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

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ABSTRACT

Natural ventilation and other low-energy cooling strategies for buildings require careful load control and heat avoidance. While exterior shading can substantially reduce solar loads through glazing, such shading can also impact breezes through open windows. The screen-like shades prevalent in contemporary architecture are particularly susceptible to breeze obstruction, yet almost no information is available in design guidelines on their aerodynamic effects. This study explores the impacts of exterior shading on the indoor airflow for occupants. This was examined via wind tunnel tests of a model of a single-story classroom with interchangeable windows and shades. The results suggest that the combination of window opening type and shade geometry has a significant impact on indoor velocity, and thus the direct occupant cooling possible. Awning windows in particular resulted substantial drag when located behind external screen shades. Sliding windows – particularly single- and double-hung – conflicted less with screen shades in terms of interior airflow obstruction, indicating a higher potential of wind-driven cooling with such a combination.

1. Introduction

Natural ventilation is an important topic in building performance and low-energy cooling. Given suitable conditions, wind-driven ventilative cooling has the potential to lower building energy use by minimising the amount of mechanical cooling needed for occupant comfort in buildings. It is especially in tropical and temperate climates where natural ventilation holds promise to reclaim some of the territory previously displaced by mechanical cooling.

Natural ventilation and other low energy cooling strategies require careful load control and heat avoidance from the building envelope. Exterior shading can substantially reduce these loads through glazing. While exterior shading is mainly for blocking direct sunlight, such projections can also block breezes through open windows. The screen-like shades prevalent in contemporary architecture are particularly susceptible to breeze obstruction, yet almost no information is available in design guidelines on their aerodynamic effects.

Though other forms of external shading have previously been studied in terms of airflow (Caudill 1954, Chand 1971, Sobin 1983, and Chandra 1986), screen shading systems, such as those present in much contemporary architecture, have yet to be analyzed in terms of indoor airflow. This is likely why little information is available in design guidelines on their aerodynamic effects on natural ventilation. Given the desire to shade and naturally cool, what are the effects of exterior shading on the indoor airflow for occupants?

The purpose of this study is to assess the impact of various shading and window configurations on indoor airflow in order to identify how specific inlet geometries impact the effectiveness of wind-driven cooling, particularly in warm humid conditions. 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. The impact of inlet façade components – in this case exterior shade screens and window types - on natural ventilation are assessed in terms of the mean spatial velocity and distribution of the airflow.

Natural ventilation provides multiple services to building occupants:

1) It provides air for breathing.
2) Direct air movement on skin aids both convective and evaporative cooling.
3) It replaces warm air within a space with cooler air, and thus lowers the indoor air temperature.
4) It removes heat accumulation in the building structure.

The primary purpose of natural ventilation examined in this study is direct occupant cooling (or item 2 above). Increasing airflow improves thermal comfort in warm, humid environments (ASHRAE Standard 55-2013 section 5.2.3). In both air-conditioned and naturally ventilated buildings, most occupants prefer to have more air movement and very few want less (Arens 2009). Unlike cooling spaces or structural elements, direct occupant cooling can be achieved with outdoor temperatures that are near or higher than indoor temperature, provided it is lower than body temperature and the air velocity is high. Additionally, the provision for occupant control of air speed has been shown to expand the zone of thermal comfort (Olesen and Brager 2004). At the warm, humid end of the comfort zone the maximum allowable airspeed is dependent on occupant preference and expectations (ASHRAE 55-2013 section 5.2.3).

Though it is particularly challenging to evenly cool with wind driven ventilation for multiple occupants, how this issue is addressed can inform natural ventilation strategies in other nondomestic space types, such as offices, schools and small low-rise buildings. Classrooms are good particularly candidates for examining the interaction of shading and ventilation for cooling; the setting tends to be uniformly and densely occupied with a number of students seated at desks. From school houses to school buildings, classrooms have a history of having narrow (one-room deep) plans, as it is common for them to be designed to access light and air.

Thermal Comfort Standards

Building designers use thermal comfort standards such as ASHRAE Standard 55, and ISO 7730 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 (Fanger 1970), the current standards have come to incorporate models for adaptive thermal comfort based on field studies (de Dear and Brager 2001). That is, the current standards recognize that thermal comfort and preferences can differ for people of different climates and habits. As such, ASHRAE 55-2010 was modified to expand the allowable range of airspeeds in neutral to warm conditions. This is important to note when assessing if natural ventilation is adequate in providing comfort at the warmer end of the comfort zone. 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 (Zelenay et al 2010). ASHRAE-55's recent modification increases the upper limit of air movement to 1.2 m/s for mechanically conditioned spaces. Note that the upper limits to velocity and the relative humidity are not as clearly defined for naturally conditioned 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 higher mean velocity (vPLAN) that is more evenly distributed, where spatial variation (csv) is low. More airspeed uniformity across the 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 stuffy or warm (i.e. far from windows) in the same room.

