fixed air velocity, the 53% of the hours fell within PMV values of -0.5 and 0.5 and 91% of the hours fell within values between -1 and 1. Note that for the afternoon block of 1-3pm, the months of February, July and September exceeded the PMV value of 1 at this fan speed. Except for December, this afternoon block (1-3pm) also exceeded PMV value of 0.5.

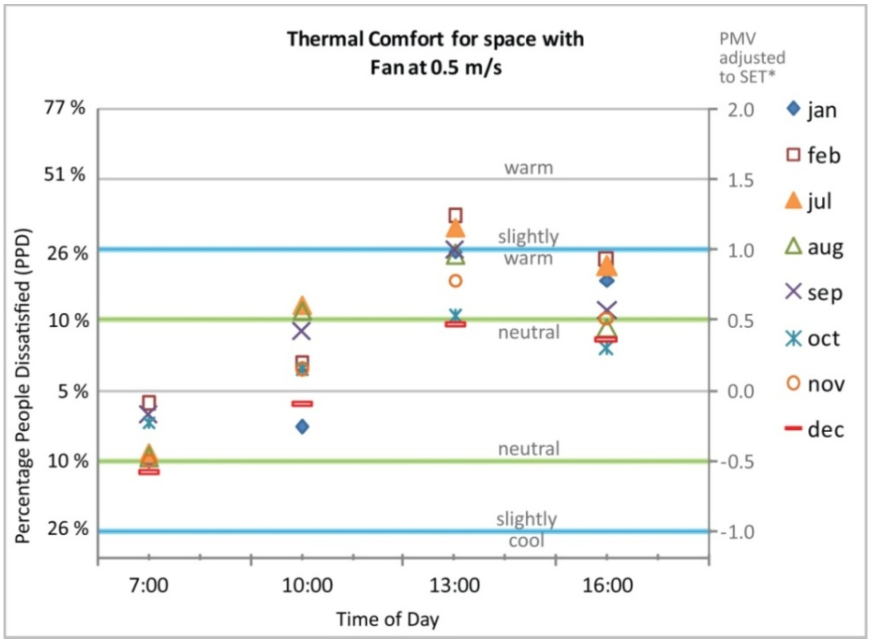


Figure 60. Thermal comfort for space with fan speeds of 0.5 m/s. 53% of the hours were considered to be thermally comfortable within the range of -0.5 to 0.5, from slightly cool to slightly warm. 91% of the hours were within -1 and 1, from cool to warm.

At this level of granularity, the results of the thermal comfort exercise suggest that this configuration at 0˚ and 45˚ to the incident wind direction may have potential to offset outdoor air temperatures during occupied hours and may warrant further studies for more specific scenarios.

5.3 LIMITATIONS OF THE METHODS

The methods utilized have involved simplifying many factors in order to proceed. This included summarizing some data into mean values, such as $\boldsymbol{v}_{plan}$ and $\boldsymbol{v}_{sect}$, and also monthly 3-hour (mean) weather data for the thermal comfort exploration. While simplifying the data this way may be helpful for general examination, this process loses detail that may be useful when applied to an actual building or for those who want to drill down.

CHAPTER 6 DISCUSSION

The objectives of this study were to characterize the impacts of a range of shading and window configurations on indoor airflow and to develop principles for designing windows and shades for wind-driven occupant cooling. The results emphasized the significant impact of the shade and window inlet geometry on airflow. The following chapter summarizes the results and evaluates them in the context of classrooms. Scenarios other than those specifically tested, such as with different outlet window locations, may yield different results, thus additional tests should be performed for scenarios where natural ventilation plays a critical role in direct occupant cooling.

6.1 What combinations of shading devices and window types create high velocity ratios across the occupied zone (0.1 – 1.7 m)?

Of those tested, the most effective shade and window configuration in terms of high plan and section velocity ratios with low spatial variation was the louver screen with a double-hung window. Moreover, if including the inlet window tests, the following facade inlet tests showed the highest velocity ratios for 0° incident wind:

1) awning window only (v_{PLAN}=50.9% and v_{SECT}=77.3%),
2) double-hung window only (v_{PLAN}=46.7% and v_{SECT}=44.6%),
3) double-hung window with louver screen (v_{PLAN}=30.9% and v_{SECT}=39.5%), and
4) double hung window with perforated panel (v_{PLAN}=32.2% and v_{SECT}=33.3%).

6.2 How do exterior shade screens in front of operable windows affect airflow and should they be used if natural ventilation is a goal? What window type is most compatible with a screen shade in terms of occupant cooling?

As mentioned earlier, natural occupant cooling can be quantified in terms of a high mean velocity ratio (in plan) v_{PLAN} with a low coefficient of spatial variation c_{SV}. Exterior shade screens create turbulence and decelerate airflow to varying degrees, depending on the size of the gaps between obstruction elements. Some, like perforated panel, limit the flow spread while others, like louver screen, disperse it. Louvers can help direct flow away from or towards occupants, depending on their tilt angle, while windows without shades generally provided higher velocity ratios than those with shades.

