Design Technology: Architects' Early Impact on Indoor Air Quality

S. Shadravan[1]; L. Fithian[2]; M. Callahan[3]; and M. Afkhamiaghda[4]

[1]Univ. of Oklahoma, Christopher C. Gibbs College of Architecture, 830 Van Vleet Oval, Norman, OK 73019. E-mail: shideh@ou.edu
[2]Univ. of Oklahoma, Christopher C. Gibbs College of Architecture, 830 Van Vleet Oval, Norman, OK 73019. E-mail: leefithian@ou.edu
[3]Univ. of Oklahoma, Christopher C. Gibbs College of Architecture, 830 Van Vleet Oval, Norman, OK 73019. E-mail: mcallahan@ou.edu
[4]Purdue Univ., Purdue Polytechnic Institute, 401 N. Grant St., West Lafayette, IN 47907. E-mail: mafkhami@purdue.edu

ABSTRACT

Indoor air quality (IAQ) has major impacts in buildings for both the occupants' health and the environment. People are healthier and less prone to disease and infections in buildings with good IAQ. For many years, sealing the building envelope from the outside environment and using forced air (mechanical heating and cooling systems) have been the main approach for reaching thermal comfort and achieving IAQ. Natural ventilation utilizing wind optimization, however, helps to save energy, lower costs, make occupants comfortable, while still providing IAQ. Access to natural ventilation varies due to structure orientation in the built environment. On a performance basis, optimizing the building's orientation allows for the design of a passive cooling ventilation system for the building. Wind and ventilation studies have traditionally been determined through intuitive manipulation, because field experiments are difficult and expensive, and computer based ventilation modeling has historically been too complex. Architects can address this difficulty by using computational fluid dynamics (CFD) in the conceptual design process to optimize early complementary wind and internal natural ventilation for their project. Using experimental data from CFD computer simulations, patterns form for building orientation and optimal airflow simply by comparing and cross-referencing airflow resistance in different orientations. Using these newer and simpler CFD platforms, architects find features to uncover ventilation options through openings for summer overheating, energy loss, poor air quality, and inadequate pressure differences between the indoor and outdoor areas. A timely performance-based design tool for designers to use in their design process, the intent of this study, is to alert architects to the benefits of CFD analysis in their work. Using a 3D model of a single story residential building in an isolated environment, we have demonstrated how manageable it is to integrate wind and internal natural ventilation performance based analyses early in the design process. The 3D model was incrementally rotated inside the Autodesk Flow (2015) CFD platform to find the wind flow pattern around the building that optimized the ventilation inside. Conclusive study results confirm computational fluid dynamics (CFD) is useful as an optimization tool within the conceptual design phase for the architect to enhance occupant comfort, increase IAQ, and building performance.

KEYWORDS: Building Performance, CFD, Design Process, Natural Ventilation

INTRODUCTION

Throughout the world, more people are living and moving to the cities (Mathiesen, 2014). Subsequently, more people are being affected by the buildings and urban environment. People spend almost 90 percent of their time inside buildings (Klepeis et al., 2001). Therefore, the environmental impact of buildings has a profound impact on human health. How the urban environment is built affects people directly and indirectly on multiple levels.

Building indoor air quality (IAQ) is a major impact on occupant health. People are healthier and less prone to disease, upper respiratory infections in places with good IAQ (Atkinson et al., 2009). Occupant performance is linked to indoor air quality (Zhang et al., 2007). For these reasons, architects have an even greater responsibility for their designs to achieve meaningful environmental and health IAQ impact. Many researchers link increased air circulation inside buildings to mitigation of warm temperatures, enabling occupants to achieve thermal comfort, and increasing air quality (Rohles et al.1974; Tanabe and Kimura 1989; Scheatzle et al. 1989; Fountain1991; Fountain et al. 1994; Mayer 1992; Arens et al. 1998).

Specifically, there is a timely performance based design tool for the architectural profession to design for IAQ. Through this study and its subsequent findings, this work seeks to alert architects to the benefits of Computational Fluid Dynamics (CFD) analysis. Using a 3D model of a single story residential building in an isolated environment, it is demonstrated how manageable it is to integrate wind and internal natural ventilation performance based analyses early in the design process. The 3D model was incrementally rotated inside the Autodesk Flow (2015) CFD platform to find the wind flow pattern around the building that optimized the ventilation inside. Conclusive study results confirm Computational Fluid Dynamics (CFD) is useful as an optimization tool within the conceptual design phase for the architect to enhance occupant comfort, and increase IAQ and building performance.