This study assumes that the maximum allowable indoor airspeed is 3 m/s and that occupants have the ability to reduce air velocity by operating windows or changing seats if speeds are higher than preferred. (Based on a discussion with thermal comfort researchers at the Center for the Built Environment, UC Berkeley, 3 m/s was considered to be an acceptable high air speed, and this is also the maximum air velocity input allowable for the ASHRAE Thermal Comfort Tool.) In terms of thermal acceptability, ASHRAE Standard 55 considers a PMV between just slightly cool (-0.5) and just slightly warm (0.5) to be acceptable, equivalent to 10% PPD (or percentage of people dissatisfied). For the purposes of this study, the threshold of thermal acceptability is a SET (or Standard Effective Temperature) adjusted PMV is between slightly cool (-1) and slightly warm (1), which equals 26% PPD. Air velocities are considered to have occupant cooling potential when they can offset higher temperatures in the SET adjusted PMV thermal comfort model.

2. Methods

Boundary Layer Wind Tunnel

Wind tunnel model testing was selected for the purposes of this study. There were a number of reasons for this: exploring the method was relatively accessible; once built, physical models were relatively easy to adjust; wind tunnel testing has allowed for both velocity measurements and flow visualization; and, the Building Science Lab at UC Berkeley has a functional boundary layer wind tunnel (BLWT) as well as researchers with direct experience with testing the built environment in this specific wind tunnel. Details on the BLWT and experimental setup are available in Hildebrand (2011).

Model Description

The 1:8 scale model represents a single classroom within a low-rise building. Indoor air movement studies warrant a larger model for visualizing the interior flow. From the point of view of wind tunnel studies for natural ventilation, low-rise buildings are ideal for testing detailed façade components. In order to work within the constraints of the BLWT, the classroom was modeled as single room with reconfigurable windows and exterior shades.

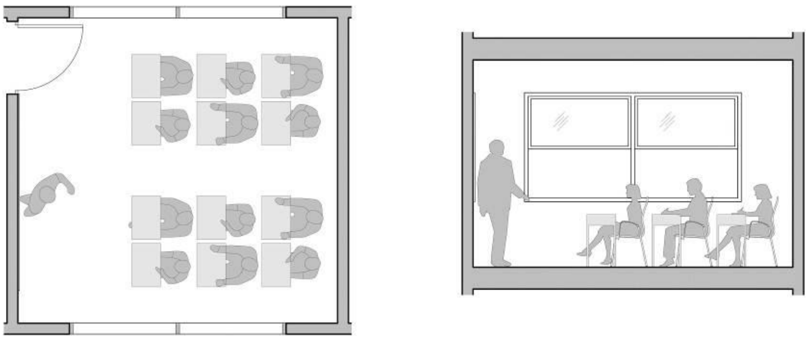

Figure 1. Plan and section of classroom model.

Windows and Shades Tested

The study examined two types of scrims, or external screen shades: a perforated panel system and exterior louvers; both shades were of equal porosity at 53%, though geometrically different. The shading devices selected for testing were based on the porosity of the perforated panels of the San Francisco Federal Building, which uses hybrid ventilation. The louver dimensions are comparable to that of commercially available exterior Venetian blinds. Both scrims were mounted 0.9 m outside of the inlet opening. Three types of operable windows were studied: awning, casement and double-hung windows. All windows fitted within the same rough opening. Examples of screen shades and window types are shown below.