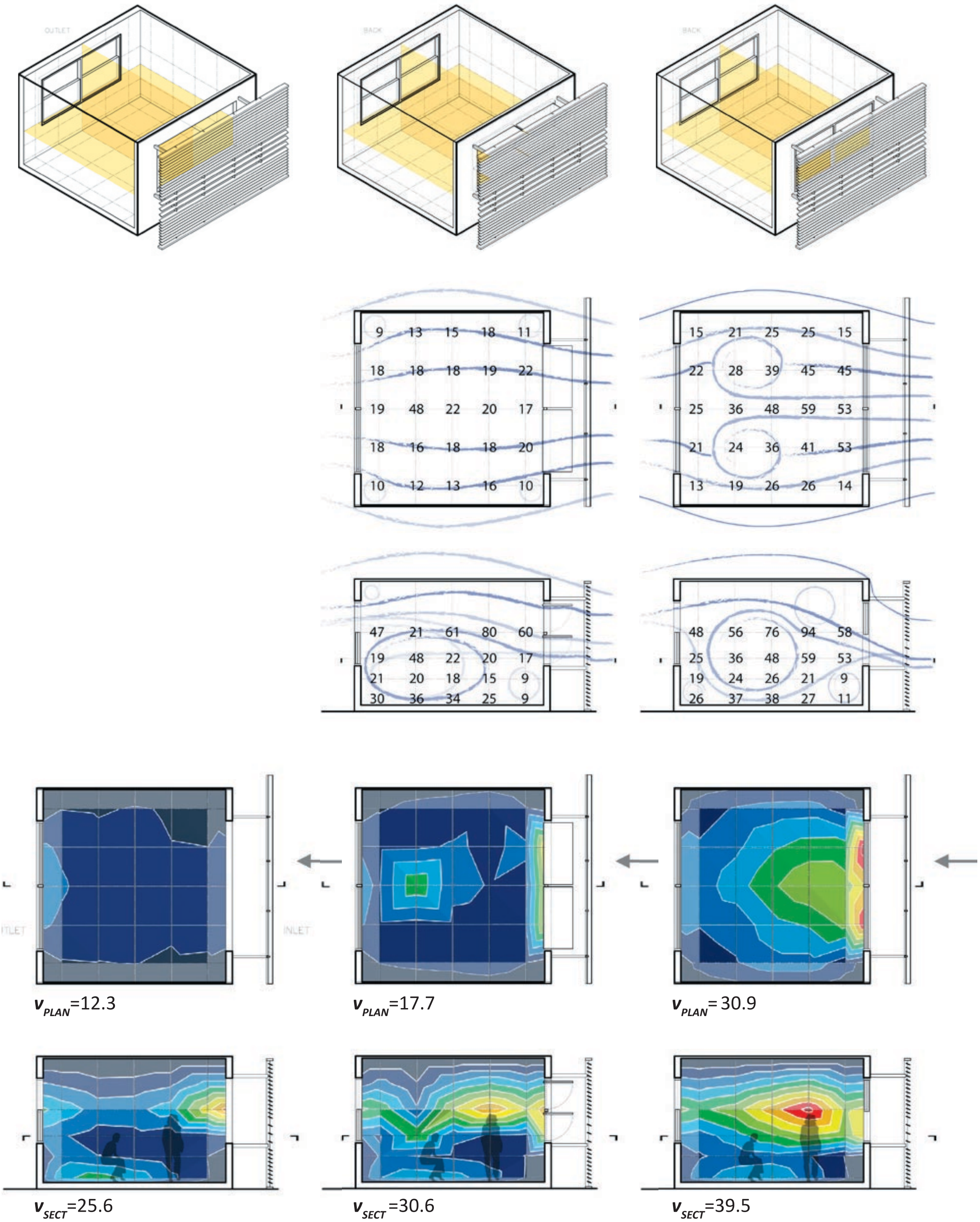
If maximizing flow speed is critical, exterior shade screens should be avoided or replaced with another form of shading – one that minimizes flow obstruction at critical times (e.g. shading that is retractable or moved). Horizontal overhangs are yet another alternative; they are aerodynamically less obstructive and can be a good option provided that they meet the project's shading needs and detailed in a way that will ensure that wind is not diverted away from the occupied zone.

Based on the results, double- single-hung windows are most compatible with screen shades from the point of view of maximizing velocity ratios. Other windows with non-projecting sashes such as horizontal sliding windows should also be further investigated.

6.3 What characteristic of the shade screen geometry reduces air velocity? How do the different types tested compare in terms of changing the velocity of airflow?

The size and orientation of the obstructing elements (like individual louvers) and the gaps between them contribute to the degree of flow deceleration. The indoor airflow is most hindered by a narrow open area (as between tightly spaced, versus loosely spaced louvers) and obstruction surfaces perpendicular to flow. The perforated panel and screens that block equally in plan and section tend to straighten while decelerating flow. In the louver screen, the long, wide gaps framed by the louvers and frame result in a decelerated velocity ratio without limiting plan spread. For the two screens tested here, the differences in velocity ratios were less than 7% with and without a window. Within the room, smaller eddies from the smaller gaps in the perforated panel dissipated the flow closer to the inlet wall than did the louver screen.

