Asia Pacific Research Initiative for Sustainable Energy Systems 2013 (APRISES13)

Office of Naval Research
Grant Award Number N00014-14-1-0054

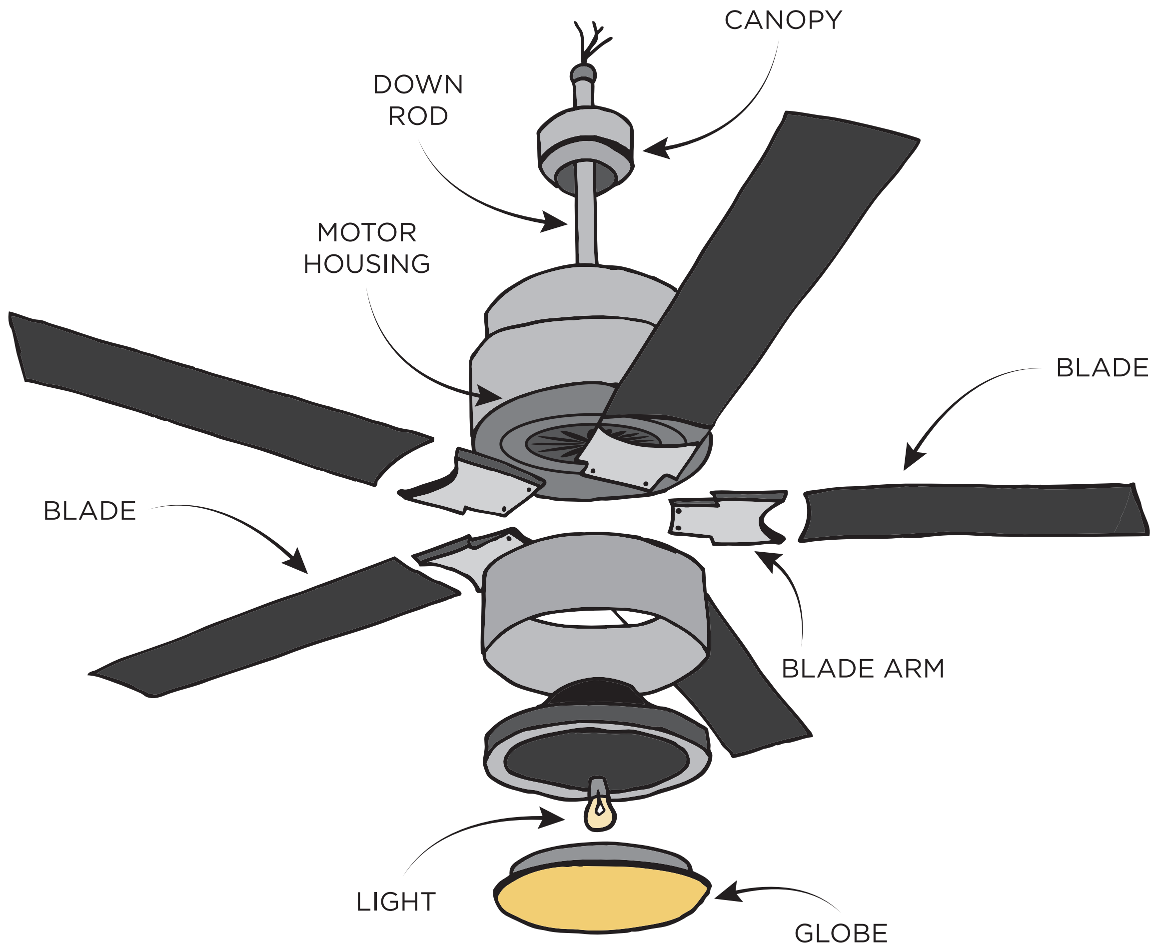
CEILING FAN STUDY: LITERATURE AND MARKET REPORT

Task 7

Prepared For
Hawaii Natural Energy Institute

Prepared By
MKThink

August 2017



DELIVERABLE 2: FINAL LITERATURE AND MARKET REPORT

CONTRACT NO. Z10152521
AUGUST 31, 2017

HNEI
Hawai'i Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawai'i at Mānoa

THiNK MK

HNEI CONTRACT NO. Z10152521

University of Hawaii's Asia-Pacific Research Initiative for Sustainable Energy Systems (APRISES)

Task 7 - Energy Efficiency

This project is supported and funded by the Office of Naval Research in grant awards: N00014-12-1-1496 and N00014-14-1-0054.

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PROJECT INTRODUCTION

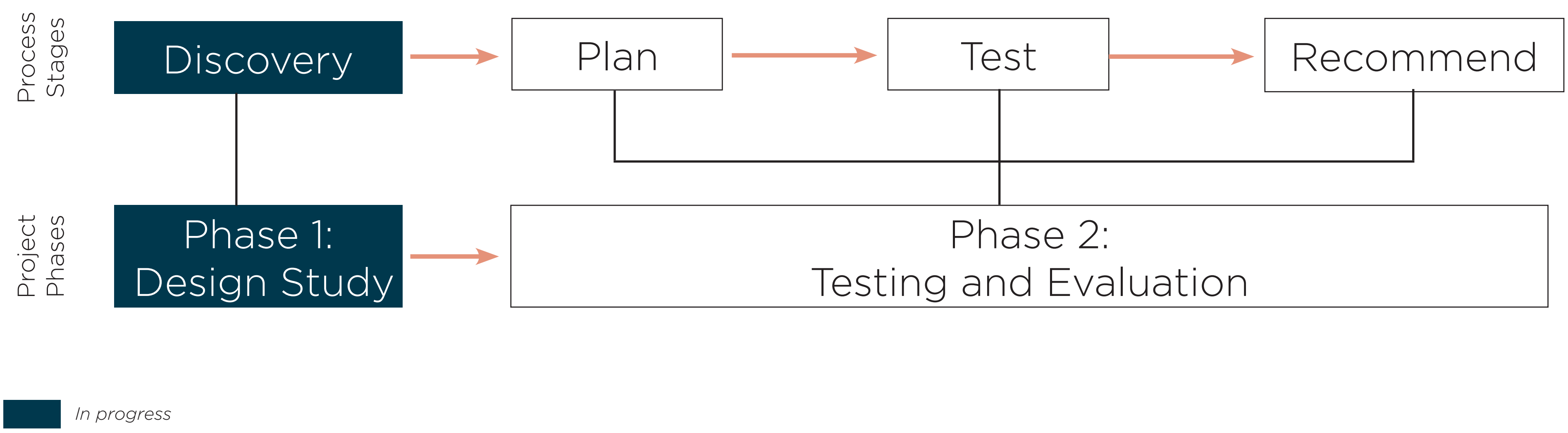
Hawaii and other tropical areas seek innovative applications to improve thermal comfort. While ceiling fans are not new, no comprehensive document is available to designers and planners to make deliberate, conscious fan selection decisions based on research, space constraints and physical characteristics of fans. This project intends to distill and compile information from a variety of sources into a report in order to address this limitation. In support of the University of Hawaii's 'Asia Pacific Research Initiative for Sustainable Energy Systems (APRISES)' Task 7 Energy Efficiency, this project will evaluate fan typologies, control options, and operational characteristics and provide research-based design guidelines to assist in space planning, design and product selection. A ceiling fan for this research is defined as is done by the Code of Federal Regulations (CF) as "a non-portable device that is suspended from a ceiling for circulating air via the rotation of fan blades".

In the subsequent pages, the overall ceiling fan project organization as well as the specific objectives for Phase 1 are outlined.

Sources: U.S. Department of Energy, 2016 (b)

PROJECT ORGANIZATION

This ceiling fan project is organized into two phases. Phase 1 focuses on acquiring and summarizing ceiling fan knowledge from academic and industry sources while identifying gaps for further study. Phase 2 defines a research study from the Phase 1 gap analysis. Furthermore, Phase 2 involves the installation, testing and evaluation of ceiling fans at a selected site in Hawaii in support of the research study.

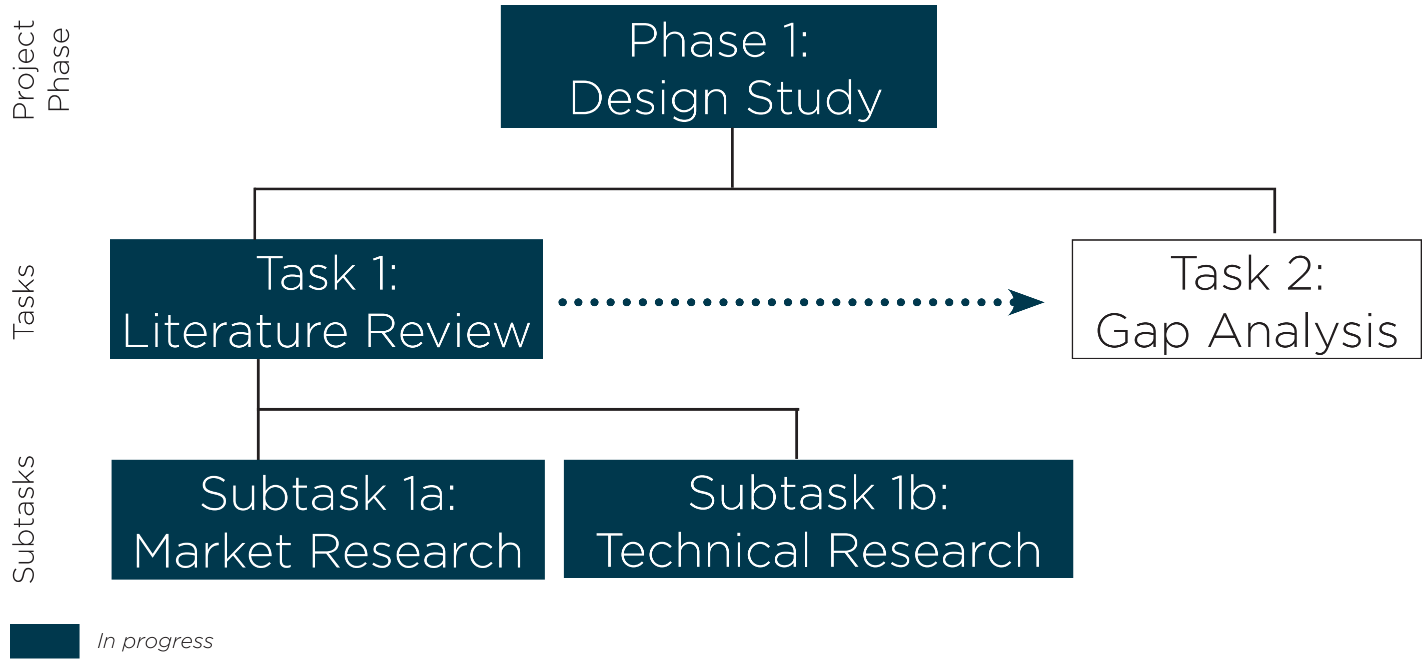


PHASE 1 OVERVIEW

The objectives of Phase 1 are:

- Define typologies of ceiling fan applications and a portfolio of existing and emerging fan technologies
- Develop metrics structure to evaluate the performance of the portfolio of fan technologies
- Conduct literature survey of current CFD simulation techniques and their applicability of quantifying performance of selected fan typologies.

Phase 1 is separated into Task 1: Literature Review and Task 2: Gap Analysis. The purpose of Task 1 is to investigate available literature to understand the current state of the ceiling fan industry. Task 2 will use the knowledge gleaned in Task 1 to determine gaps in knowledge and research. This report only examines Task 1 which is comprised of Subtask 1a: Market Research and Subtask 1b: Technical Research, and both are discussed on the following page.



TASK 1 RESEARCH METHODOLOGY

The goal of Task 1 was to examine the available literature to understand the current state of the ceiling fan industry in the United States. While the ceiling fan industry is ever expanding and changing, this research focused on two key areas. Subtask 1a analyzed manufacturer and industry organization information to understand current design features (e.g. motors, blades, controls) and performance characteristics (e.g. placement and sizing guidelines, comparison metrics) of ceiling fans. Information was obtained through sources such as conference artifacts, technical specifications, newsletters, and phone conversations. Subtask 1b summarized academic and governmental research to better identify future emerging trends and technologies. In particular, this effort focused on the impact of air movement on occupant comfort and satisfaction. Information was obtained through peer-reviewed articles, governmental reports and phone conversations with researchers.

At a high level, the approach began with a focused look at each Subtask 1a & 1b across the contract specific categories (e.g. design, placement, energy, thermal comfort) using a source hierarchy. The source hierarchy prioritized credible sources such as government and academic research over personal blogs. This approach ensured both breadth and quality of information. Each source often had multiple articles on different aspects of ceiling fans. In order for quick access and recall, each article was recorded into a matrix with key information extracted related to the contract categories. In practice, content crossed subtask boundaries. For example, air movement was discussed in ceiling fan design (Subtask 1a) and also how air movement impacted occupants (Subtask 1b). Therefore the following literature review is organized around content areas which have a mixture of Subtask 1a & 1b sources and articles.

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Ceiling Fan Overview

Ceiling Fan Design Study Introduction	8
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CEILING FAN DESIGN STUDY INTRODUCTION

The following Ceiling Fan report is organized around five primary sections namely Ceiling Fan Overview, Design, Sizing and Placement, Operations and Literature Review based on information gathered through available industry and academic literature supplemented with phone conversations with relevant industry professionals.

The Ceiling Fan Overview looks into the history, market characteristics and main types of ceiling fans.

The Design section introduces key hardware components (i.e. blades, motors, and controls) and generalized air movement profiles of flat blades and airfoil blades. Also, ceiling fan modeling is included as a design tool that helps professionals understand room air temperature and speed distribution.

The Sizing and Placement section discusses single and multiple ceiling fan sizing guidelines related to room size (width x length) and placement with respect to horizontal and vertical room obstructions.