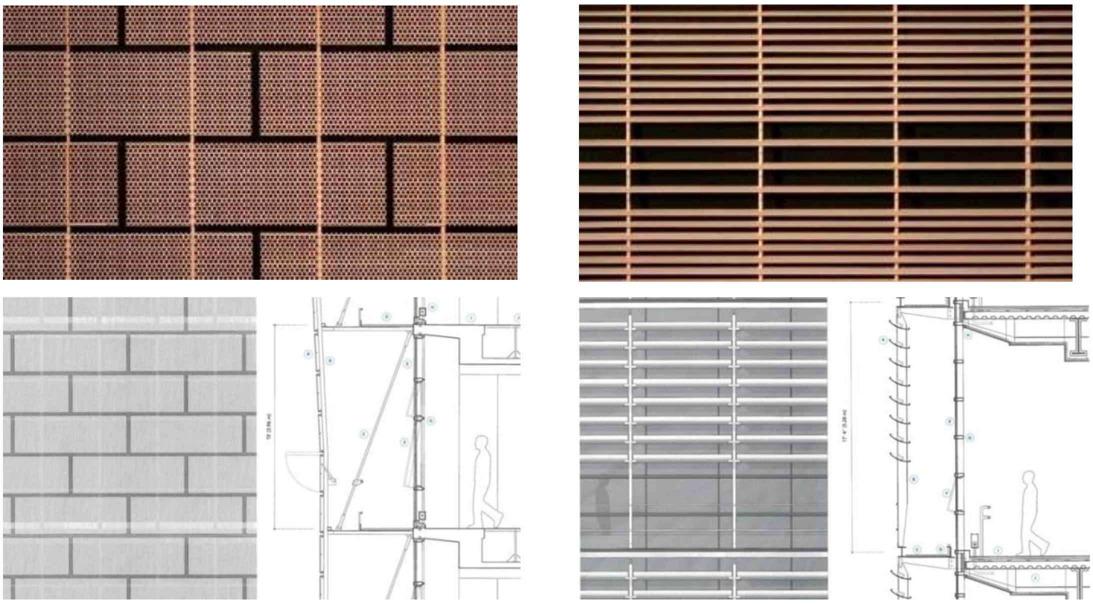

Figure 2. Scrims as modeled for wind tunnel testing (above) and architectural examples of the shades and windows investigated (below). (left) The SFFB has awning windows behind a perforated panel screen, shown in elevation and section drawings. (right) The New 42nd Street Studios, New York, has awning windows behind a louver screen. (image from Murray 2009)

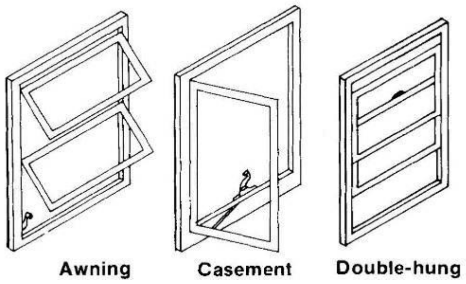

Figure 3: Illustrations of the window types studied.

Velocity Measurements and Flow Visualisation

Velocity measurements were taken with a TSI hotwire anemometer. The hot-wire sensor is most accurate at measuring airflow normal to the wire, which in this case means locations in horizontal planes parallel to the wind tunnel floor. The 1-minute mean wind velocity at each interior point divided by the reference velocity – taken from an unobstructed location in the approach flow – provides the velocity ratio.

Flow visualization was observed with ‘smoke’ created with an ultrasonic fogger attached to a compressed air hose and later a theatrical smoke machine. (This particular BLWT is open circuit within a shared office space. The type of smoke used is required to be safe for human breathing. This ruled out the use of titanium tetrachloride, which is toxic.) Video footage and photographs were captured from these physical studies in order to observe interior flow direction. Though images alone are not highly descriptive, as the fog did not photograph well, video footage was helpful in reviewing what was empirically observed in space.

Experimental Plan

Testing began with individual components first and built up to combinations of components; this included measuring and observing indoor air movement from three sets of wind tunnel studies. The first set established the effects of the base model with and without windows. The second set studied the effects of individual components – three windows and two shades – on the base model. The third set tested the combined effects of multiple components.

Each test involved taking 40 interior air velocity measurements (25 in plan and 20 in section) inside the model at the three angles of incidence of 0˚, 45˚, and 90˚. Air velocities results are described through iso-velocity contour maps in plan and in section. Flow patterns are then described in drawn plans and sections based on smoke studies, both observed first hand and as captured on video.

3. Results

Each test was characterized by a mean velocity ratio in plan and in section (or v_{PLAN} and v_{SECT} respectively), the coefficient of spatial variation c_{SV} and by the corresponding contour maps describing the relative velocity distribution within the room. The shape of airflow was very different in the three windows tested. Each performed with maximum v_{PLAN} and v_{SECT} values at different angles of incidence. The awning window had maximum values for at an incident wind of 0°; the double-hung at 45°; and the casement window at 90°.

When the perforated panel and louver screens were each tested individually, the results were not dramatically different from one another; the mean velocity ratios for the louver screen tended to be slightly higher (thought no more than 6%) at 0° and 45°, while the perforated panel had higher values for velocity ratios at 90° incident wind.

The most significant differences became apparent in the combined window and shade tests. While the dampening effect of the screen shades combined with the double-hung window was expected, the substantial diminishing effect of each shade combined with the awning window was surprising, at nearly a 40% drop in mean velocity.