6.3.2 Louver Screen Comparisons

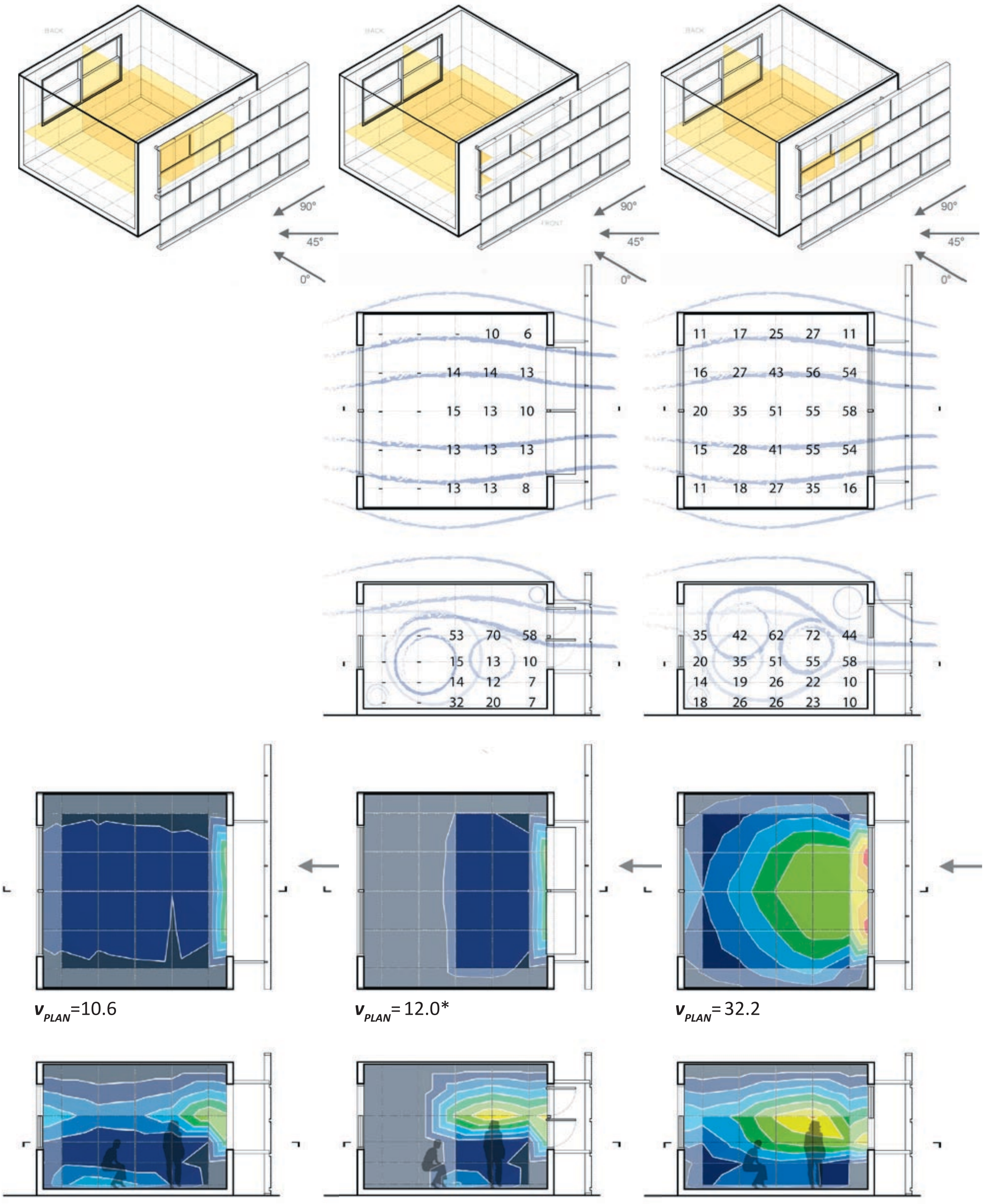


Louver Screen over Rough Opening
+ Double-hung, Upper Open

Louver Screen over Awning Window
+ Double-hung, Upper Open

Louver Screen over Double-hung, Lower Open
+ Double-hung, Upper Open

6.3.1 Perforated Panel Comparisons



v_{PLAN}=10.6

v_{SECT}=21.7

Perforated Panel over Rough Opening
+ Double-hung, Upper Open

v_{PLAN}= 12.0*

v_{SECT}=25.9*

Perf Panel over Awning Window
+ Double-hung, Upper Open

v_{PLAN}= 32.2

v_{SECT}= 33.3

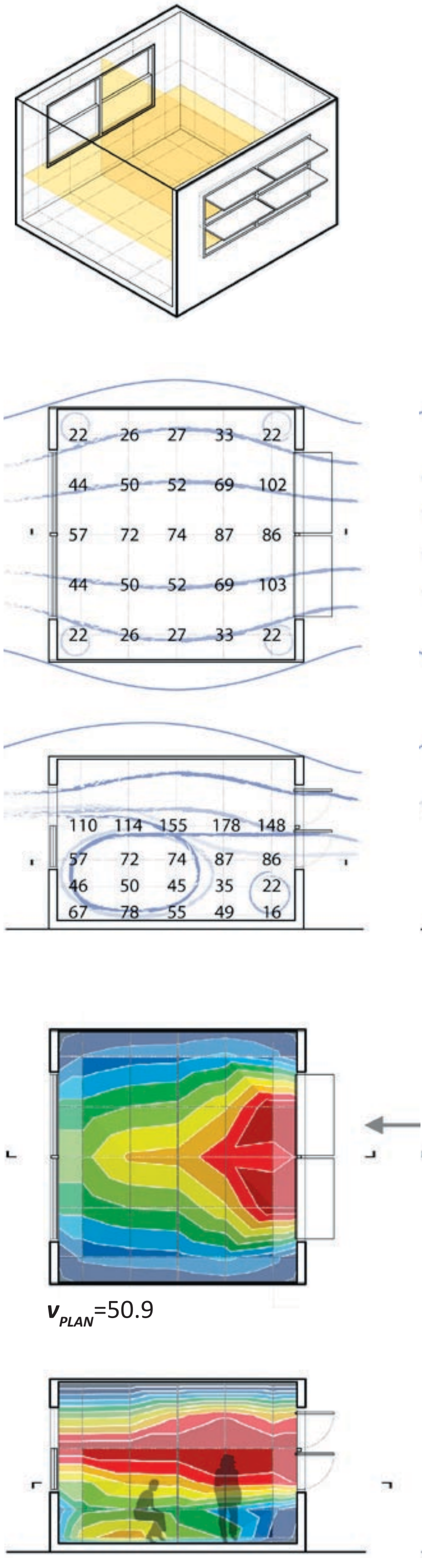
Perf Panel over Double-hung, Lower Open
+ Double-hung, Upper Open

6.4 How does the airflow vary with window type?

Windows operable area, sash size and the degree of opening impact flow direction and hence effectiveness in terms of cooling in the occupied zone. There was greater difference between the mean velocity ratios for the three window types than between the two shading types tested. Of course in terms of airflow, the windows and shades tested are simply different types and scales of physical flow obstructions.

For the awning window, flow appears to run along the plane of the projected sash and into the space at the same angle of the sash position. The casement window in series (or four in a row as tested in this study) results in lower velocity ratios, yet distribute air evenly, also at the angle as the sash. The asymmetrical flow pattern in plan at 0˚ incidence angle suggests that their arrangement – all opened in series to the same right side – plays a role. For the double-hung window, a sheet of air following the geometry of the open window steadily meanders through the space to find its outlet and creates large secondary eddies along the way. The sill, jambs and sash edge are predominant parts of the opening geometry and affect the shape and direction of flow. In contrast to projecting windows, the angle of indoor flow in sliding windows is not as dependent on the degree of opening.