The Operations section outlines energy consumption and efficacy information to help estimate operational costs. Also, air speed, direction and intermittency are explored in their relation to occupant thermal comfort.

The Literature Review section categorizes the sources which have informed the content in the previous sections.

CEILING FAN HISTORY

20th Century

Early 2000's

Current Decade

Technology

1981
First CFD modeling package commercially available

1998
FSEC tests on air-foil blades efficiency
First HVLS fan market prototype

2001
Air-foil blades commercially available

2008
Research on higher demand for indoor air movement

2014
Ceiling fan controls based on environmental conditions (e.g. SenseME)

Standards

1957
EPCA: ceiling fan design standards

1966
ASHRAE-55: Standards first developed

2002
ENERGY STAR ceiling fan standards launched

2005
DOE codified EPCA design standards

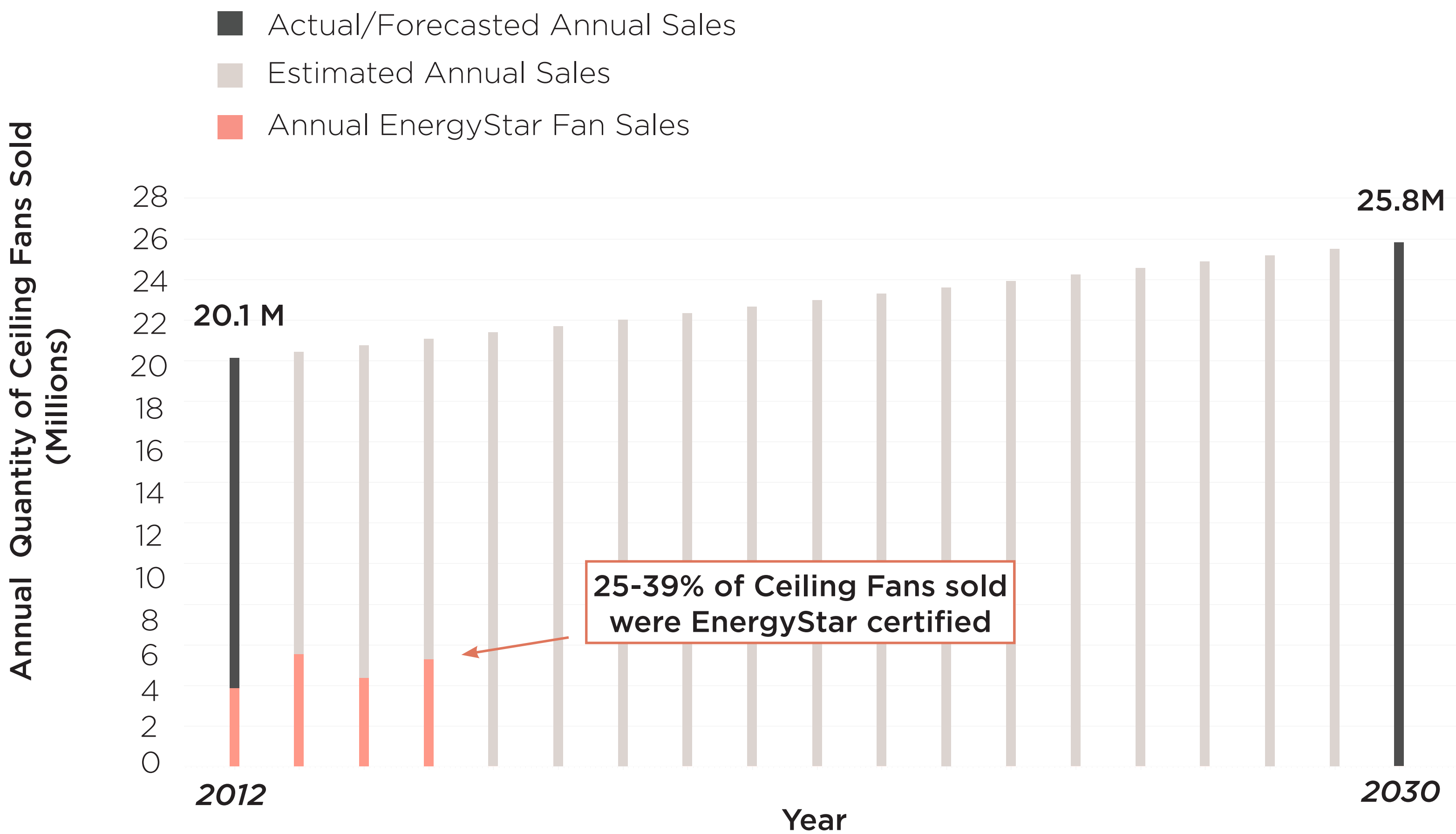
2007-2008
ANSI/AMCA-230: Testing procedures refined
ASHRAE-55: Comfort equation expanded
ASHRAE-55: 3 heights air movement guidance

2016
DOE revised CF energy efficiency test procedures

Sources: Paliaga, 2017. MacroAir Fans, 2017. Ullman, 2013. ASHRAE, n.d., Big Ass Solutions, 2014 (a), Gossamer Wind, n.d, ENERGY STAR, 2016, Symscape, 2008

US CEILING FAN MARKET

The United States Ceiling Fan Market is steadily growing. Although there is little information available on market trends, key player distributions and competitive landscapes, shipment data and sales forecasts are used below to arrive at actual and forecasted sales values. The annual quantity of ceiling fans sold in 2012 was 20.1 million and is predicted to reach 25.8 million in 2030. The market share of ENERGY STAR rated ceiling fans also grew with a penetration of 25-39% between 2012-2015.



Sources: Sathaye, et al, 2012. Energy Star, 2012-2015

CEILING FAN BLADE SPAN MARKET DISTRIBUTION

Periodically, the U.S. Department of Energy (DOE) reviews energy efficiency standards for consumer products and commercial or industrial equipment such as ceiling fans in order to determine if energy efficiency standards need to be updated and if so, if these improvements are technologically viable and economically justifiable. To better understand the impact of more stringent standards on ceiling fan consumers, the DOE conducts estimations of the existing market share distribution by common blade size for different fan types. To do so, data is acquired online and through in-person discussions with large fan retailers, and then validated by retailers, such as Westinghouse Lighting in a public review. The below information is the blade span market distribution for standard and large-diameter fans that are greater than 7 feet (HVLS ceiling fans) for the year 2015 in the no-new standards scenario with no efficiency standards improvements. These two types of ceiling fans are defined in the following page.

2015 Market Share Distribution by Blade Span

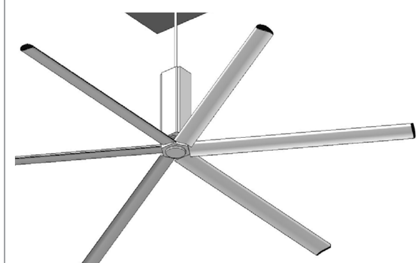
	Standard Ceiling Fan			Large-Diameter Ceiling Fan (HVLS)		
Fan Diameter (inches)	44”	52”	60”	96”	144”	240”
Market Share (%)	21.1%	72.5%	6.5%	22.0%	27.0%	51.0%

Sources: U.S. Department of Energy, 2016 (b). Paliaga, 2017

FAN TYPES

Several types of ceiling fans exist and are emerging to satisfy evolving demands for energy-efficient ventilation and improved air movement distribution. Each fan type differs in either functionality, design or performance and the applications vary from residential, commercial and industrial. To compare each fan type's performance, CFM (cubic feet per minute) is used to determine the amount of airflow per minute with respect to each fan type's average diameter size or range. For fan's larger than 7 feet in diameter, is common to see either volumetric (CFM) or velocity metrics (fpm (feet per minute)) represented.

Standard Technology → Emerging Technology

	Standard Fan	Dual-Head Fan	HVLS Fan (High-Volume Low Speed)	Smart Ceiling Fan
Definition	Conventional fans are fans with diameters that are equal to or less than 7 feet (84"), whose lowest point on the blade is more than 10 inches from the ceiling	Dual-head fans have two opposing head fixtures that direct air in the direction they face, allowing for more targeted air motion and enhanced spread	HVLS fans are fans with airfoil blades and diameters greater than 7 feet (84") that operate at low speeds and distribute large volumes of air	Smart ceiling fans are fans that automatically adjust fan settings and speed levels based on a room's occupant activity and environmental conditions
Avg Configuration	42" - 49" (3.5 - 4 ft) diameter 	(2) 44" - 52" (3.6 - 4.3 ft) diameter 	192" (16 ft) diameter 	52" - 84" (4.3 - 7 ft) diameter 
Avg CFM	1,999 - 5,000 CFM	6,300 - 8,300 CFM	166,000 CFM	~ 5,300 - 25,000 CFM

Sources: E3T: Energy Efficiency Emerging Technologies, n.d. U.S. Department of Energy, 2016 (a). U.S. Department of Energy, 1989. Wayfair, n.d. Hollist, 2017. MacroAir Fans, 2016. Leading Edge: Marley Engineered Products, 1999. CeilingFan.Org, 2000. Hansen Wholesale, n,d (a). Blue Giant, 2007
Image Sources: Gromol Niy, 2014, Pinterest, n.d., Arcat, n.d., MakeUseOf, n.d

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Design

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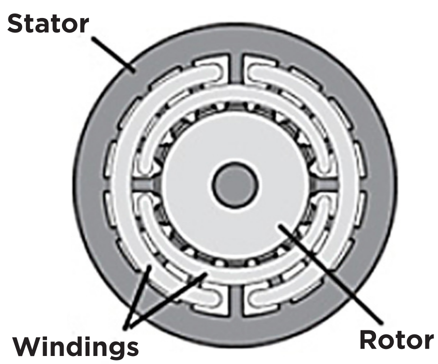
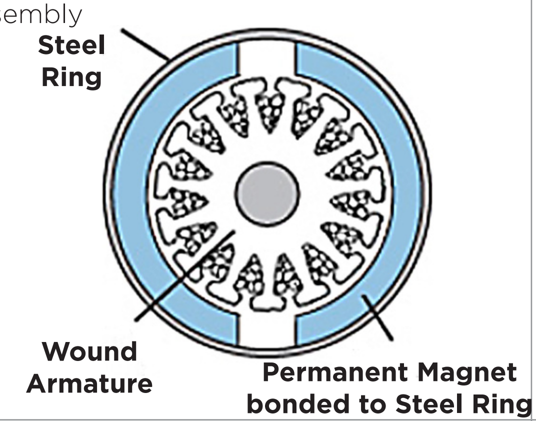
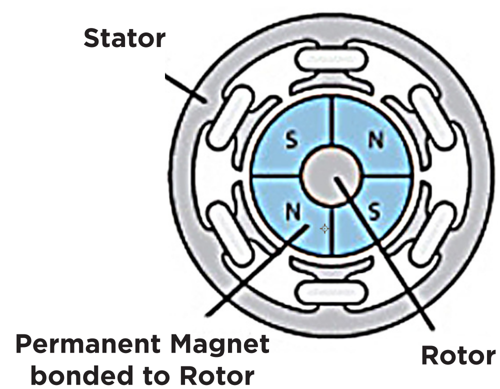
MOTOR TYPES

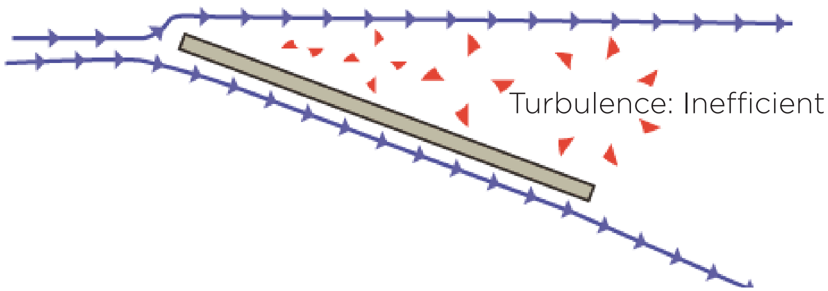
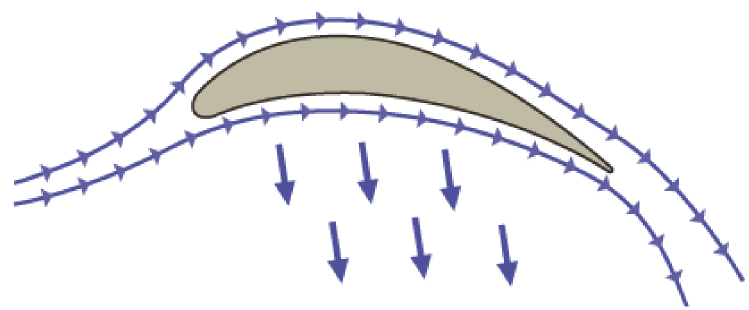
Motor efficiency increases from Alternating Current (AC) Induction motors to Brushless Direct Current (DC) motors. The motor types differ in energy efficiency, cost and durability. The table below shows the technologies for motors, ranging from the standard and traditional components to the emerging ones.