BACKGROUND

For many years, the main approach for achieving thermal comfort (and addressing energy efficiency concerns) was to seal the building envelope from the outside environment, using only HVAC systems for outside air delivery.

Currently, the thinking is to employ passive systems inside the building, such as natural ventilation, in addition to using a centralized HVAC system, which can result in a wider and more responsive comfort range (Yasue. et.al, 2013). For future consideration, this paper suggests architects use CFD software early in their design process to engage passive design strategies in their work:

- Wind properly utilized, assists the natural ventilation process, helping to save energy, lower costs, and make occupants comfortable. In addition, natural ventilation helps enhance indoor air quality by bringing fresh outside air inside the building (Allard, 2002). As Wouters et al. (1996) illustrated, the air flow in the building decreases pollutants in a space exponentially, sustaining the health of the residents of a building.
- Ventilation equipment does consume a high level of energy, and can have negative impacts on the environment (Martin & Fitzsimmons, 2000).
- Natural ventilation can vary throughout the year, so the building’s orientation within its surrounding microclimate plays an important role. It is crucial that architects understand their data early in the design process. Environmental microclimatic factors can be significantly different when compared to the hourly temperature and wind speed datasets that are typically collected from nearby airport data (CIBSE, 2006).
- Using the new CFD platforms, architects find features to uncover ventilation options specifically using schematic floor plans. It is clearly a timely performance-based design tool for designers to use in their design process. Comparing the results found from CFD

tests with experimental data, the applications have been proven to be valid methods for studying real time wind behavior around a building by many researchers (Oberkampf and Trucano, 2002; DeeHaan, et al, 2008; Blocken and Carmeliet, 2007). When used in the design process, CFD enables the architect to quickly observe the effects of air flow around.

Today, it is recognized that the architect's early design work can easily incorporate performance-based results. Concepts can now serve as a dashboard for evaluating key ventilation impacts for human comfort and articulate energy cost savings for the builder. The architect can set project goals in the schematic design phase (Farias & Francisco, 2015) for addressing sustainability performance. The current drawback and a key influence in energy analysis, a primary motivation in passive ventilation studies, is usually not performed until the final steps of the design and after the main morphological shape has been formed (Bragança et al., 2014). By this time, it is almost too late to alter the design and certainly not economically rational to make amendments to the building form (Jernigan, 2007). This is an important and manageable shift in traditional architectural design process. Using new CFD software, architects must be responsible for outlining a sustainable energy design strategy before the design development documents go forward.

INVESTIGATION

The new CFD software was used to study and observe wind flow behavior around and through buildings. Then, as noted above, important IAQ design priorities were manipulated in the CFD platform, especially with regard to function and use of the building.

Methodology

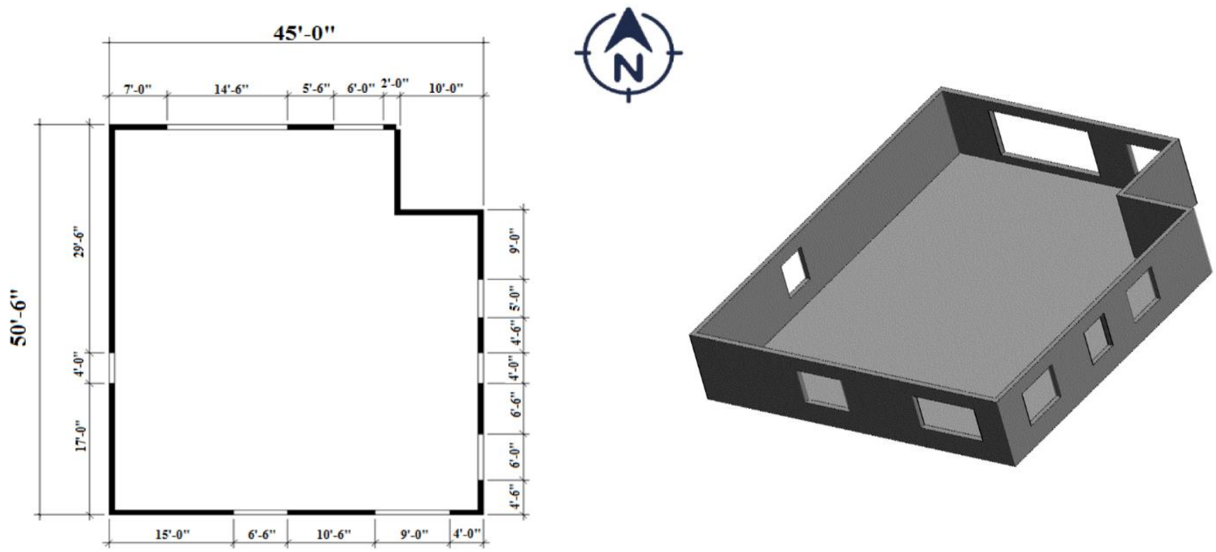
The hypothesis of this study indicates: when architects design according to the outdoor climate and stress factors of each region, using integrating Computational Fluid Dynamics (CFD) as an optimization tool within the design process, the results are an absolute positive impact on building performance and enhances occupant comfort thereby contributing to better IAQ.