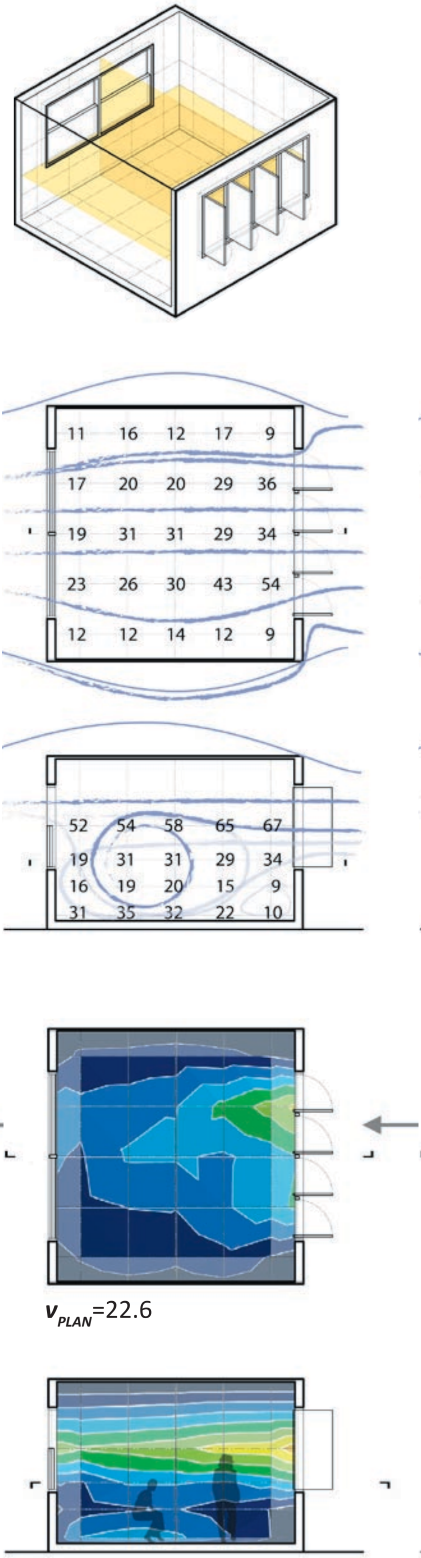
6.4.1 Window Comparisons



$v_{PLAN}=50.9$

$v_{SECT}=77.3$

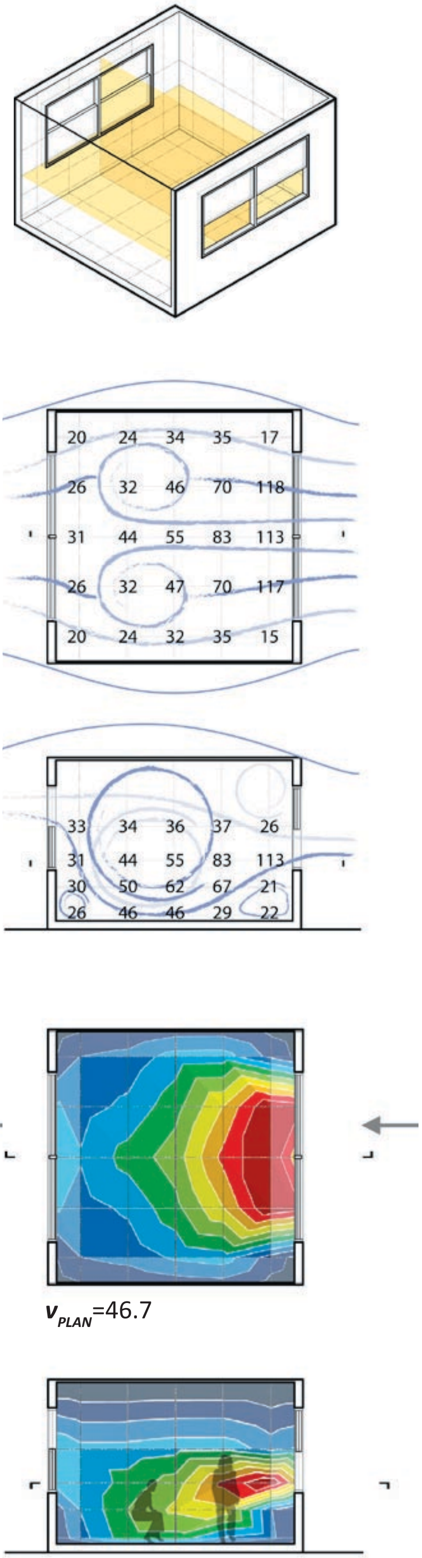
Awning Window
+ Double-hung, Upper Open



$v_{PLAN}=22.6$

$v_{SECT}=32.4$

Casement Window
+ Double-hung, Upper Open

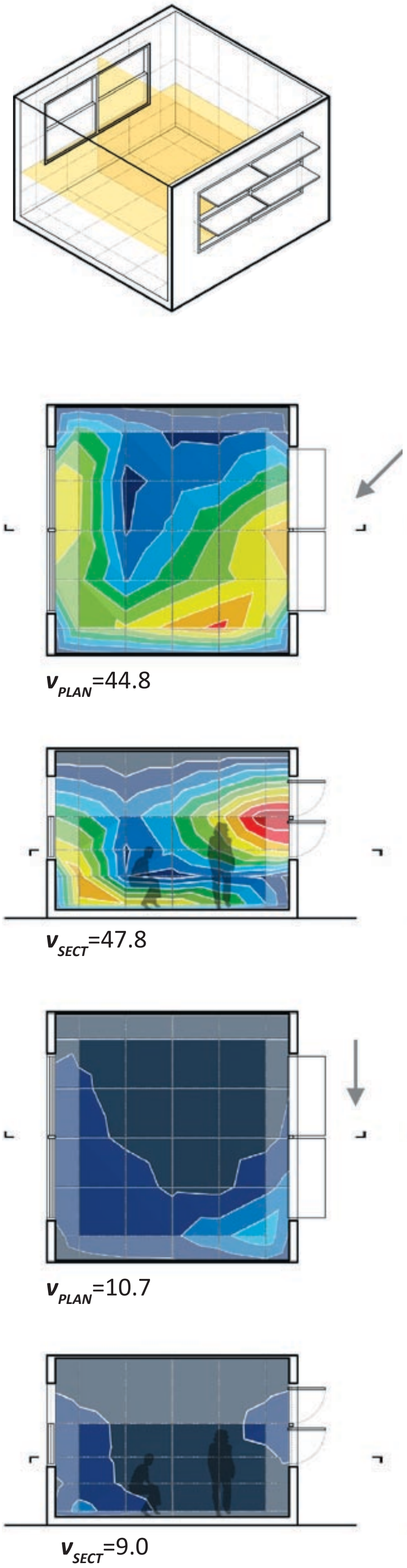


$v_{PLAN}=46.7$

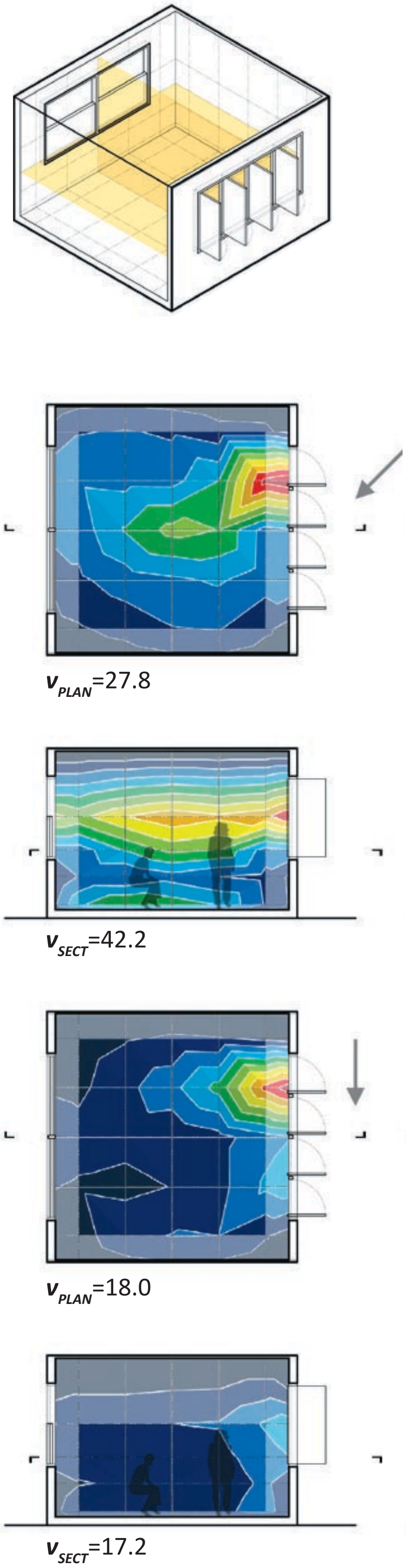
$v_{SECT}=44.6$

Double-hung, Lower Open
+ Double-hung, Upper Open

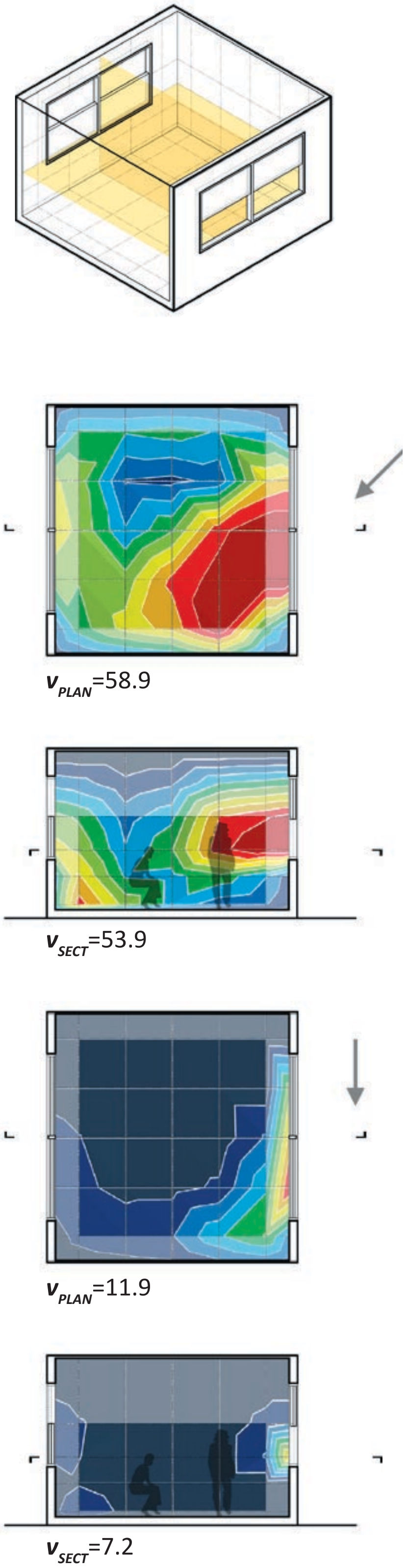
6.4.2 Window Comparisons at 45° and 90°



Awning Window
+ Double-hung, Upper Open

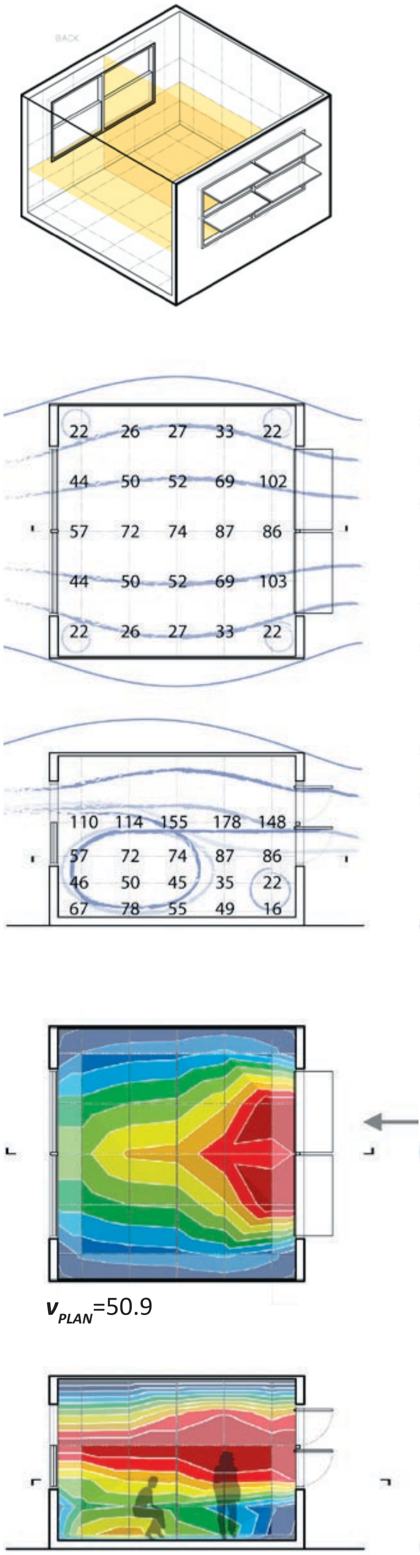


Casement Window
+ Double-hung, Upper Open



Double-hung, Lower Open
+ Double-hung, Upper Open

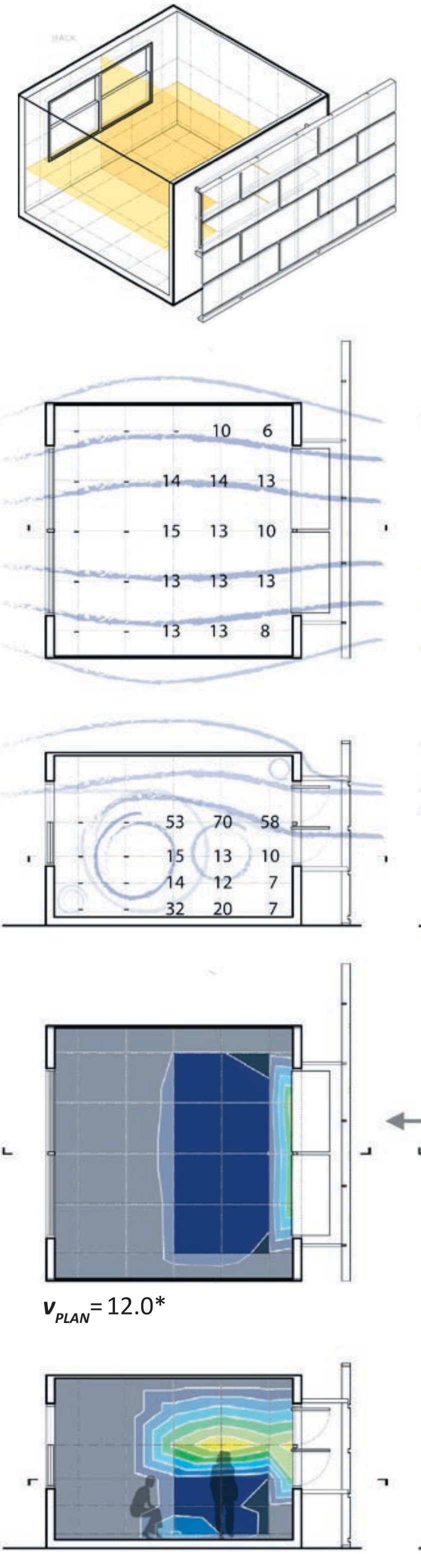
6.4.3 Awning Window Comparisons



v_{PLAN}=50.9

v_{SECT}=77.3

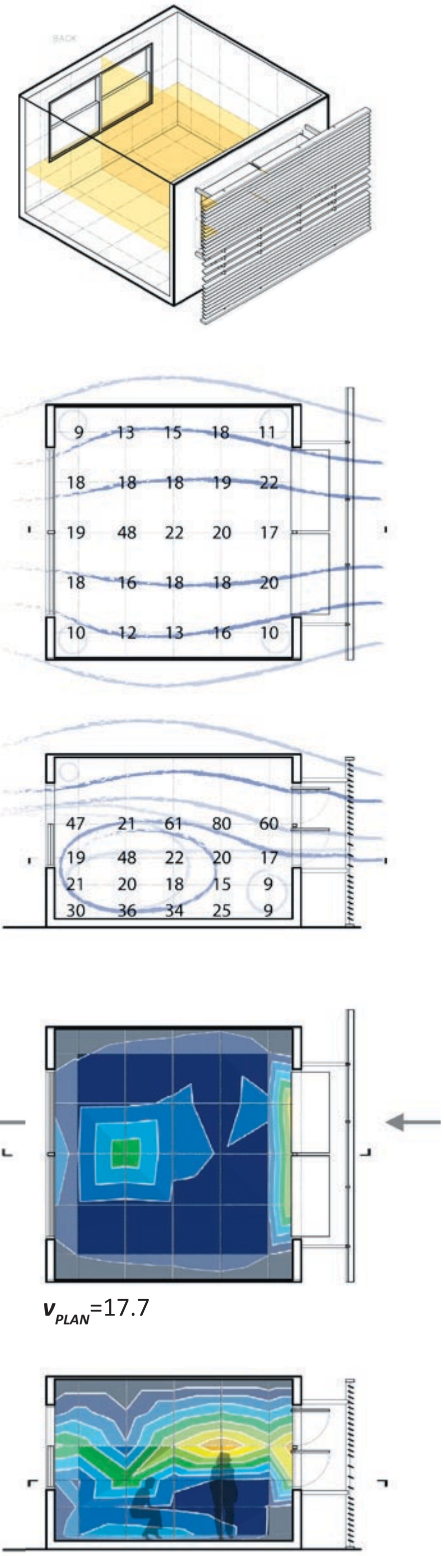
Awning Window
+ Double-hung, Upper Open



v_{PLAN}= 12.0*

v_{SECT}=25.9*

Perf Panel over Awning Window
+ Double-hung, Upper Open

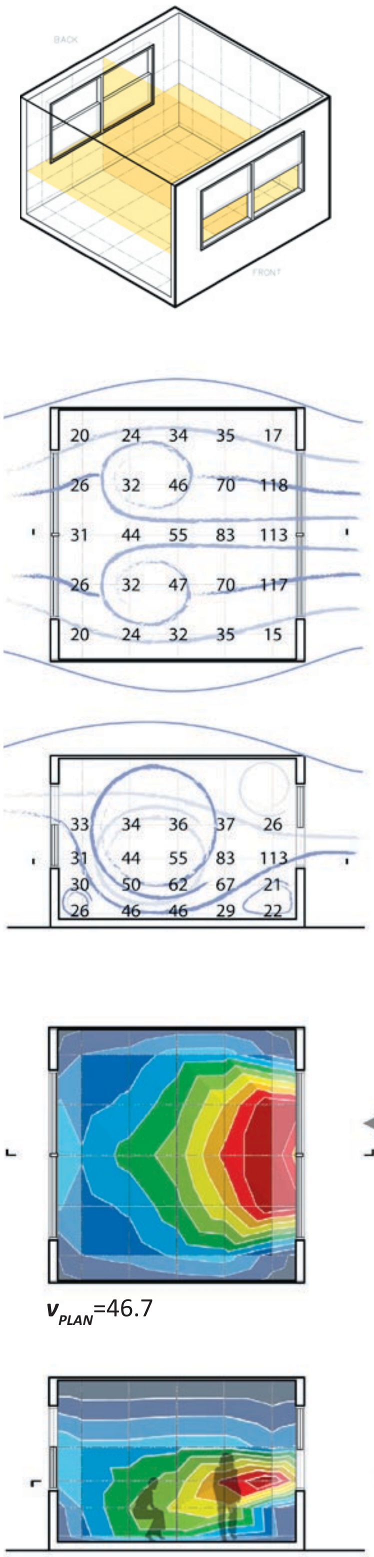


v_{PLAN}=17.7

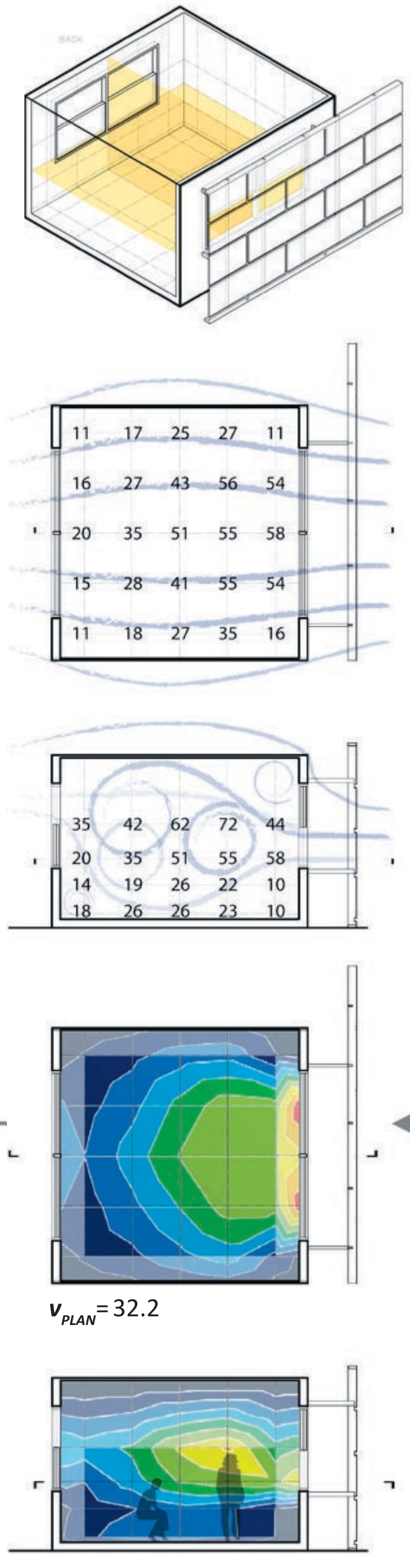
v_{SECT}=30.6

Louver Screen over Awning Window
+ Double-hung, Upper Open

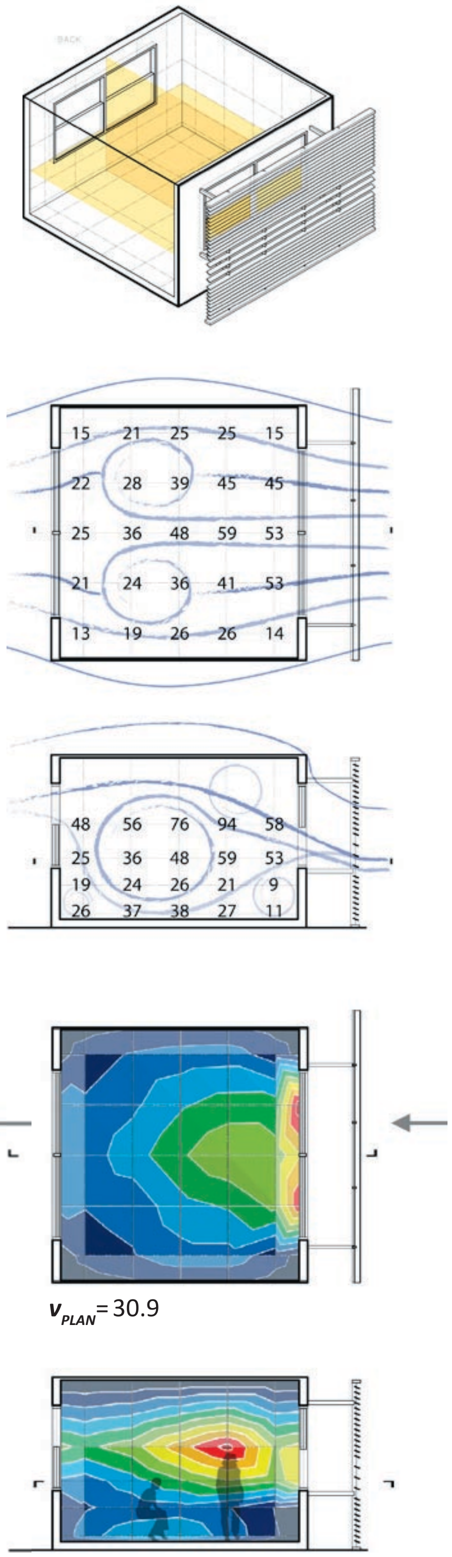
6.4.4 Double-hung Window Comparisons



Double-hung, Lower Open
+ Double-hung, Upper Open



Perf Panel over Double-hung, Lower Open
+ Double-hung, Upper Open



Louver Screen over Double-hung, Lower Open
+ Double-hung, Upper Open

6.5 Given a combination of shades and windows that effectively promotes air movement in the occupied zone, at what times is wind-driven cooling acceptable for thermal comfort? What factors can expand the use of natural cooling in a classroom setting?