Standard Technology → Emerging Technology			
	AC Induction Motors	Permanent Magnet DC (PMDC) Motors	Brushless DC Motors
How It Works	The moving magnetic field causes rotor movement or rotation	The segmented commutator rotates within a stationary magnetic field which produces mechanical switching of the armature current	The magnetic field rotates and commutation occurs when the stator current direction is switched at precise intervals in relation to the rotating magnetic field
Cross-Section	Windings are in stator assembly and there is a squirrel cage rotor 	Windings are in rotor assembly and permanent magnets are for stator assembly 	Rotor has permanent magnets and stator has windings 
Advantages	• **Constant, even airflow** provided as opposed to variable, uneven flow from DC fans • **Cheaper** than DC motors	• **Higher horsepower per pound and dollar,** than any AC fan • **Flat torque over wide speed range**, while AC motors often lose torque as speed increases	• **Most energy efficient**, consuming 70% less energy than AC motors • **Quietest**, due to lack of friction • **Longer service life** than PMDC motors

Sources: Galco Industrial Electronics, n.d., Bodine Electric Company, 2003. Pelonis, 2014. Manley, 2013. Henley Fan, 2013. Sawyers, 2011
Image Source: Orientalmotor, n.d

BLADE SHAPE

Blade shape has evolved from flat or slightly curved blades to airfoil blades to increase efficiency. Optimal blade design requires a balance between maximizing air speed, creating uniform air speed along the fan radius and maximizing airflow coverage. The table below compares flat or slightly curved blades with airfoil-style blades commonly found on HVLS fans.

	Standard Technology	Emerging Technology
	Flat/Slightly Curved Blades	Airfoil-style Blades
Cross-Section		
Advantages	• **Cheaper** than airfoil-style blades • **Quicker to manufacturer** than airfoil-style blades	• **Increased efficiency** as energy lost to turbulence and flow-separation is minimized • **Quieter** than flat/slightly curved blades

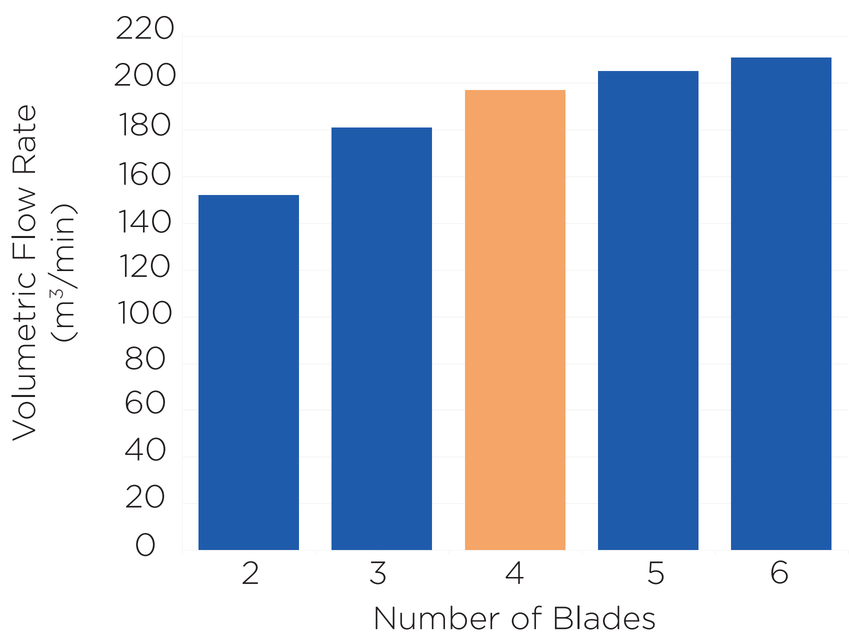
Source: CeilingFan.Org, 2000
Image Source: Make Use Of, 2016

BLADE QUANTITY

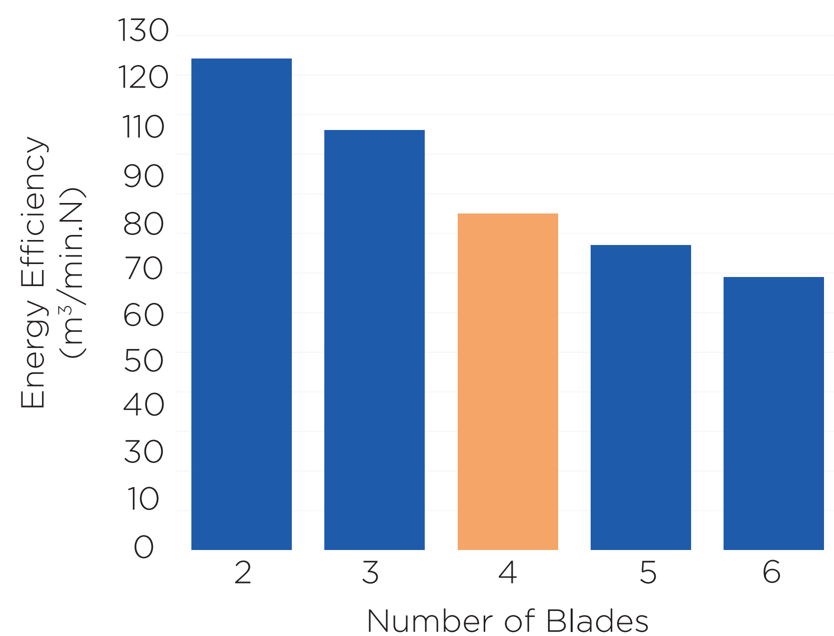
The number of blades on a ceiling fan is important to its performance. While additional blades create more airflow, fan weight and drag also increase, which requires the fan motor to work harder. Studies show that the airflow behavior improves by less than 10% when the number of blades exceeds four flat blades.

Key Takeaway: Four ceiling fan blades are often used in residential buildings to optimize for both airflow and energy efficiency

Comparison of Airflow and Blade Quantity



Comparison of Energy Efficiency and Blade Quantity

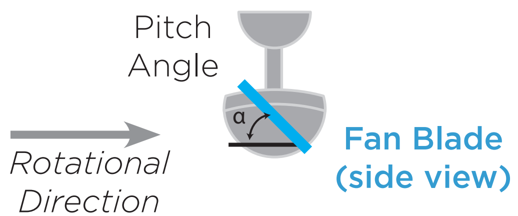


Sources: Adeeb, et al, 2016. Adeeb, et al, 2015

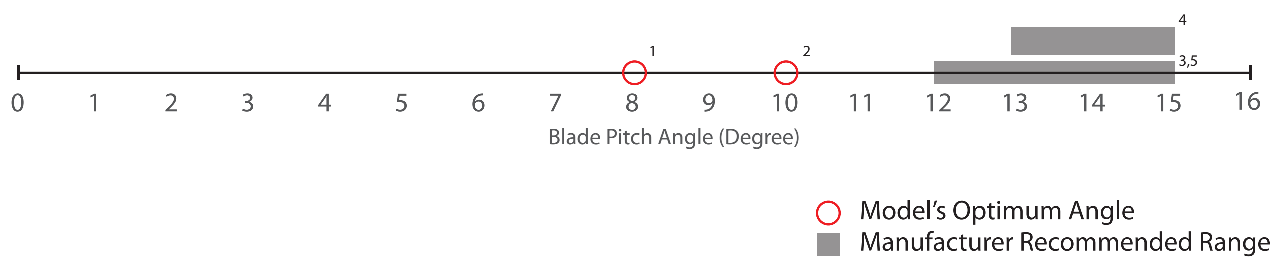
BLADE PITCH

A ceiling fan's blade pitch is the angle between a horizontal plane and the blade tilt that assists in generating airflow. As this angle becomes steeper, more airflow is created, however this requires the motor to progressively work harder to maintain the same speeds. For residential fans, academic modeling studies have found the optimal blade pitch to be 8-10° while manufacturers recommend 12-15°.

Ceiling Fan Blade Pitch Angle



Residential Ceiling Fan Blade Angle Recommendations



Sources: Swaroop, 2017. Sali, 2016. Lumen Light and Living, 2017. CeilingFans.com, 2017. Littman Bros Lighting, 2017
Image Source: Singh, 2014

CONTROL TYPES

The table below shows the technologies for ceiling fan controls, ranging from the standard and traditional technologies to emerging technologies. The ceiling fan control types are Pull Chain, Wired Wall Control, Wireless Wall Control/Remote Control, Wifi/Bluetooth Connectivity and Smart Mode. These control types have different features, such as the number of speeds and fans that can be controlled, all of which is discussed in subsequent pages.

Standard Technology →					Emerging Technology
	Pull Chain	Wired Wall Control (No Receiver)	Wired/Wireless Wall Control or Remote Control (Receiver)	Wi-Fi/Bluetooth Connectivity	Built-in Sensor
					
How It Works	• Pull chains either adjust the fan's speed or the fan's light	• Single slide control or rotary knob controls for fan speed • Dual slide control for fan speeds and light	• Wall control and receiver inside ceiling fan both have dip switches, which are set to create a frequency combination	• Smartphone applications used to program fans using Bluetooth or Wi-Fi networks	• Built-in sensors, such as occupancy sensors cause the fan to turn on/off

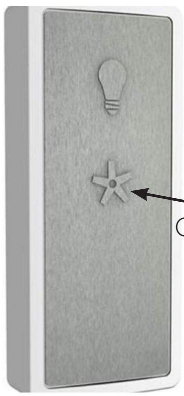
Sources: ENERGY STAR, 2016, Bermudez, 2014
Image Sources: Lowes, n.d., Tanger Ecoles, n.d. Hunter Fan, n.d. New Atlas, 2014

CONTROL MODES

Various control modes exist and are emerging within ceiling fan control devices. These control modes are either Fixed Mode, Multi-Speed Mode, Variable Speed Mode or Continuous Smart Mode. Each control mode differs in the number of speeds that it can control, and newer technologies such as the Continuous Smart Mode are also able to automatically alter speeds at different times throughout the day to simulate natural breezes.

Standard Technology → Emerging Technology

Fixed Mode



Ceiling Fan Switch

Multi-Speed Mode

Variable Speed Mode

Intermittent Smart Mode

Intermittent Smart Mode (i.e. Haiku Whoosh)

	Fixed Mode	Multi-Speed Mode	Variable Speed Mode	Intermittent Smart Mode
How It Works	• Fixed Mode refers to a control switch whose options are either on or off • Number of speeds: 1	• Multi-Speed Mode refers to a control switch with a a few distinct speed options such as low, medium and high • Number of speeds*: 3	• Variable Speed Mode is a control option with speeds varying from 0 to 100% • Number of speeds: 100	• Intermittent Smart Mode can be turned on to automatically alter speeds at different times • Number of speeds*: 6

* The number of speeds noted for Multi-Speed Mode and Intermittent Smart Mode are specific to the devices shown above, and may vary by control model. For the Intermittent Smart Mode, the number of speeds refer to the speeds that are available on the device that the fan will adjust to at irregular intervals once the Whoosh Mode is turned on. In this scenario, the fan will adjust to either of the six available speeds.

Sources: Home Depot, n.d. (b), Home Depot, n.d. (c), Acer Trading Group, 2017, Haiku Home, 2017, Haiku Home, 2015
Image Sources: Home Depot, n.d. (b), Home Depot, n.d. (c), Acer Trading Group, n.d., Haiku Home, 2017

MULTIPLE FAN CONTROL TYPES

Several options exist for controlling multiple ceiling fans with one control technology. Existing ceiling fans can integrate wall, remote and smart-control systems by installing new electrical equipment. In comparison, built-in occupancy sensor controls are embedded into an existing fan or control system, therefore acquiring sensor features requires the purchase of a new ceiling fan. Below are brief explanations on how to incorporate multiple ceiling fans into the different control types.

Existing Ceiling Fan?

Wall Control: The amperage of the wall control unit is the determining factor for figuring out the number of ceiling fans which can be simultaneously controlled. As an example, considering that one ceiling fan draws close to 1 amp, a wall control unit that has a load capacity of 5 amps would only be able to control about 4-5 ceiling fans simultaneously. Different types of wall control devices have different load capacities, and the maximum load capacity that can be found on a device is 15-20 amps.

Remote Control: Linking multiple ceiling fans to a single, individual remote control involves purchasing additional receivers per additional ceiling fan, and then resetting frequency settings such that the dip-switches in the receiver and the remote control match.

Smart-Control: Like the remote control pairing process, linking multiple ceiling fans to a Wi-Fi/ Bluetooth Plug-In Controller control requires purchasing an additional Bluetooth compatible receiver per additional fan and installing it within the fan's canopy. Some Bluetooth Plug-In Controllers, however, only work within a certain range, for instance less than 80 feet.

New Ceiling Fan?

Built-In Sensor: Smart occupancy sensors are enabled either within the ceiling fan or in the wall-mounted control, however these cannot be added to an existing fan as they come embedded in a new system. The control of multiple ceiling fans therefore is not a result of the occupancy sensor control additive, but rather the capacity load of the wall control it is originally embedded into.

Sources: Hunter Fan, 2015., Envirofan, n.d. (b), Home Depot, 2015., Hunter Fan, 2013., SkyBlade Fans, 2017 (a), SkyBlade Fans, 2017 (b)., Big Ass Solutions, n.d. (b), Big Ass Solutions, 2016 (a, c, d), Big Ass Solutions, 2017, Lutron, 2017, Crestron, 2017, Hunter Fan, 2017

MULTIPLE FAN CONTROL TYPE COMPARISON

Ceiling fan control technologies vary in physical design and functionality, therefore when selecting for a multiple fan control device, control options as well as speed and lighting features need to be considered. The number of fans that can be simultaneously controlled depends on fan size, type and model and so the range of values that can be found in the below table are aggregations of several existing products. In other words, the maximum values of fans and speeds that can be controlled does not apply to all available products, rather it is simply the upper range found in the industry.

Control Type	Control Location	Personal Control	Number of fans controlled	Number of Speeds	Lighting Controls
1. Pull Chain	In room	Yes	1	N/A*	N/A*
2. Wall Control	In room	Yes	Standard: 1- 20 HVLS: Unlimited	Fixed: 3 Variable: by %	Yes
3. Remote Control (Receiver)	In Room, Out of Room (*depends on room size, remote range)	Yes	Standard: 1-12 HVLS: 1-24	Fixed: 6 Variable: by %	Yes
4. Smartphone Device	In Room, Out of Room	Yes	HVLS: Unlimited	6	Yes
5. Built-In Occupancy Sensor (Smart-Fans)	In Room, Out of Room	No	7	7	Yes

*As pull chains cannot control multiple ceiling fans, speed and lighting control options for multiple fan control do not apply.