The initial steps for this study began with:

- Used a 3D model of a simple building (Figure 1);
- Identified wind flow from different climate zones for the specifically designated project using the climate data extracted from weather data sites;
- Studied and tested multiple simulations of the wind/ventilation environments using the CFD program to demonstrate the airflow between high and low-pressure regions surrounding the models and stagnant places within the models;
- Examined the building orientation against the dominant wind change for each scenario; and
- Integrated the pressure difference relationship with the wind direction against the building with openings.

Once these steps were completed, experimental data results were collected from the CFD software analyses and compared in order to study the effect of building orientation on wind flow patterns. Finally, a comparison between each simulation's airflow resistances was distinguished in different orientations with the airflow pressure difference. This was helpful in discovering a general pattern between the building orientation and the optimal airflow within the building. The

Autodesk Flow Design's virtual wind tunnel condition and size were selected following Autodesk guidelines (2015). In order to harness the maximum efficiency of wind speed, the building was modeled in an isolated environment without any trees, buildings, or other objects. Figures 1.a. and b. show the dimensioned building (case/sample) and 3D perspective, respectively. The size and design of the building were kept constant with 45 x 50.5 ft (13.7 x 15.4 m) and height of 10.8 ft (3.3 m).



a) Dimensioned plan b) 3D perspective showing the openings

Figure 1. Residential Complex 3D model, (unit conversion: 1 ft= 305 mm=0.305 m, 1in=25.4 mm)

Climate Zone and Natural Ventilation

Using the climatic data from the U.S. Department of Energy (DOE) database (National Renewable Energy Laboratory), a comparison was made between the relevance of using natural ventilation in each of the six main climate zones in mainland United States (Figure 2, Zone Two to Seven).

As shown in Figure 2, natural ventilation plays an enormous role in comfort in Miami, FL with 30.2% (Climate Zone 2). This makes natural ventilation an integral part of the design method for hot climate regions, especially for hot-humid regions. Lack of ventilation in confined spaces located in this climate zone can also lead to areas with stagnant air flow. This will result in increasing the chance of mold and fungus growing in the space (Polyzois et al., 2016), which is harmful for both the health of the occupants and the longevity of building materials (Institute of Medicine, 2004). The average impact of natural ventilation for the other five climate zones is closer to six percent (6%). This concludes that if buildings are oriented properly to the prevailing wind, especially in Climate Zone 2, the cooling loads can be reduced significantly without additional cost due to the perception of comfort through air movement, which subsequently leads to energy reduction. It is understood that humidity reduction is difficult through natural ventilation alone, but the use of centralized HVAC as a dehumidification device as well as for ventilation has large energy efficiency concerns. The use of localized dehumidification coupled with natural ventilation and air movement is better for IAQ and human comfort.