While this study did not consider the tropical Southeast Asian summer months of March through June, the results do suggest that both seasons considered - winter and monsoon - have potential for wind-driven occupant cooling in suburban Bangkok. Afternoon periods are challenging in terms of natural cooling as outdoor indoor and temperatures reach their daily maximum. Whether or not wind-driven ventilation might be acceptable for thermal comfort will depend largely on site factors (such as diurnal temperature ranges and wind availability,) and building use factors (occupant schedules, dress code, internal loads and temperatures). While influencing use factors are outside the typical scope of traditional building design practice, some factors are within the scope of what schools typically dictate.

Recommendations can also be incorporated through building signage and into a building tenant manual that would help address these patterns in the context of the building's natural ventilation scheme. Furnishings and other obstructions should be selected carefully so as to minimally obstruct airflow path. Seats and chairs on the other hand, can add to the clothing insulation level and contribute to feeling too warm. Backup cooling systems should be considered for when there is no wind, or times when natural ventilation is not an option. Occupant control of shades, windows and/or fans can have a significant impact on the thermal comfort in a space. Other considerations outside the immediate scope of this study that have impacts on natural ventilation include daylighting, acoustic control, pollution, weatherproofing and maintenance.

CHAPTER 7 CONCLUSIONS and FUTURE WORK

7.1 CONCLUSIONS

This work also proposes one way of using climate data and wind tunnel studies to inform design – from schematic decisions like façade orientation to construction details of inlet openings – and helps to relate the physical phenomena of air movement to design decision making. If one thing is taken from this work, it is that there are aerodynamic implications associated with shades and windows which should be considered when weighing different options.

The main conclusion of this study is that shades and windows can minimally or significantly diminish the velocity and distribution of indoor flow and the degree of this obstruction is not obvious. This is significant if wind-driven ventilation is to be used to achieve comfort and offset some of the energy and resources required for air conditioning. The list below covers key conclusions drawn from this study and the following section offers suggestions for future work.

1. While exterior shade screens do not eliminate the possibility of using natural ventilation for occupant cooling, air velocity through windows is higher without them.