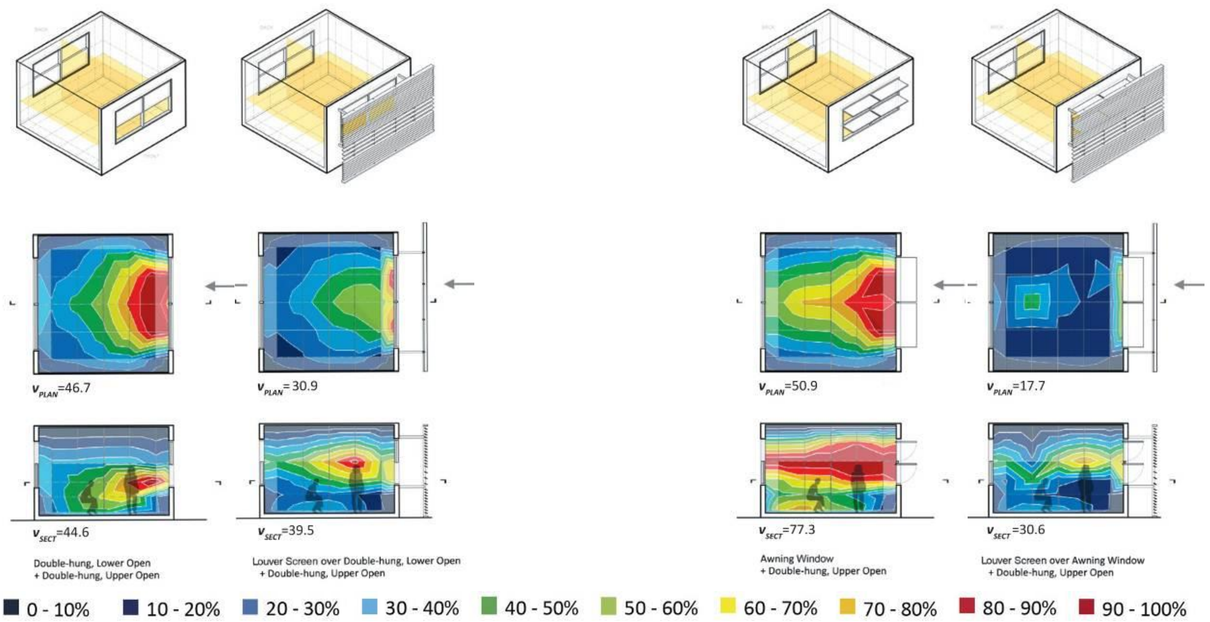

Figure 4. Velocity airflow plan and section contour maps comparing (left) a double-hung window alone and combined with a screen shade at 0˚ incident wind, and (right) an awning window alone and combined with a screen shade at 0˚ incident wind. Colours indicate velocity ratios at for each location.

4. Discussion

The results suggest that the combination of window and shade has a significant impact on indoor velocity ratios, and thus the direct occupant cooling possible. The awning window in particular can result in substantial drag when placed behind a screen-like element. The double-hung (sash) window appears to conflict less with screen shades in terms of flow obstruction to the interior, indicating a higher potential of wind-driven cooling with such a combination. In temperate climates, this dampening effect may actually be desirable in cooler, windier conditions, as higher airspeed in cooler environments tends to be undesirable. This should be researched and considered alongside other design parameters.

5. Conclusions

Aerodynamic implications associated with shades and windows should be considered when assessing façade design options for naturally ventilated buildings. These elements significantly impact direction and diminish velocity, momentum 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 occupant comfort and offset some of the energy and resources required for air conditioning. The key conclusions are that:

1. Window opening area is only partially informative; any shades, window opening type, sash size, opening degree, window construction details (sill, sash, etc.), and other aspects of constructed buildings are critical when assessing façade aerodynamics.
2. Window type has a significant impact on airflow shape, direction, speed and the optimum incident wind angle (at which the mean indoor air velocity reaches a maximum)
3. The scale of the shading element is critical in maximizing flow. The clear openings between flow obstructions (such as shading elements or window sashes) are directly proportional to the resultant indoor velocity and momentum of flow.
4. In screen shades, the orientation and cross section of the constructed elements, and dimension of the gaps between them, impact the magnitude of flow reduction, where it is directed, and if the resultant flow has enough momentum to distribute across the space.
5. When shade screens are installed in front of a pivoting or projecting (i.e. awning) window at an inlet opening, air speed and distribution are significantly impeded; thus, this combination is not ideal for scenarios where direct occupant cooling is a critical factor.

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