Sources: Big Ass Solutions, n.d. (b), Hunter Fan, 2015., Big Ass Solutions, 2013 (b)., Hunter Fan, n.d., EnviroFan, n.d. (a), Marley Engineered Products, 2016, Gescan, 2013., Maxim Integrated, 2011., Big Ass Solutions, 2016 (b)., Home Depot, 2015., The Gadget Reviews, 2016., Y-Lighting, n.d., Home Depot, n.d. (a), Hunter Fan, n.d., Hunter Fan, 2013., SkyBlade Fans, 2017 (b)., SkyBlade Fans, n.d. (b), Hunter Fan Store, n.d., Duke, 2002, Big Ass Solutions, 2017. Lutron, 2017. Crestron, 2017. Hunter Fan, 2017, SkyBlade Fans, 2017 (a)

MULTIPLE FAN CONTROL LIMITATIONS

As evidenced in the previous page, ceiling fan controls are limited in their scope, or in the number of fans they are able to control simultaneously. This limitation can best be explained by (a) electrical equipment load capacity and (b) practical design considerations, both of which are discussed below.

(a) As mandated by National Electric Code standards, a circuit breaker, which is an electrical switch that protects an electrical circuit from damage by over-current should not carry more than 80% of its rated current. Thus, electrical equipment load such as a ceiling fan's load, or amperage size is limited to 80% of the corresponding circuit breaker's size. Therefore, a standard 15-20 amperage circuit breaker will only allow for a 12 amperage load, or about a 12 fan linkage (1 fan ~ 1 amperage). This example excludes other potential appliances such as fan light fixtures that would also exist and draw power from the same circuit. When control technologies are able to control more than 12 fans, as is seen for standard fans and HVLS fans on the previous page, it is due to either smaller load capacities of the fans (smaller diameters, motors) or daisy-chaining fans together, as is commonly done for HVLS fans. HVLS fans are often daisy-chained together, meaning that a master fan is linked to a control device and all remaining fans operate via a Variable Frequency Drive (VFD) command that is linked to the master fan. Daisy-chaining thus allows for a larger load bigger than 12 fans to be linked together, which explains why HVLS fan control devices are able to link unlimited amounts of fans together.

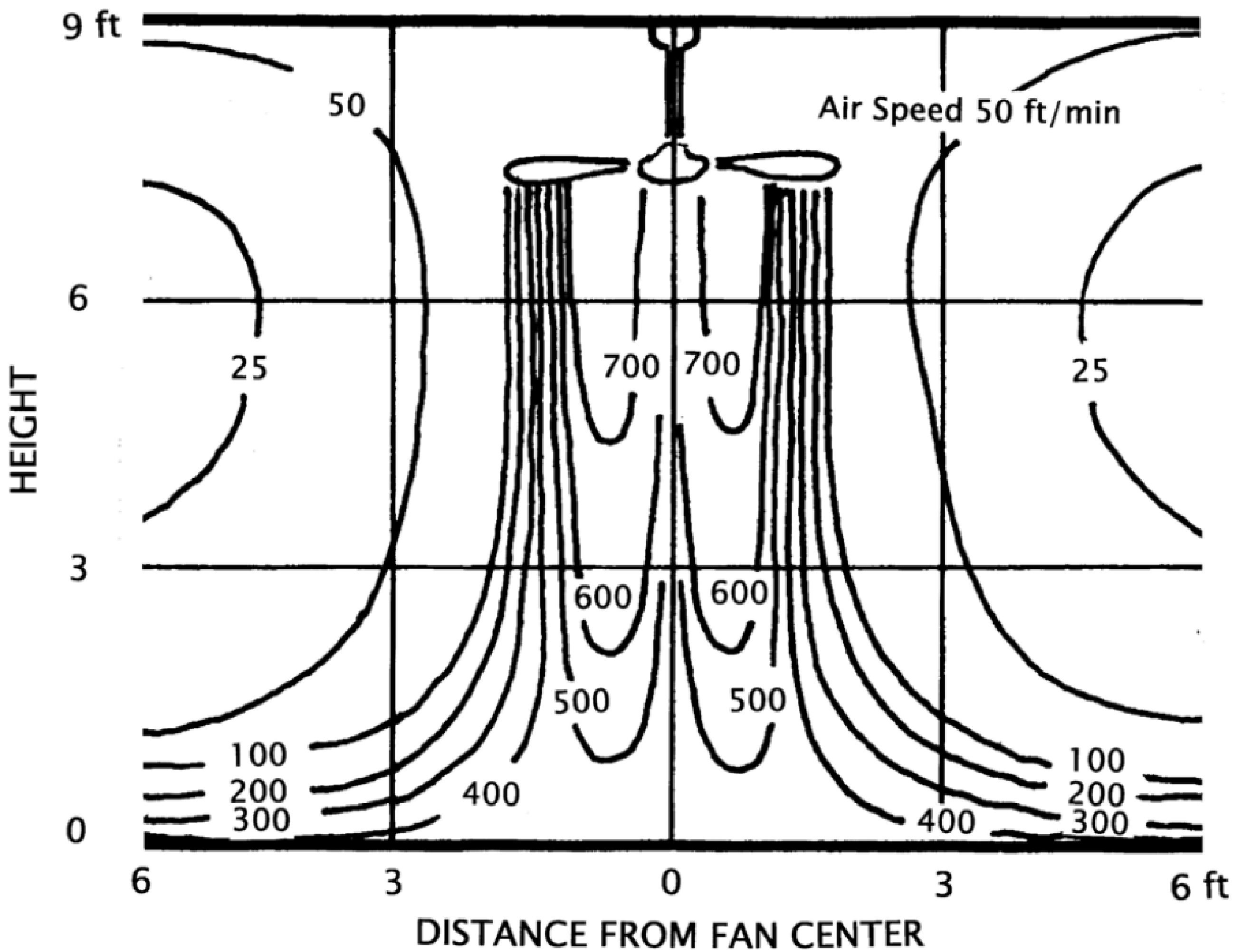
(b) To design for practicality, a cap in the number of ceiling fans that can be controlled by a single control technology will arise. This cap results from the diversity of desired air movement within a space, which limits the practicality of operating multiple fans simultaneously. For instance, in large industrial spaces, demand for multiple fan control often does not exceed 20 to 30 fan linkages as building managers recognize that fan speeds need to be accommodated to the specific space and to the needs of nearby occupants. Therefore, speed settings may vary from slower speeds that produce little to no wind and destratify air to create an even temperature gradient to faster speed settings when a stronger breeze is preferred. Thus, unless a smart-sensor is deployed that contains occupant preferences and environmental conditions, the number of fans controlled by one control device will be constrained.

In theory, the listed control limitations would cover all control issues. In practice, however, further issues may arise that are specific to certain fan or control devices. These are to be dealt with on a case by case basis with the designated fan or control manufacturer.

Sources: Home Depot, n.d (a), Duke, 2002. Big Ass Solutions, 2017, Lutron, 2017, Crestron, 2017, Hunter Fan, 2017, MacroAir Fans, 2017

FLAT BLADE FAN ROOM AIR MOVEMENT PROFILE

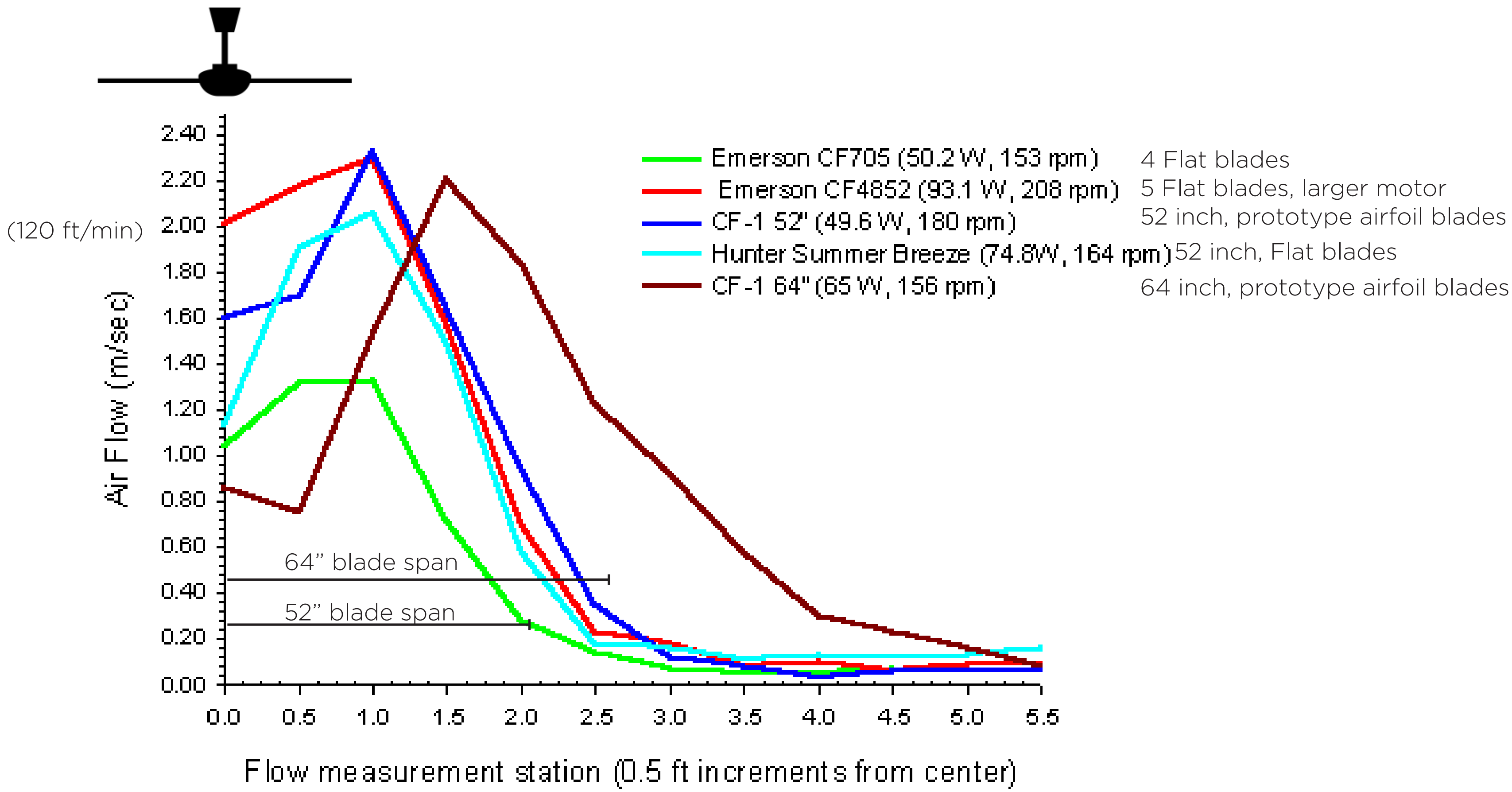
A typical air movement profile of a flat blade fan operating in the summer that is positioned 9 feet off the floor is seen below. Understanding ceiling fan air movement is important in sizing and placing ceiling fans in a space.



Source: Aynsley, 2008
Image Source: Aynsley, 2008

FLAT AND AIRFOIL BLADE FAN AIR SPEED PROFILE

The air movement profile of a ceiling fan varies with fan blade design and size. The figure below shows the air speed profile from the center of 5 different ceiling fans measured at 43 inches off the floor. Three of the below ceiling fans have flat blades, while two have airfoil blades.

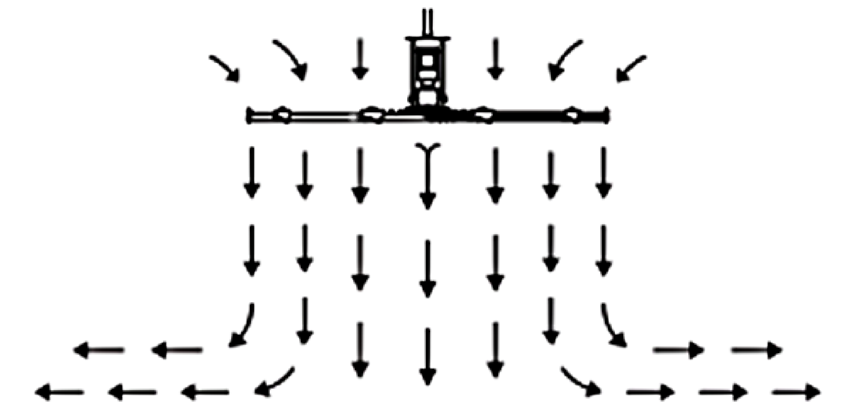


Source: Parker et al, 1999
Image Source: Parker et al, 1999

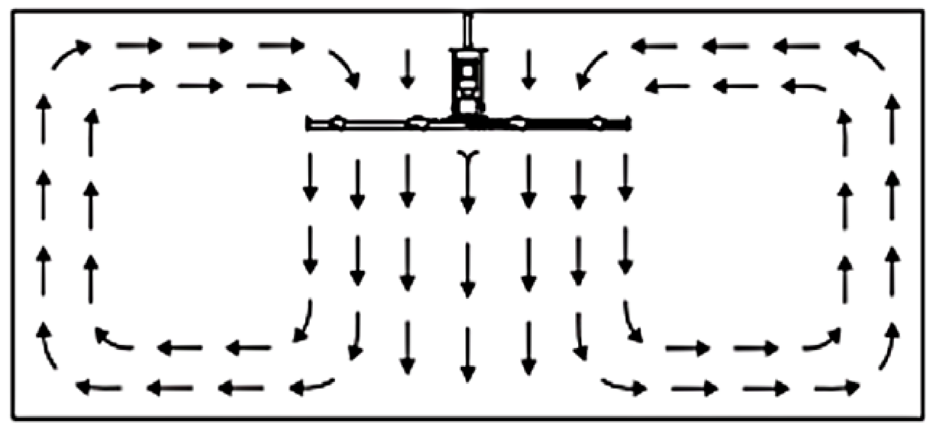
AIRFOIL BLADE HVLS FAN AIR MOVEMENT PROFILE

The typical air movement distribution for an HVLS fan in an open and enclosed area is pictured below. Understanding the air movement profile of an HVLS fan allows designers and installers to better understand a ceiling fan's airflow distribution within a room. The airflow profile of an HVLS fan in an open area can be seen on the left. In this scenario, air moves from the fan blades to the floor and is deflected outward upon reaching the floor. This deflection off the floor is called a "floor jet." On the other hand, the airflow profile of an HVLS fan in an enclosed area, pictured on the right, begins with air radiating outward until it hits a wall, which deflects the air upward above the fan blades. As the area above the ceiling fan is a low-pressure zone, air moves into it until it is then pulled down, which creates a convective current and allows the air movement to sustain its circular pattern and generate a cooling effect.