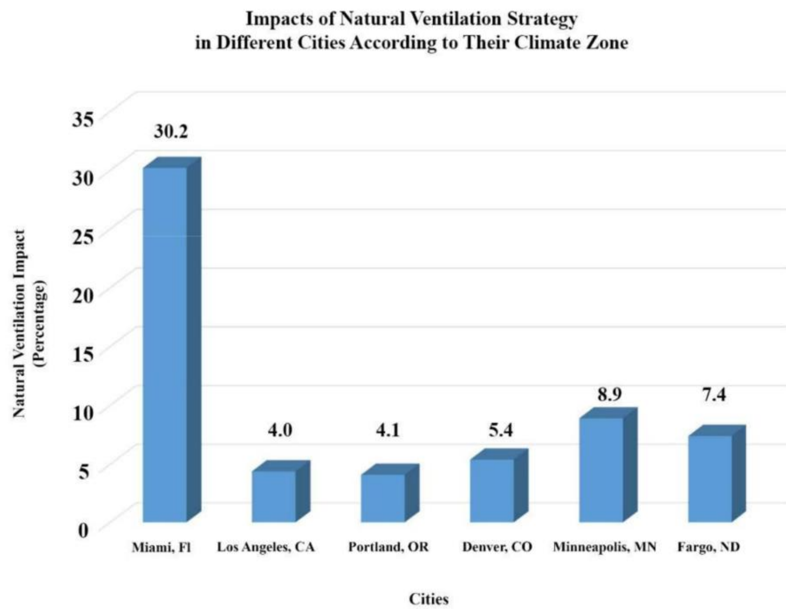


Figure 2. Natural Ventilation Strategy and Indoor Climate

Building Orientation Effect on Natural Ventilation

As wind hits an obstacle, friction between the wind and surfaces alters the kinetic energy of the air flow into potential energy of pressure on various parts of buildings (Onouye & Kane, 2012). Therefore, the marginal turbulence experiences some pressure changes when wind is applied to the building. A positive pressure is created on the windward of the building while there is a negative pressure on the sides and leeward of the building. This pressure discrepancy between the leeward and windward of the building leads to the air circulation within the space if operable fenestration exists, as air moves from a high-pressure region to a low-pressure region (Center for Science Education, 2017). The focus of this research is only on the effect of building orientation on the pressure difference between the inside and outside of the building with considering of building with openings to enhance natural ventilation.

To observe how different orientations of the building toward the dominant wind can influence wind flow pattern around the building and the air circulation inside, twenty-four different scenarios were created and tested in the Autodesk Flow platform. In each scenario the single-story residential building (Figure 1) was rotated 15 degrees counter clockwise from the previous orientation. It is worth noting that all other factors which might affect the wind flow, such as, height of the building and microclimate, were held constant in this experiment. In all of the scenarios, the wind is flowing from south to north, and the wind speed is set as 13.2 ft. /s (4.02 m/s), which is the average of highest speed and lowest speed of wind through the year in each region. The wind speed is extracted from Climate Consultant software from EPW weather data files. The 13.2 ft. /s (4.02 m/s) wind speed is counted as a gentle breeze in Beaufort scale and less than the comfortable wind speed specified by ASHRAE (ASHRAE, 2010).

The building is single story with the wind flow plane hitting the building on the opening levels. To avoid redundancy and reiteration, this test will be referred as test α for the remainder of this manuscript. Each of the twenty-four scenarios have been tested and recorded in the condition for the building with openings. The building with openings was studied in order to illustrate how the building orientation affects the natural ventilation inside the building with the openings which are shown in Figure 1. The model with noticeable air flow changes on the building have been shown in Figure 3. This figure shows air flow inside the building when the windows and doors are open. The start point of orientation began with the south wall of the building (Fig 1a) being perpendicular to the dominant wind.

Orienting the building accordingly, the dominant wind penetrates the openings at a perpendicular angle results in more airflow entering the building (CIBSE, 2006). However, there are many limits to this type of design such as not being able to use fixed interior partitions, the necessity of having windows on opposite sides, and optimized design resulting in only narrow buildings (Walker, 2016). These limitations make this type of design difficult in practice. Also, the difference of airflow volume between a perpendicular wind and an angular wind approaching the window is insignificant since the difference in these two situations is just 0.25. However, by orienting the building at an angle to the dominant wind, this study is augmenting the area of inlet openings which has significant impact on the volume of airflow coming into the building.

Creating the maximum number of regions with air pressure differences between the inlet and outlets and creating scenarios where the openings are at a diagonal angle to the wind, eventually leads to more efficient natural ventilation. Since flow is created by a pressure difference between two points (Larsen & Heiselberg, 2008), the highest amount of ventilation in the space can be seen in these situations.