2. In screens, the orientation, size and shape of the elements and gaps between them contribute to the amount of flow that is reduced, where it is directed and if the resultant flow has enough energy to distribute across the space. The clear openings between flow obstructions (such as shading elements or window sashes) have more influence over the resultant indoor velocity than do window or shade porosity alone.
3. When shade screens are installed in front of a projecting window (such as awning windows) at an inlet opening, air speed and distribution are significantly impeded; thus, this combination is not ideal for direct occupant cooling.
4. Opening size is only partially informative; any shades, window opening type, sash size, opening amount, window construction details, and other such aspects of constructed buildings must be considered while assessing facades for natural cooling. Window operation type determines the shape of indoor airflow and thus where the air travels.

7.2 SUGGESTIONS for FUTURE WORK

There are many directions in which future work could proceed. These studies, as grouped by similarity might involve:

- Adding more mass to the model, as to more closely simulate a low-rise multistory building. At some angles, the reattachment zones are critical for air movement.
- Testing more shades, such as shading systems that wrap around corners. How do perforated louvers compare to solid louvers? Rough louvers compared with smooth louvers?
- Comparing wind tunnel and CFD results, highlighting the different inputs and outputs required.
- For an actual classroom, calculating the thermal comfort based on actual internal loads and thermal mass and then running a building energy simulation based on this.