Airflow (Open Area)



Airflow (Enclosed Area)

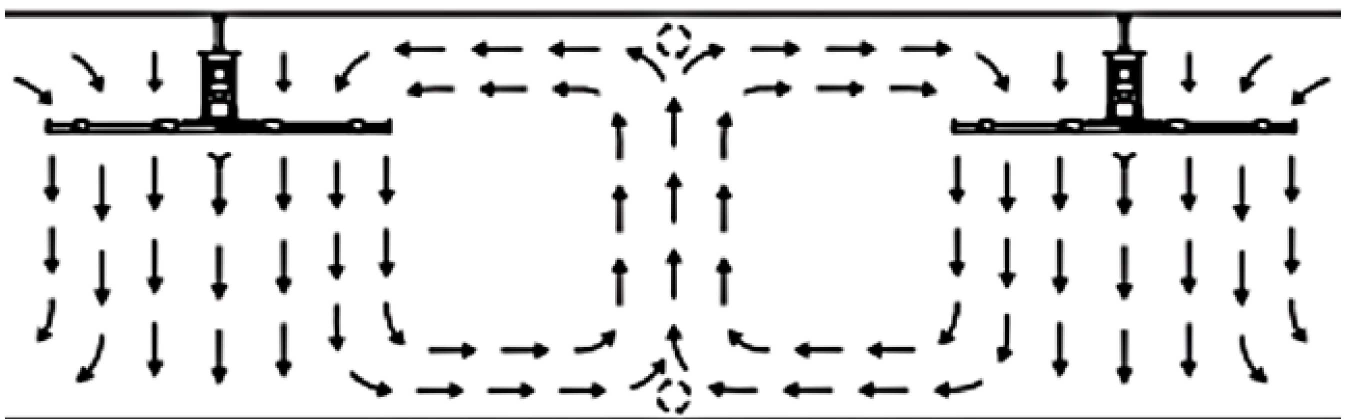


Sources: Big Ass Solutions, 2014 (b), Big Ass Solutions, 2017
Image Source: Big Ass Solutions, 2014 (b)

AIRFOIL BLADE HVLS MULTI-FAN AIR MOVEMENT PROFILE

The typical airflow pattern when multiple HVLS fans are placed in a room are shown below. When HVLS fans are appropriately spaced apart, the performance of each fan can be enhanced by the presence of an adjacent fan. Initially, airflow of multiple HVLS fans is directed downward and it eventually flows outward until it reaches a pressure zone, which is formed when the two fan's air movement meets. The pressure zones behave like walls, as air similarly rebounds off and is pulled upward to the low-pressure zone area above the fan. Usually, the performance of a single HVLS fan improves when working simultaneously with other fans because the pressure zones that form ensure that air is bounded, which causes air to be targeted to a narrower area. This narrow area would not be as adequately served if no nearby fan existed as circulating air would simply continue to disperse outward until it hit the nearest wall.

Airflow (Multiple Fans)

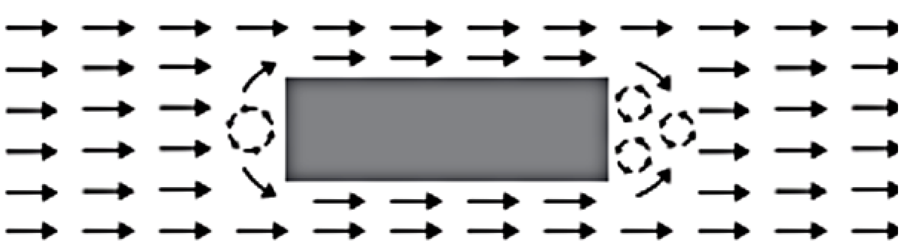


Sources: Big Ass Solutions, 2014 (b). Big Ass Solutions, 2017
Image Source: Big Ass Solutions, 2014 (b)

Airflow distribution patterns of an HVLS fan with floor obstructions that are either streamlined (thin) or blunt (wide) are provided below. Floor obstructions affect air movement and alter the reach and velocity of air circulating to certain areas within a room. Specifically, for thin or streamlined obstructions, air streaming horizontally is blocked and diverted to pass smoothly around its outside boundaries, with only small bits of air stagnating behind. On the other hand, wide or blunt obstructions change the direction of airflow, causing a larger amount of stagnating air to remain behind the obstruction. Although obstructions are often overlooked in the planning process, the air movement profile with obstructions should be considered when placing or installing HVLS fans as intended cooling or destratification may be undesirably affected. Further, no specific dimensions qualify an obstruction as either streamlined or blunt, and rather what determines the obstruction type is whether the body of the obstruction is parallel or perpendicular to the horizontal air movement.

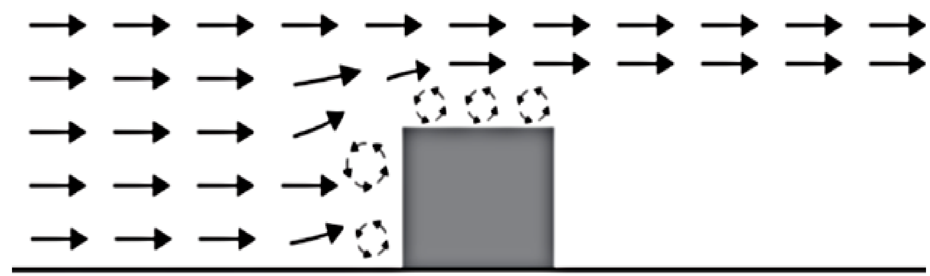
Airflow (Obstruction)

Streamlined Obstruction - Overhead View



Thin, streamlined floor obstructions minimally impact air movement

Blunt Obstruction - Side View

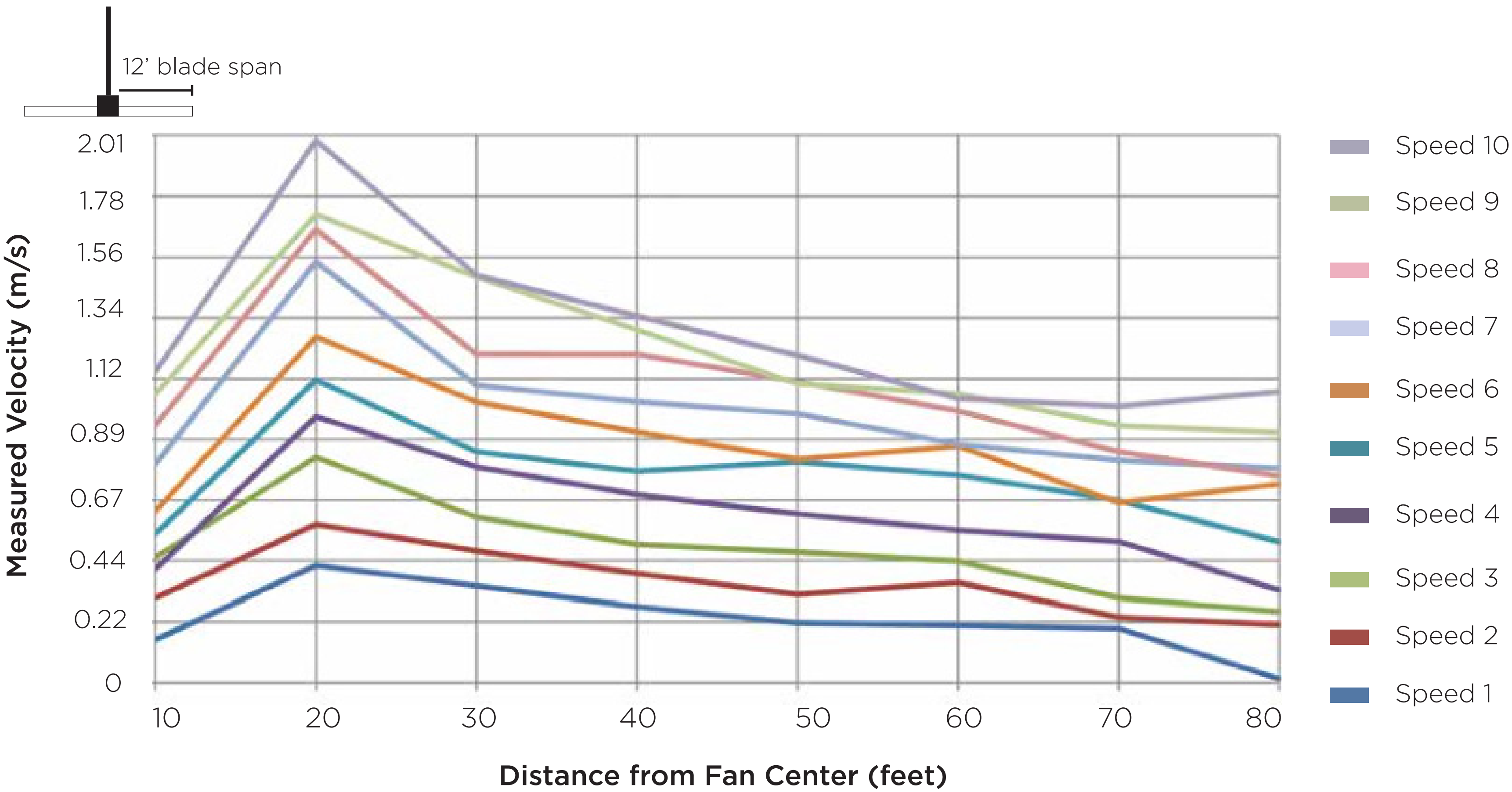


Wide, blunt floor obstructions significantly impact air movement

Sources: Big Ass Solutions, 2014 (b), Entrematic Fans, 2016 (b), Big Ass Solutions, 2017
Image Source: Big Ass Solutions, 2014 (b)

AIRFOIL BLADE HVLS FAN AIR SPEED PROFILE

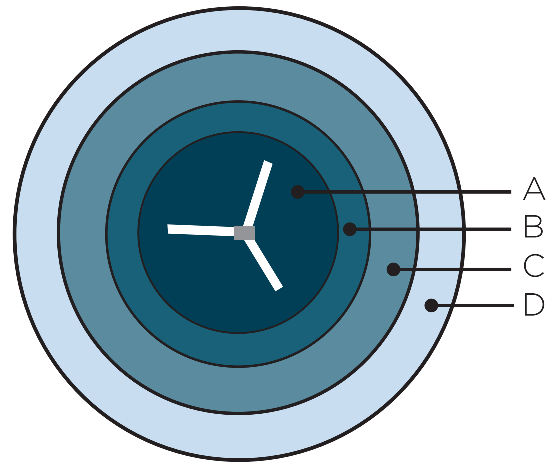
The figure below shows the air speed profile for a 24 foot diameter HVLS fan from the center of the fan at 0 feet to 80 feet away from the fan. Airflow readings were taken at four different heights: 4”, 24”, 43”, 67” and were then combined to determine the combined average air velocity at each radial distance. Ten speeds are shown, with the maximum speed (Speed 10) being 58 RPM. As can be seen below, the maximum velocity is achieved slightly outside the fan perimeter, and this is because as moving air is deflected off the floor, it accelerates initially and then slows as it moves further from the fan’s center. Since currently no standardized models exist on air speed profile over space for different blade types, the figure below is simply intended to be an initial diagram by which to better understand HVLS fan air movement speed profile over space.



Sources: Knoop, n.d. Pelaga, 2017
Image Source: Knoop, n.d

AIRFOIL BLADE HVLS FAN AREA OF INFLUENCE

Placement of an HVLS fan is dependent on the fan's area of influence, or the maximum area that the fan can effectively circulate air. Typically, the larger the fan, the larger the area of influence. The below image depicts an HVLS ceiling fan and the corresponding areas of influence A, B, C, D which are organized by the fan's average air velocity within a given area. The accompanying chart details the average air velocity, perceived cooling and diameters of coverage per area of influence. Although this information differs by fan model and manufacturer, the below information is intended to provide general insight on the cooling abilities and coverage capacities of HVLS ceiling fans.



Area of Influence	Average Air Velocity (m/s)	Perceived Cooling (°F)	Diameters of Coverage (ft): 8 ft Fan Diameter	Diameters of Coverage (ft): 16 ft Fan Diameter	Diameters of Coverage (ft): 24 ft Fan Diameter
A	2.8 m/s	11-14 °F	8 ft	16 ft	32 ft
B	1.3 m/s	5-9 °F	15 ft	40 ft	50 ft
C	0.9 m/s	6-8 °F	20 ft	60 ft	120 ft
D	0.5 m/s	4-5 °F	128 ft	182 ft	190 ft

Source: BladeTec Fans, 2012

MODELING OVERVIEW

Computational Fluid Dynamics (CFD) is a modeling technique that helps predict fluid flow by using mathematical modeling, numerical methods and software tools. Architects and engineers often use CFD to simulate airflow phenomena and thermal distribution in a space to better inform room and building design.