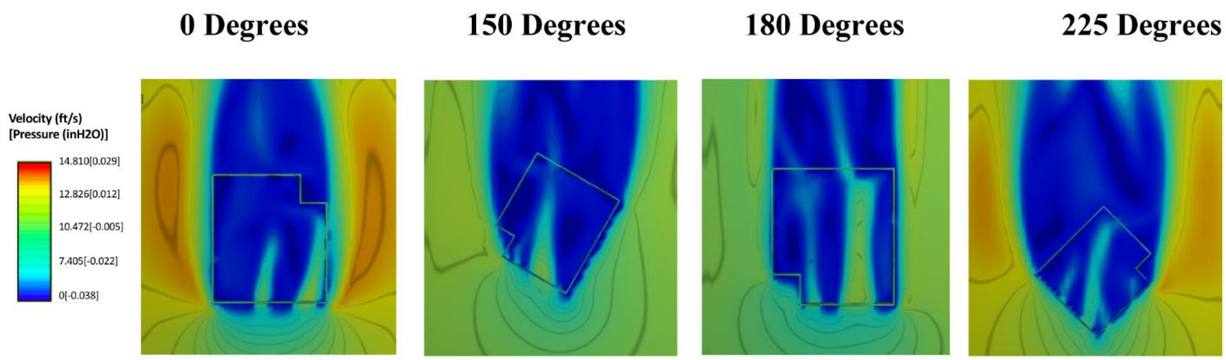


Figure 3. Pressure difference relationship with the wind direction against the building with open windows and doors, (unit conversion: 1 ft/s= 0.305m/s, 1 H2O=248.8 pascal)

The results from Figure 3 showed that the building orientation affects the flow resistance on both windward and leeward. It can be seen that when the wall is perpendicular to the dominant wind, there is a high resistance to the flow on the windward of the building which results in a high-pressure region. This high pressure applied to the windward side of the building will result in intolerable wind pressures on the exposed sides of the buildings due to turbulence. Likewise, a relative vacuum on the other side of the structure is created that cause lack of comfort within the building. It can be also concluded that the opening has positive impact on ventilation and indoor air quality that increases energy efficiencies in the building and result in occupant comfort.

CONCLUSION

It has been concluded that it is best if the natural ventilation impact on the building form and / or orientation is part of the early design processes specifically as a factor in the architects' Schematic Design Phase. Quickly, with schematic drawing findings, it became apparent how important it is to educate architects on the benefits of this new computer analysis tool.

The capacity to quickly generate information gathered from the CFD study enables designers to quickly identify the optimum rotation for orienting the building within its climatic environment. We have demonstrated that building orientation does influence interior ventilation, indoor air quality, and occupant comfort, effectively increasing energy efficiencies for a single project.

Through performance-based analysis (inserting the prevailing wind direction and speed at the site), architects are able to maximize ventilation through their building design thereby clearly defending the building's orientation as a major factor to achieve optimal natural ventilation. By observing the simulated airflows through the building with the CFD platform, architects play with forms early in Schematic Design Phase and before the morphology of the building is fixed.

REFERENCES

Allard, F. (2002). "Natural Ventilation in Buildings: A Design Handbook." *London: James & JonesLtd.*

American Society of Civil Engineers. (2003). "Minimum Design Loads for Buildings and Other Structures." Reston*: The American Society of Civil Engineers*.

Arens, E., Xu, T., Miura, K., Zhang, H., Fountain, M., & Bauman, F. (1998). "A Study of Occupant Cooling by Personally Controlled Air Movement." *Building Energy*, *27*, 45–49.

ASHRAE, *ANSI/ASHRAE Standard 55-2010. Thermal Environmental Conditions for Human Occupancy*. 2010, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Atkinson, J., Chartier, Y., & Pessoa-Silva, C. (2009). "Natural Ventilation for Infection Control in Health-Care Settings." *Geneva: Word Health Organization*.

Autodesk (2014). Autodesk Flow Design. Retrieved, <http://download.autodesk.com/us/flow_design/Flow_Design_Preliminary_Validation_Brief_01072014.pdf>

Autodesk. help, (Feb 12 2015). Wind Tunnel. Retrieved, <https://knowledge.autodesk.com/support/flow-design/learn-explore/caas/CloudHelp/cloudhelp/ENU/FlowDesign/files/GUID-9B85F4A0-5072-454D-8710-CCFF26507BE9-htm.html>

Blocken, B., and Carmeliet, J. (2007). "Validation of CFD Simulations of Wind-Driven Rain on a Low-Rise Building Facade." *Building and Environment*, 2530–2548.

Bragança, L., Vieira, S. M., & Andrade, J. B. (2014). "Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs." *The scientific world journal*, *2014*.

Center for Science Education. (2017). "The Highs and Lows of Air Pressure." Retrieved, <https://scied.ucar.edu/shortcontent/highs-and-lows-air-pressure>

CIBSE. (2006). Environmental Design, CIBSE Guide A (7th edition). Norwich: Page Bros. (Norwich) Ltd.