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APPENDIX A: THERMAL COMFORT EXPLORATION RESULTS

		INPUT						Av Velocity Ratios				OUTPUT								-0.5 < PMV < 0.5				-1 < PMV < 1			
	Time (montly 3-hr mean)	Air temp (°C)	MRT (°C)	RH (%)	Air velocity (m/s)	MET	clo	(from WT studies) VB DH 0	VB DH 45	VB DH 90	FAN 0.5 m/s	VB-DH 0°		VB-DH 45°		VB-DH 90°		FAN 0.5 m/s		0°	45°	90°	0.5 m/s	0°	45°	90°	0.5 m/s
												-- SET adjusted --															
												PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD	72%	84%	28%	53%	100%	100%	38%	91%
jan	7-9	23.4	23.4	0.79	see Average Air Velocity by Angle	1	0.9	0.25	0.38	0.08	0.50	-0.22	0.06	-0.39	0.08	0.01	0.05	-0.49	0.10	-	-	-	-	-	-	-	-
	10-12	28.2	28.2	0.66		1	0.4	0.47	0.70	0.15	0.50	-0.16	0.06	-0.46	0.10	0.66	0.14	-0.24	0.06	-	-	1	-	-	-	-	-
	13-15	31.6	31.6	0.55		1	0.4	0.56	0.84	0.17	0.50	0.92	0.23	0.66	0.14	1.91	0.72	1.00	0.26	1	1	1	1	-	-	1	-
	16-18	31.1	31.1	0.56		1	0.4	0.53	0.80	0.17	0.50	0.76	0.17	0.50	0.10	1.7	0.62	0.80	0.19	1	-	1	1	-	-	1	-
feb	7-9	25.2	25.2	0.79		1	0.9	0.46	0.70	0.14	0.50	-0.05	0.13	-0.20	0.20	0.02	0.05	-0.08	0.05	-	-	-	-	-	-	-	-
	10-12	29.5	29.5	0.59		1	0.4	0.68	1.03	0.21	0.50	0.03	0.05	-0.19	0.06	0.85	0.20	0.20	0.06	-	-	1	-	-	-	-	-
	13-15	32.3	32.3	0.45		1	0.4	0.76	1.14	0.24	0.50	0.99	0.25	0.78	0.18	1.79	0.67	1.25	0.37	1	1	1	1	-	-	1	1
	16-18	31.5	31.5	0.48		1	0.4	0.74	1.12	0.23	0.50	0.70	0.15	0.47	0.10	1.5	0.52	0.94	0.23	1	-	1	1	-	-	1	-
jul	7-9	27.6	27.6	0.77		1	0.4-0.6	0.50	0.76	0.16	0.50	0.02	0.06	-0.20	0.06	0.44	0.09	-0.43	0.09	-	-	-	-	-	-	-	-
	10-12	30.6	30.6	0.64		1	0.4	0.78	1.18	0.24	0.50	0.31	0.07	0.06	0.05	1.23	0.37	0.62	0.13	-	-	1	1	-	-	1	-
	13-15	32.0	32.0	0.59		1	0.4	0.80	1.21	0.25	0.50	0.85	0.02	0.61	0.13	1.75	0.64	1.17	0.34	1	1	1	1	-	-	1	1
	16-18	31.3	31.3	0.63		1	0.4	0.75	1.14	0.24	0.50	0.61	0.13	0.35	0.08	1.52	0.52	0.90	0.22	1	-	1	1	-	-	1	-
aug	7-9	27.5	27.5	0.78		1	0.4-0.6	0.50	0.75	0.16	0.50	-0.46	0.09	-0.11	0.05	0.41	0.08	-0.46	0.09	-	-	-	-	-	-	-	-
	10-12	30.5	30.5	0.65		1	0.4	0.69	1.04	0.22	0.50	0.35	0.08	0.09	0.05	1.28	0.39	0.58	0.12	-	-	1	1	-	-	1	-
	13-15	31.5	31.5	0.62		1	0.4	0.75	1.13	0.23	0.50	0.69	0.15	0.44	0.09	1.64	0.58	0.98	0.25	1	-	1	1	-	-	1	-
	16-18	30.2	30.2	0.68		1	0.4	0.74	1.12	0.23	0.50	0.18	0.06	0.07	0.05	1.13	0.32	0.46	0.09	-	-	1	-	-	-	1	-
sep	7-9	27.0	27.0	0.81		1	0.6	0.41	0.61	0.13	0.50	-0.45	0.09	-0.26	0.06	0.37	0.08	-0.16	0.06	-	-	-	-	-	-	-	-
	10-12	30.1	30.1	0.67		1	0.4	0.58	0.88	0.18	0.50	0.32	0.07	0.04	0.05	1.32	0.41	0.43	0.09	-	-	1	-	-	-	1	-
	13-15	31.6	31.6	0.61		1	0.4	0.61	0.92	0.19	0.50	0.87	0.21	0.60	0.13	1.86	0.70	1.01	0.27	1	1	1	1	-	-	1	1
	16-18	30.5	30.5	0.66		1	0.4	0.59	0.90	0.19	0.50	0.46	0.09	0.18	0.06	1.43	0.47	0.58	0.12	-	-	1	1	-	-	1	-
oct	7-9	26.9	26.9	0.87		1	0.4-0.6	0.30	0.46	0.09	0.50	-0.24	0.06	-0.30	0.07	0.39	0.08	-0.21	0.06	-	-	-	-	-	-	-	-
	10-12	29.4	29.4	0.72		1	0.4	0.52	0.79	0.16	0.50	0.15	0.05	0.07	0.05	0.98	0.25	0.16	0.06	-	-	1	-	-	-	-	-
	13-15	30.4	30.4	0.65		1	0.4	0.61	0.93	0.19	0.50	0.40	0.08	0.12	0.05	1.38	0.44	0.54	0.11	-	-	1	1	-	-	1	-
	16-18	29.8	29.8	0.70		1	0.4	0.52	0.79	0.16	0.50	0.28	0.07	-0.01	0.05	1.34	0.42	0.31	0.07	-	-	1	-	-	-	1	-
nov	7-9	25.8	25.8	0.74		1	0.6-0.9	0.40	0.60	0.13	0.50	-0.36	0.08	0.00	0.05	0.23	0.06	-0.48	0.10	-	-	-	-	-	-	-	-
	10-12	29.4	29.4	0.59		1	0.4	0.47	0.71	0.15	0.50	0.20	0.06	0.00	0.05	1.11	0.31	0.16	0.06	-	-	1	-	-	-	1	-
	13-15	31.1	31.1	0.54		1	0.4	0.53	0.80	0.17	0.50	0.76	0.17	0.50	0.10	1.68	0.60	0.80	0.18	1	-	1	1	-	-	1	-
	16-18	30.4	30.4	0.57		1	0.4	0.53	0.80	0.17	0.50	0.49	0.10	0.23	0.06	1.4	0.46	0.53	0.11	-	-	1	1	-	-	1	-
dec	7-9	23.5	23.5	0.66		1	0.9	0.40	0.60	0.12	0.50	-0.48	0.10	-0.64	0.14	-0.06	0.05	-0.57	0.12	-	1	-	1	-	-	-	-
	10-12	27.4	27.4	0.52		1	0.9	0.49	0.73	0.15	0.50	0.46	0.14	0.32	0.23	0.17	0.06	-0.08	0.05	-	-	-	-	-	-	-	-
	13-15	30.4	30.4	0.44		1	0.4	0.54	0.81	0.17	0.50	0.45	0.09	0.24	0.06	1.27	0.39	0.49	0.10	-	-	1	-	-	-	1	-
	16-18	30.1	30.1	0.45		1	0.4	0.55	0.83	0.17	0.50	0.33	0.07	0.15	0.05	1.15	0.33	0.38	0.08	-	-	1	-	-	-	1	-