CFD modeling can predict several thermal-fluid phenomena, which can be found below. The model output allows designers and architects to better evaluate and understand the interaction between indoor environmental quality, building envelope, ventilation system performance and thermal comfort.

(1) Simultaneous Heat Flows
  (e.g. heat conduction within building enclosures via velocity, temperature measurements)
(2) Phase Changes
  (e.g. condensation and evaporation)
(3) Chemical Reactions
  (e.g. combustion)
(4) Mechanical Movements
  (e.g. fan and occupant movement)

Sources: Kuzmin, n,d., Cham, n.d, Jameson, n.d, English, 2017

MODELING ACCURACY

CFD modeling has evolved into an important computational tool for several industries. The increased use of CFD modeling in design and analysis has generated demand for standardized accuracy standards or guidelines to ensure quality control of the models' output. Currently, other engineering professional organizations such as the American Society of Mechanical Engineers (ASME) and the American Institute of Aeronautics and Astronautics (AIAA) provide guidance on performing CFD simulations and validating the results. Efforts have occurred within ASHRAE to set forth guidelines on the use and validation of CFD models which has led to the development of a CFD manual, however no formal, comprehensive standard is currently available.

The accuracy of a CFD model strongly depends on the proper setting of boundary conditions and simulation parameters. Currently, and as a result of the complexity of CFD codes and the expansive range of applications, no robust accuracy guidelines and/or protocols govern CFD modeling. This lack of streamlined has led to diverse settings in CFD simulations and disagreement among professionals on exact accuracy procedures. However, the primary way to currently assess accuracy in CFD models is by means of validation and verification (V&V) procedures. Validation is the process of assessing how well computational results compare to experimental data, or real-life observations. Verification is the process of identifying and quantifying errors in the model. V&V procedures are used to test the model's accuracy, which may be affected by errors and inaccuracies that arise from imprecise input data, limited computer power and gaps in scientific knowledge.

To summarize, while independent V&V procedures are used for quality assurance of CFD modeling, no over arching guideline currently exists that details best practices and standardized verification methods for CFD and CFD codes.

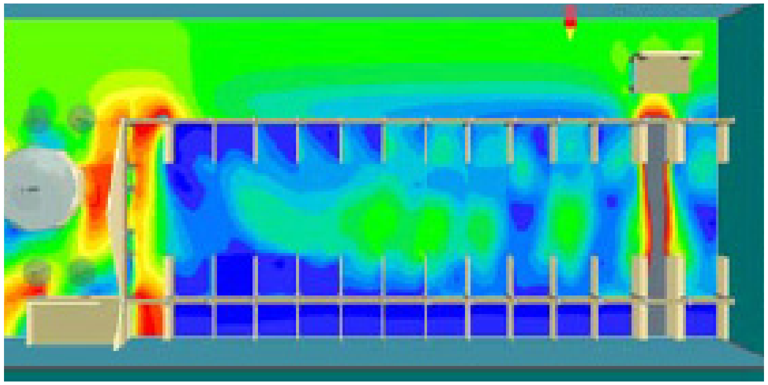
Sources: Gungor, 2015. Srebric, et. al, 2002, NASA, 2008. Chen, n.d. Gungor, 2015, Franke, et. al. 2007, Judkoff, et.al. 2006, Begg, 2012

CFD MODELING: EXAMPLE STUDY

Wong et. al (2006) perfomed a study in Singapore and ran CFD simulations to investigate the effectiveness of different mechanical ventilation systems in reducing thermal discomfort in dining centers. As ceiling fans were considered, this study serves as an example as to how CFD modeling can be used to understand the impact of ceiling fans on indoor environmental conditions. Provided below is an example of air velocity contour plots obtained with CFD modeling for both a no-ceiling fan scenario and a ceiling fan scenario. The colors in the velocity contour plots represent the velocity magnitude in the studied space, with warmer colors, such as red representing faster air velocity and colder colors, such as blue representing slower air velocity. In using CFD modeling to understand air velocity or air temperature distributions, designers and planners can make more informed decisions on room and building design.

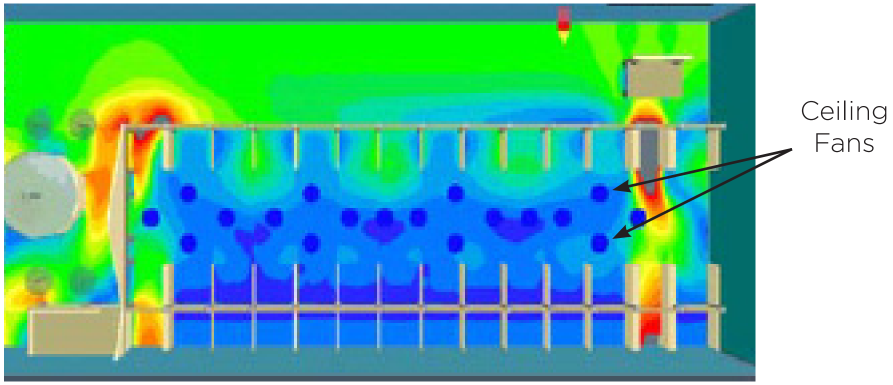
Air Velocity Distribution (No Ceiling Fan)

(Plan view)



Air Velocity Distribution (Ceiling Fan)

(Plan view)



Color:	Blue	Green	Yellow	Orange	Red
Air Velocity:	.02-1.0 m/s	1.6-2.13 m/s	2.99-3.20 m/s	3.46-3.73 m/s	+ 4 m/s

Slower → Faster

Sources: Wong, 2006., Kinnear, et.al., 2006
Image Source: Wong, 2006

CODES & STANDARDS

Applicable ceiling fan codes and standards can be found under equipment testing or air movement as it relates to thermal comfort.

Energy
Energy Policy and Conservation Act of 1975 (EPCA): defined and established design standards for ceiling fans. The EPCA for ceiling fans was updated in 2017 to require more stringent efficiency standards effective 2020.

Testing
ANSI/AMCA 230-07: *Laboratory Methods of Testing Air Circulating Fans for Rating and Certification.* 2007

10 CFR part 430, subpart B, appendix U: *Uniform Test Method for Measuring the Energy Consumption of Ceiling Fans.* (2017)

Thermal Comfort
ANSI/ASHRAE 55: *Thermal Environmental Conditions for Human Occupancy.* 2013

EN ISO 7730: *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* 2005

EN 15251: *Indoor environmental parameters for design and assessment of energy performance of buildings - addressing indoor air quality, thermal environment, lighting and acoustics*. 2007

Upcoming
ASHRAE Standards Project Committee 216: Standard method of test for individual fans (public comment anticipated end 2017)

4

Sizing and Placement

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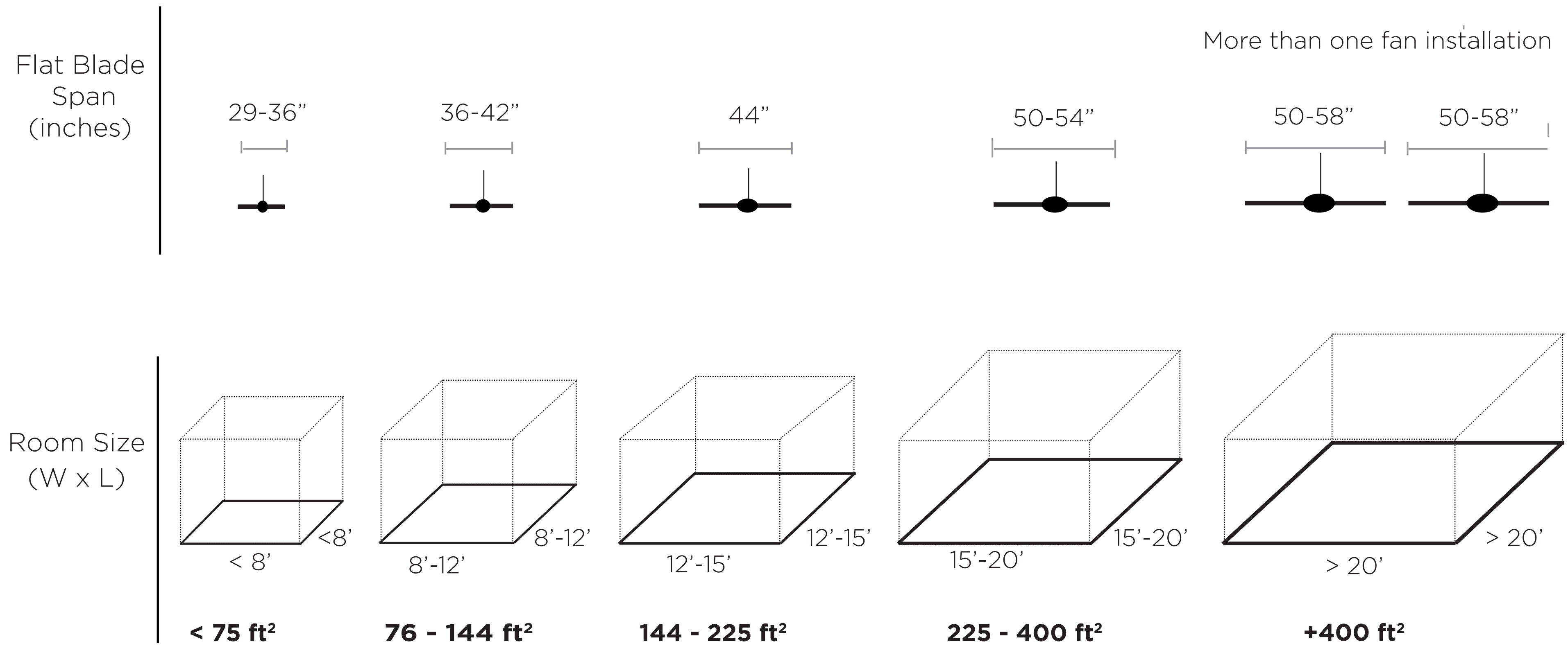
FLAT BLADE FAN SIZING

To appropriately determine a ceiling fan's size, a measurement of the room's size (width, length) or area (square footage) is required. With this information, optimal flat blade fan size can be decided upon. General industry guidelines exist that provide recommended flat blade span diameters for different room sizes. When installing fans, however, it is common to down-size from the guidelines so that only occupied space is covered. The figure below gives guidance on ceiling fan flat blade span (size) in conjunction with total room size.



Sources: Bermudez, 2016 (a). Bermudez, 2013 (a). CeilingFan.com, n.d. (a) Hawaii State Energy Office, n.d

FLAT BLADE FAN PLACEMENT

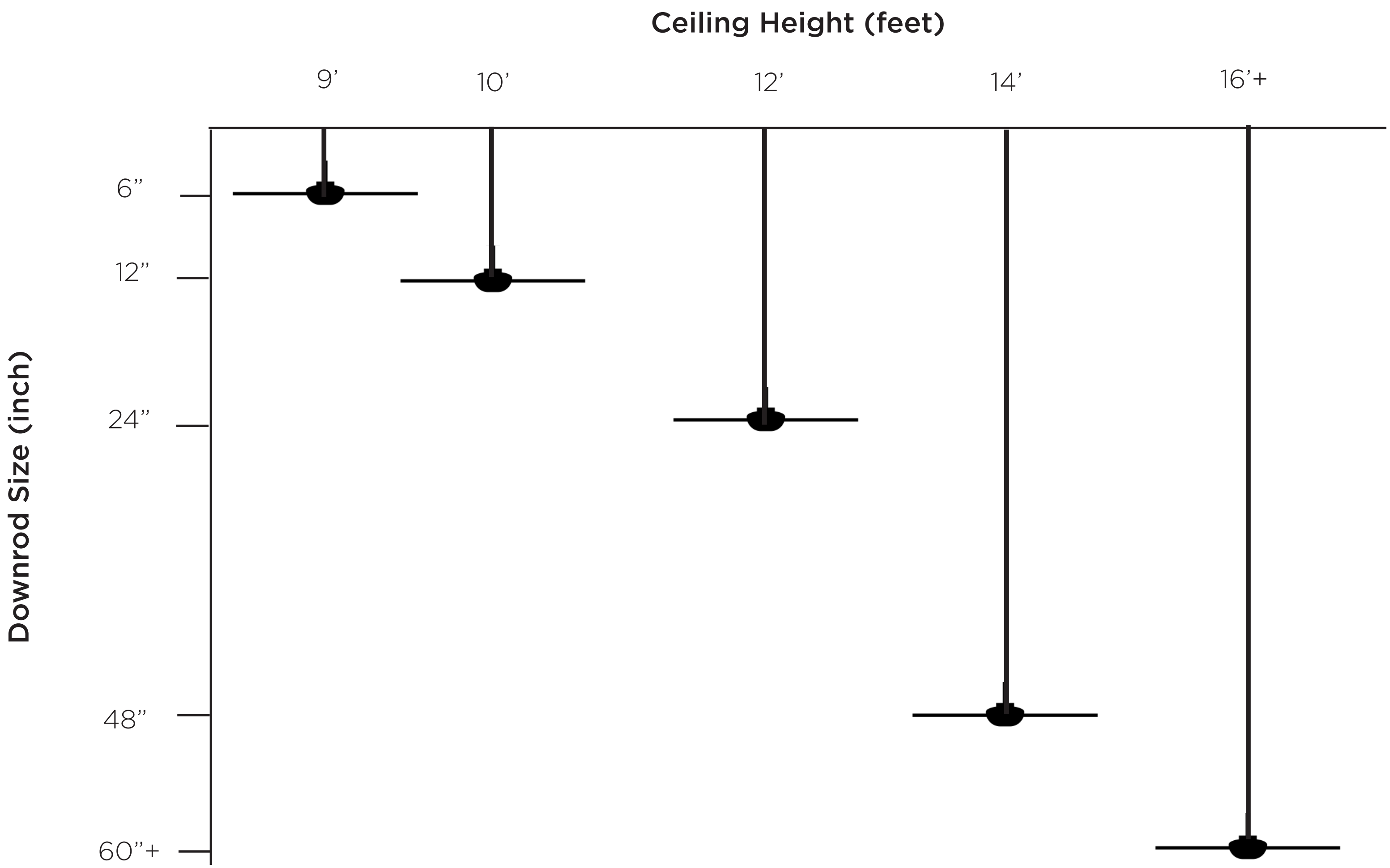
Placement of a ceiling fan is determined by ceiling height and room size. The industry standard for the minimum clearance between a fan's blades and the ceiling is 8 inches. Additionally, and as recommended by manufacturers and the International Association of Certified Home Inspectors (InterACHI), fan blades of residential ceiling fans are required to be at least 7 feet from the floor in order to prevent accidental contact with blades. In commercial spaces, fan blades are required to be 10 feet from the building floor. For smaller rooms with ceiling heights of less than 8 feet, low-profile ceiling fans with no downrods are recommended. For larger rooms, with ceiling heights greater than 9 feet, downrods are to be installed so that the fan does not sit too far from the floor and inadequately cool occupants. As shown below, downrod size guidelines for flat blade ceiling fans vary by ceiling height.