DeeHaan, M. A., Vassberg, J. C., Rivers, S. M., & Wahls, R. A. (2008). "Development of a Common Research Model for Applied CFD Validation Studies (pp. 18–21)." *Presented: AIAA Applies Aerodynamics Conference, Honolulu: American Institute of Aeronautics & Astronautics.*

Farias, S., and Francisco, J. (2015). "A Standard Process for Sustainable Design." *Int. J. of Thermal & Environmental Engineering*, 121–128.

Fountain, M. (1991). "Laboratory Studies of the Effect of Air Movement on Thermal Comfort: A Comparison and Discussion of Methods." *ASHRAE Transactions*, *97*, 863–873.

Fountain, M., Arens, E., Richard, de D., Bauman, F., & Miura, K. (1994). "Locally Controlled

Air Movement Preferred in Warm Isothermal Environments.” *ASHRAE Transactions, 100,* 937– 952.
Institute of Medicine. (2004). “Damp indoor spaces and health.” *The National Academic Press*.
Jernigan, F. E. (2007). Big BIM, little bim: The practical approach to building information change-what-are-the-worst-impacts-facing-America Ventilation Centre. *Book*.
Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., and Engelmann, W. H. (2001). “The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants.” *Journal of Exposure Science and Environmental Epidemiology*, *11*(3), 231.
Larsen, T. S., & Heiselberg, P. (2008). “Single-Sided Natural Ventilation Driven by Wind Pressure and Temperature Difference.” *Energy and Buildings*, *40*(6), 1031-1040.
Martin, A., & Fitzsimmons, J. (2000). “Making Natural Ventilation Work. Brekshire: BSRIA.
Mathiesen, K. (2014, May 6). Climate Change: What Are the Worst Impacts Facing America?” *The Guardian*. Retrieved, http://www.theguardian.com/environment/2014/may/06/climate-
Mayer, E. (1992). “New Measurements of the Convective Heat Transfer Coefficients: Influences of Turbulence, Mean Air Velocity and Geometry of Human Body.” In *ROOMVENT’92* (Vol. 3, pp. 263–276). Lyngby, Denmark.
National Renewable Energy Laboratory. (n.d). Weather data. Retrieved, <https://energyplus.net/weather>
Oberkampf, W. L., & Trucano, T. G. (2002). “Verification and Validation in Computational Fluid Dynamics.” *Progress in Aerospace Sciences*.
Onouye, B., & Kane, K. (2012). “Statics and Strength of Materials for Architecture and Building Construction.” *New Jersey: Pearson Education*.
Polyzois, D., Polyzoi, E., Wells, J. A., & Koulis, T. (2016). “Poor Indoor Air Quality, Mold Exposure, and Upper Respiratory Tract Infections—Are We Placing Our Children at Risk?” *Environmental Health*, *7*, 20–27.
Rohles, F. H., Woods, J. E., & Nevins, R. G. (1974). “The Effect of Air Movement and Temperature on the Thermal Sensations of Sedentary Man.” *ASHRAE Transactions*, *80*, 101–119.
Scheatzle, D., Wu, H., & Yellott, J. (1989). “Extending the Summer Comfort Envelope with Ceiling Fans in Hot, Arid Climates.” *ASHRAE Transactions*, *94*, 269–280.
Tanabe, S., & Kimura, K. (1989). “Thermal Comfort Requirements under Hot and Humid Conditions.” Presented at the First ASHRAE Far East Conference on Air Conditioning in Hot Climates, Singapore, pp. 3–21.
Walker, A. (2016). National Institute of Building Science. Retrieved, <https://www.wbdg.org/resources/natural-ventilation>
Wouters, P., Vandaele, L., & Ducarme, D. (1996). “What do We Mean with Natural Ventilation?” *Lyons: AIOLOS*.
Yasue, R., Habara, H., Nakamichi, A., and Shimoda, Y. (2013). “Modeling the Occupant Behavior Relating to Window and Air Conditioner Operation Based on Survey Results.” *Presented at the 13th Conference of International Building Performance Simulation Association*, Chambe’ry, France.
Zhang, H., Arens, E., Abbaszadeh Fard, S., Huizenga, C., Paliaga, G., and Brager, G. (2007). “Air Movement Preferences Observed in Office Buildings.” *Int J Biometeorol*, *51*, 349–360. https://doi.org/10.1007/s00484-006-0079-y