Ceiling Height	Recommendation	
Less than 8'	Choose a low-profile, hugger ceiling fan with no downrod, whose motor housing mounts directly to the ceiling	
Greater than 9'	Choose a ceiling fan downrod according to the ceiling height. The next page contains the downrod guidelines for specific ceiling heights	

Sources: Gromicko, n.d., Stephens, n.d., CeilingFan.com, n.d. (a), Bermudez, 2016 (a), Bermudez, 2016 (b)
Image Sources: Home Depot, n.d. (d), Lumens, n.d

FLAT BLADE FAN PLACEMENT

As is discussed in the previous page, when a ceiling height exceeds 9 feet, a downrod should be installed on the flat blade ceiling fan in order to provide adequate air circulation for occupants below. The below graph shows the recommended downrod sizes for different ceiling heights. As can be observed, the taller a ceiling is, the larger a downrod is recommended to be.

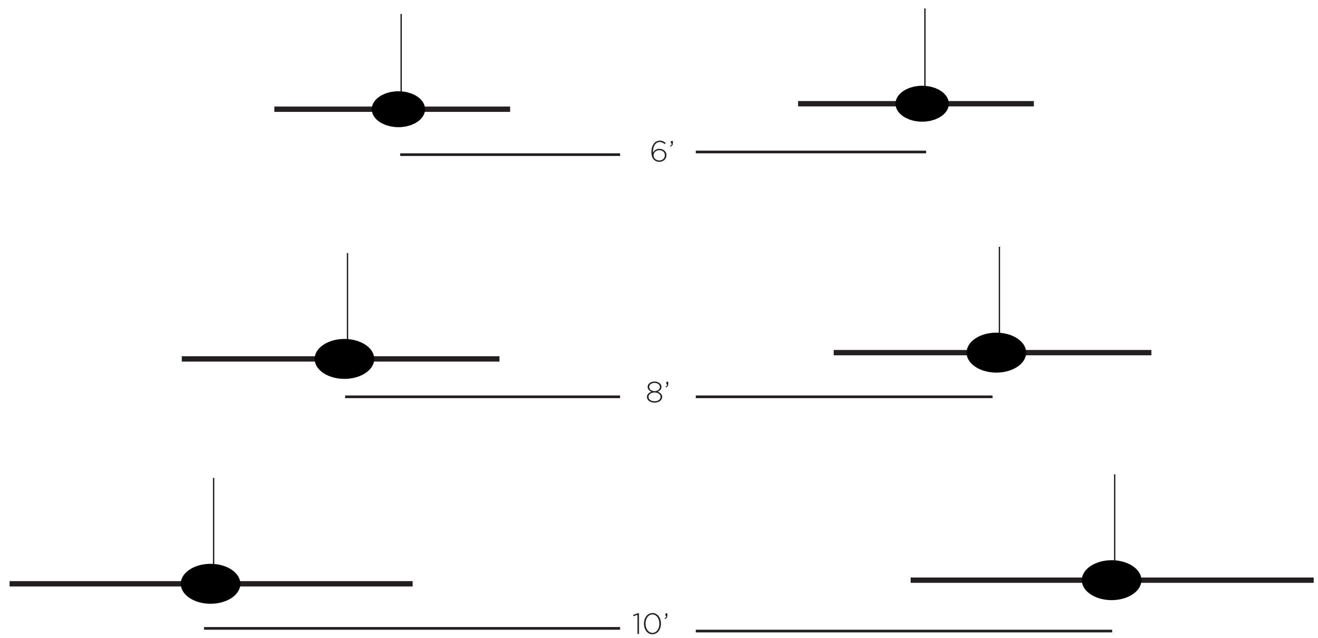


Source: Ceiling Fan.com, n.d (a)

FLAT BLADE MULTI-FAN PLACEMENT

Multiple flat blade ceiling fans may be used to distribute larger volumes of air throughout a room. Currently, no standardized placement guidelines exist for multiple ceiling fans by fan size or diameter. Generally, industry recommends placing fans equidistantly from all vertical walls and these industry recommendations were used to calculate the approximate minimum spacing requirements (in feet) between two fans as shown. Center-to-center spacing refers to the measurement taken from the center of one fan to the center of another neighboring fan.

Fan Diameter (inches)	Minimum Spacing Between Flat Blade Fans (Center-Center) (feet)
42”	
48”	
56”	



Source: Blogbyusha, 2015, Hansen Wholesale, n.d. (b)

OBSTRUCTIONS: FLAT BLADE FAN

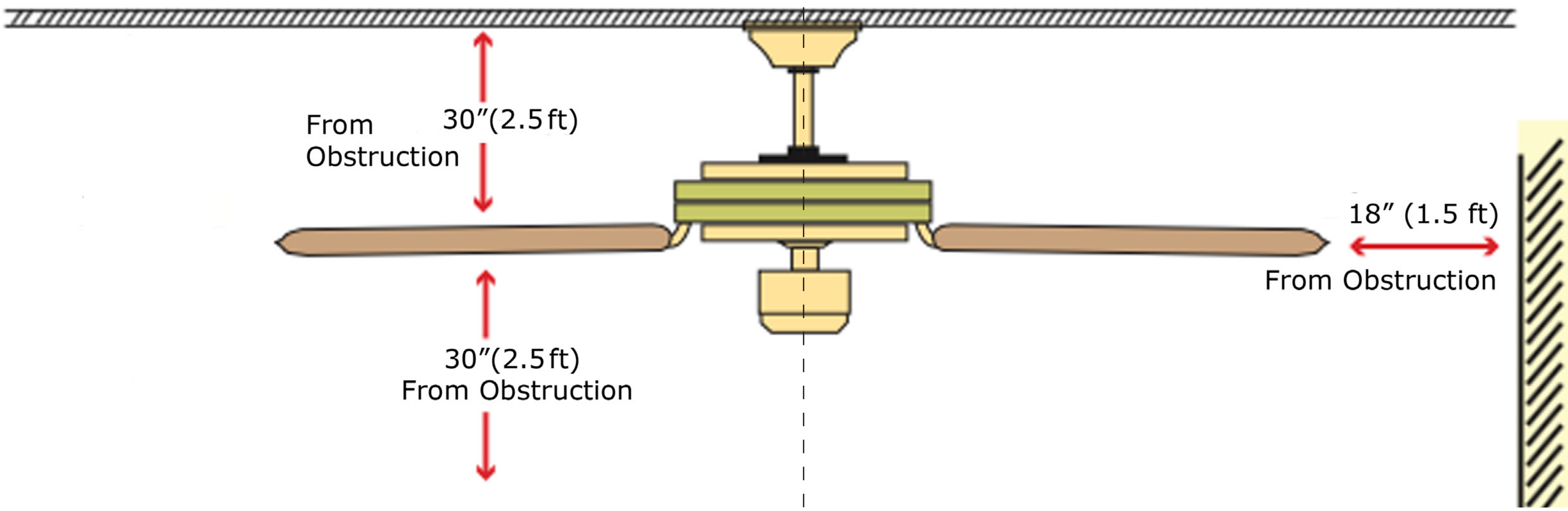
Obstructions on the ceiling (light fixtures, fire sprinklers, pipes) as well as on the floor (walls, cabinets, floor equipment) have a direct impact on air circulation and distribution since air bounces off objects, causing turbulence. The guidelines below provide information on the maximum allowable distance recommended from flat blade ceiling fans and objects above and below (vertical) as well as to the side (horizontal). Since obstruction guidelines differ by fan model and manufacturer, provided below are the conservative values found in industry publications and specification documents.

Vertical Obstructions

All sized standard fans should allow for a minimum clearance of 30" both above and below blades.

Horizontal Obstructions

All sized standard fans should allow for a minimum clearance of 18" (1.5ft) around the sides, starting at the tips of the blades.



Sources: Hunter Fan, 2002; Westinghouse, n.d., Casablanca, 2014
Image Source: Westinghouse, n.d

OBSTRUCTIONS: FLAT BLADE FAN

Minimum distance guidelines for specific obstructions, such as fire-sprinklers and lighting are provided below for flat blade ceiling fans. While a formal association, the National Fire Protection Agency (NFPA) determines placement guidelines of ceiling fans with respect to fire-sprinklers, no such formalized standards exist for lighting, and the provided lighting guideline listed below is acquired from industry articles that provide common guides and tips.

Fire Sprinklers: The National Fire Protection Agency (NFPA) creates standards regarding fire sprinkler systems, coined NFPA 13 and 13R. These standards include minimum distance requirements from fire-sprinklers to ceiling fans, which have been developed through testing and evaluation within the NFPA.

- Standard 13 requires residential pendent sprinklers to be located at least 3 feet from the center of the fan. Residential sidewalls are to be located at least 5 feet from the center of the fan.

- Standard 13 states that blades of ceiling fans are not considered obstructions when the surface area of the fan blades encompass less than 50% of the total fan's area from a plan view. Thus, from a plan view, the non-fan area or the open area needs to be at least 50% open for ceiling fans to no longer be considered obstructions for fire-sprinklers. See example (1) on the next page for further specification.

- Standard 13 requires sprinklers to be positioned away from obstructions (such as ceiling fans) at a minimum distance of four times the maximum dimension of the obstruction (ceiling fan). See example (2) on the next page for further specification.

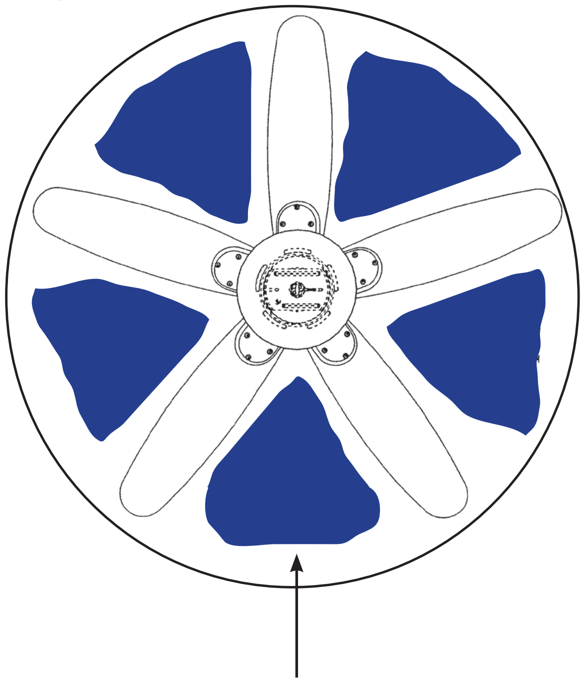
Lighting: Lighting fixtures are potential obstructions whose placement can conflict with a ceiling fan. Currently, the minimum clearance recommended between a ceiling fan's blades and light fixtures is 39 inches.

Sources: NFPA, 2016., Faninfl, 2017., City of Colorado Spring, n.d., Ceiling Fan Select, 2017

OBSTRUCTIONS: FLAT BLADE FAN

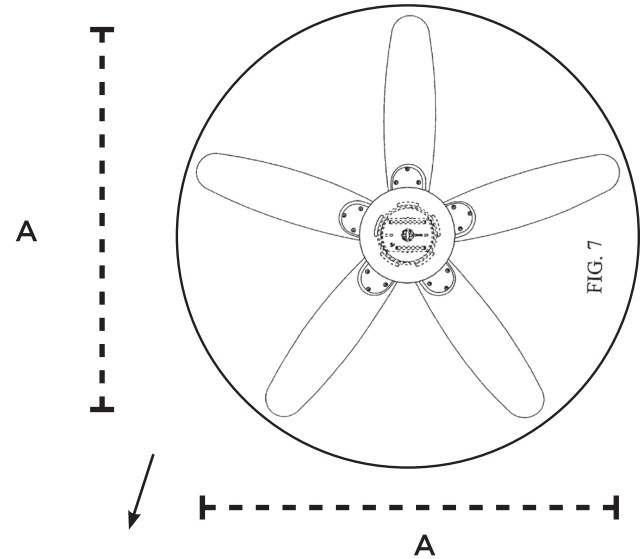
Below are visual representations of the fire-sprinkler obstruction standards outlined in the previous page. Example 1 refers to the standard qualifying ceiling fans as obstructions, while Example 2 refers to distance guidelines from obstructions, such as ceiling fans.

Example 1

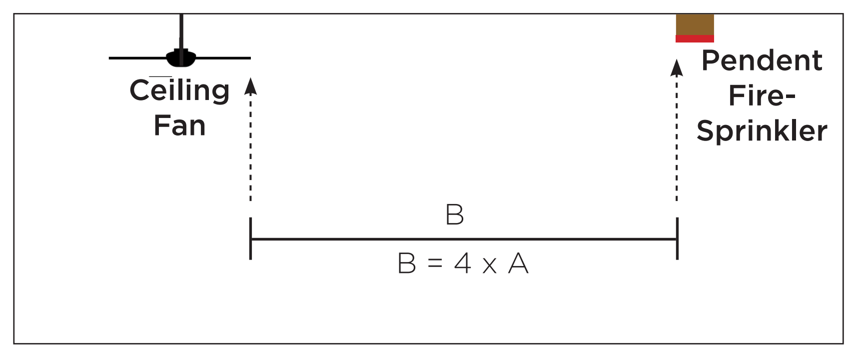


The shaded blue area indicates the open area of the plan view that needs to be at least 50% open for obstructions to be disregarded in fire-sprinkler placement

Example 2



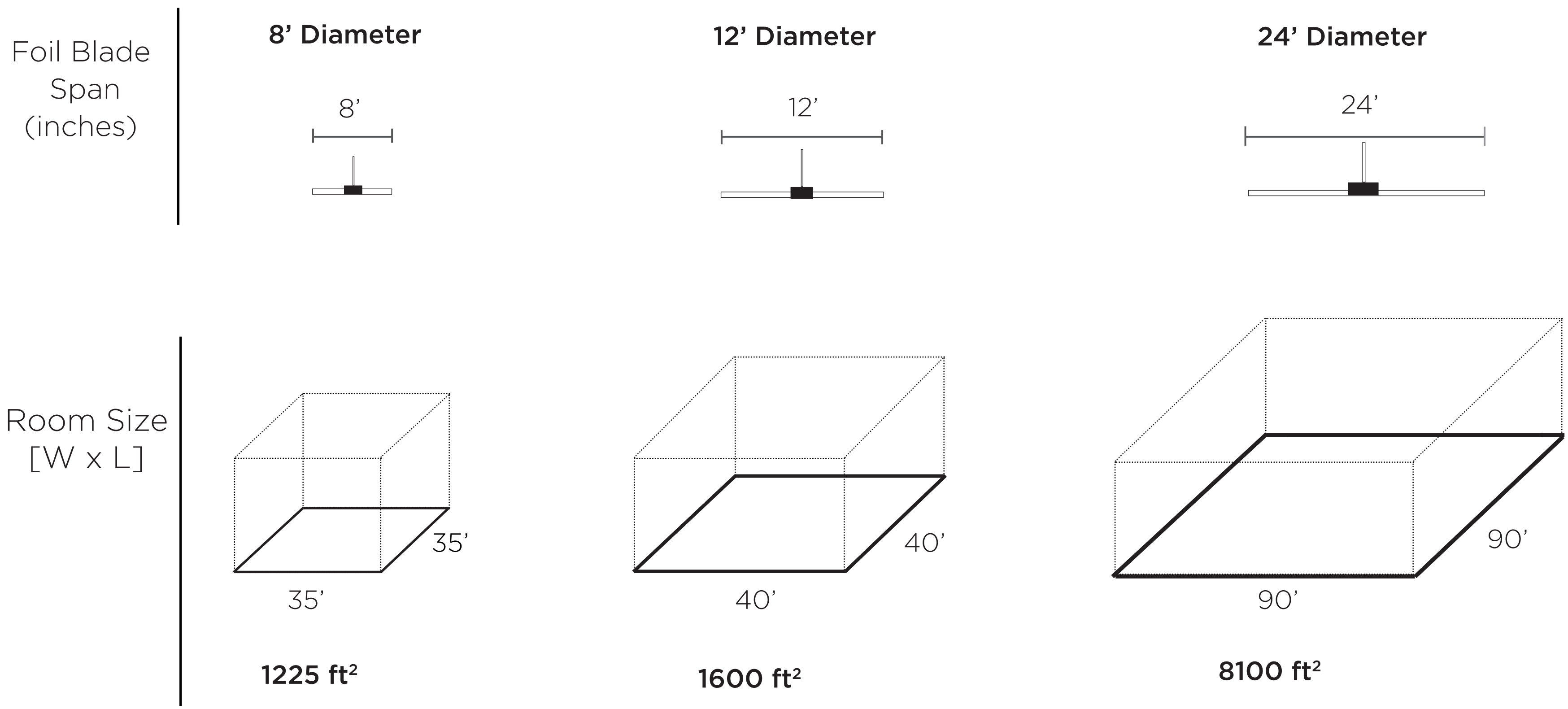
Minimum Distance Guidelines:



Sources: NFPA, 2014. City of Colorado Spring, n.d. DSPS, n.d
Image Source: Google, 2011

AIRFOIL BLADE HVLS FAN SIZING

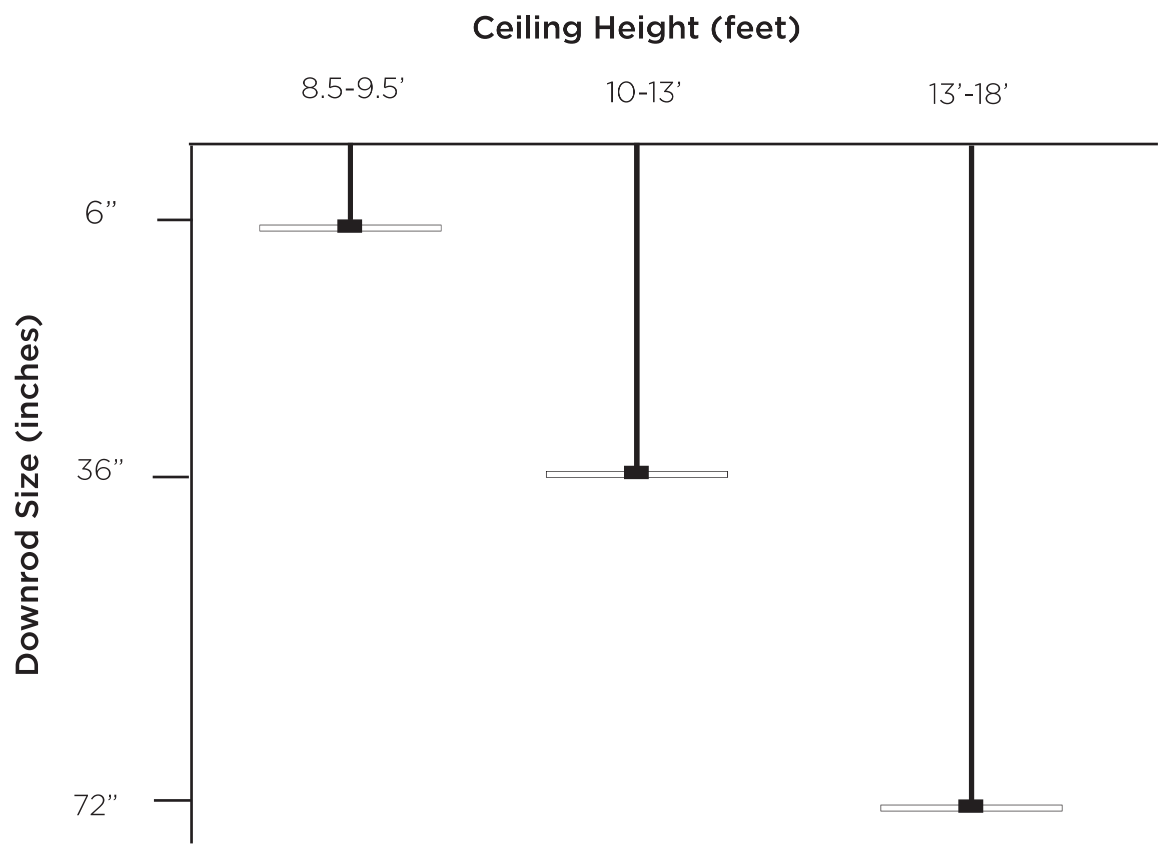
Standard sizing guidelines for HVLS fans with airfoil blade diameters of 8, 12 and 24 feet are shown below. These guidelines are developed by determining the area of the room (length, width) as well as the ceiling height and then assessing the amount of space each fan can effectively cool. These sizing guidelines are obtained from manufacturer specifications, therefore they do not apply to all airfoil blade HVLS fans and are solely meant to provide the general idea of airfoil blade HVLS fan sizing. To understand how ceiling height affects fan placement, see next page.



Sources: Whalenado, 2015, SkyBlade, n.d. OSHA, n.d. Blue Giant, 2017

AIRFOIL BLADE HVLS FAN PLACEMENT

Similar to flat blade ceiling fan placement, the placement of an airfoil blade HVLS fan is dependent on ceiling height. For commercial spaces, in which HVLS fans are commonly used, fan blades should be located at least 10 feet above the floor. As commercial and industrial spaces often have tall ceilings, downrods are used to lower a fan and optimize airflow or destratification. Just as was the case for flat blade ceiling fan placement, downrod size is proportional to a ceiling's height. As no comprehensive and standardized HVLS fan placement guideline currently exists, the recommended placement guidelines shown below are obtained from manufacturer documentation, and therefore should only be consulted as a preliminary guideline when making placement decisions.



Sources: Gromicko, n.d. MyFan, n.d

AIRFOIL BLADE HVLS MULTI-FAN PLACEMENT

In large industrial spaces or facilities, the use of multiple HVLS ceiling fans can more effectively distribute air throughout all desired areas. To ensure optimal performance and minimize overlap of coverage, spacing the fans properly and equidistantly is of vital importance. Below are spacing guidelines by ceiling fan size (in feet) that are based on the general rule that HVLS fans should be spaced at a center-to-center distance that is at least 2.5 times the fan's diameter. Center-to-center spacing refers to the measurement taken from the center of one fan to the center of another neighboring fan.

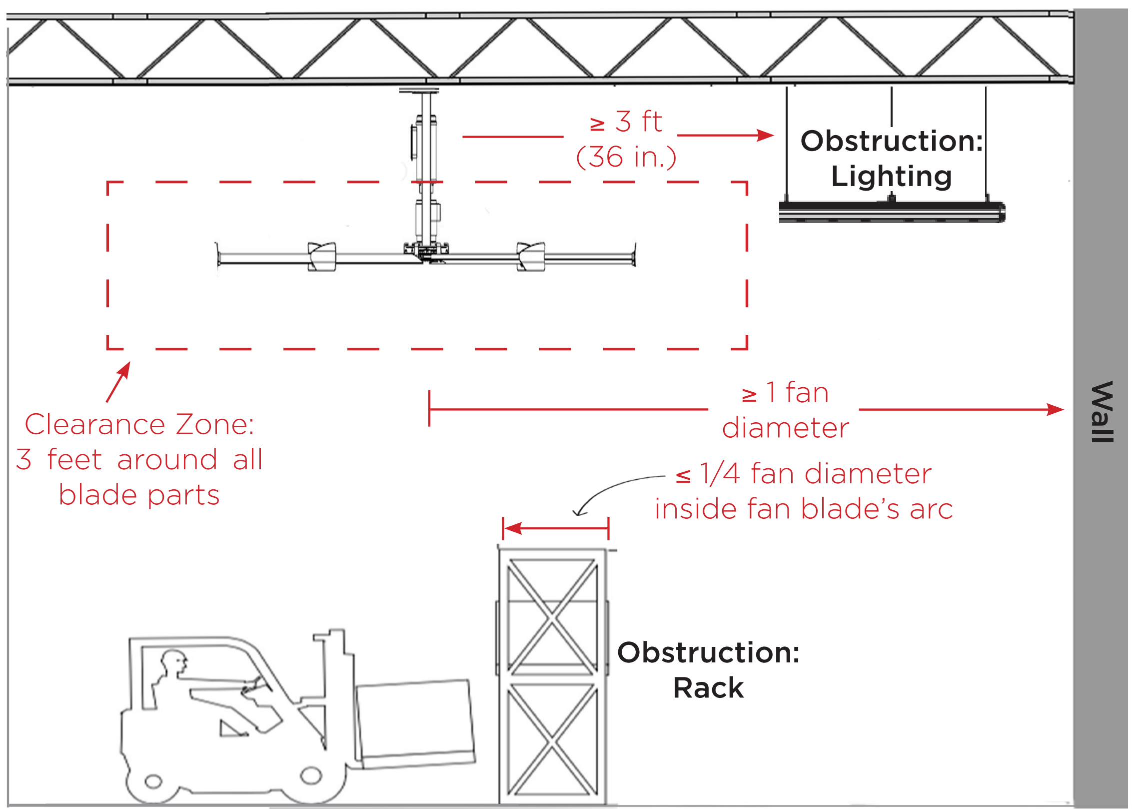
Diameter Size (feet)	Minimum Spacing Between HVLS Fans (Center-Center) (feet)
8'	20'
12'	30'
24'	60'

Sources: Hansen Wholesale, n.d (b), Big Ass Solutions, 2014 (b)

OBSTRUCTIONS: AIRFOIL BLADE HVLS FAN

Large commercial and industrial spaces typically require HVLS ceiling fans to circulate large volumes of air on large floor spaces. In these vast spaces, obstructions can exist to the side as well as below the ceiling fan. To properly and safely place HVLS ceiling fans so that they do not conflict with occupants, neighboring equipment, fire-sprinklers or lights, placement guidelines that recommend minimum clearances have been developed, and those that are of horizontal orientation are seen below. The below clearance guidelines are explained in further detail in following pages. It is important to note that obstruction guidelines are design and manufacturer specific, and so the distances listed below and on the next page are the conservative guidelines found in the industry.

Horizontal Obstruction Guidelines

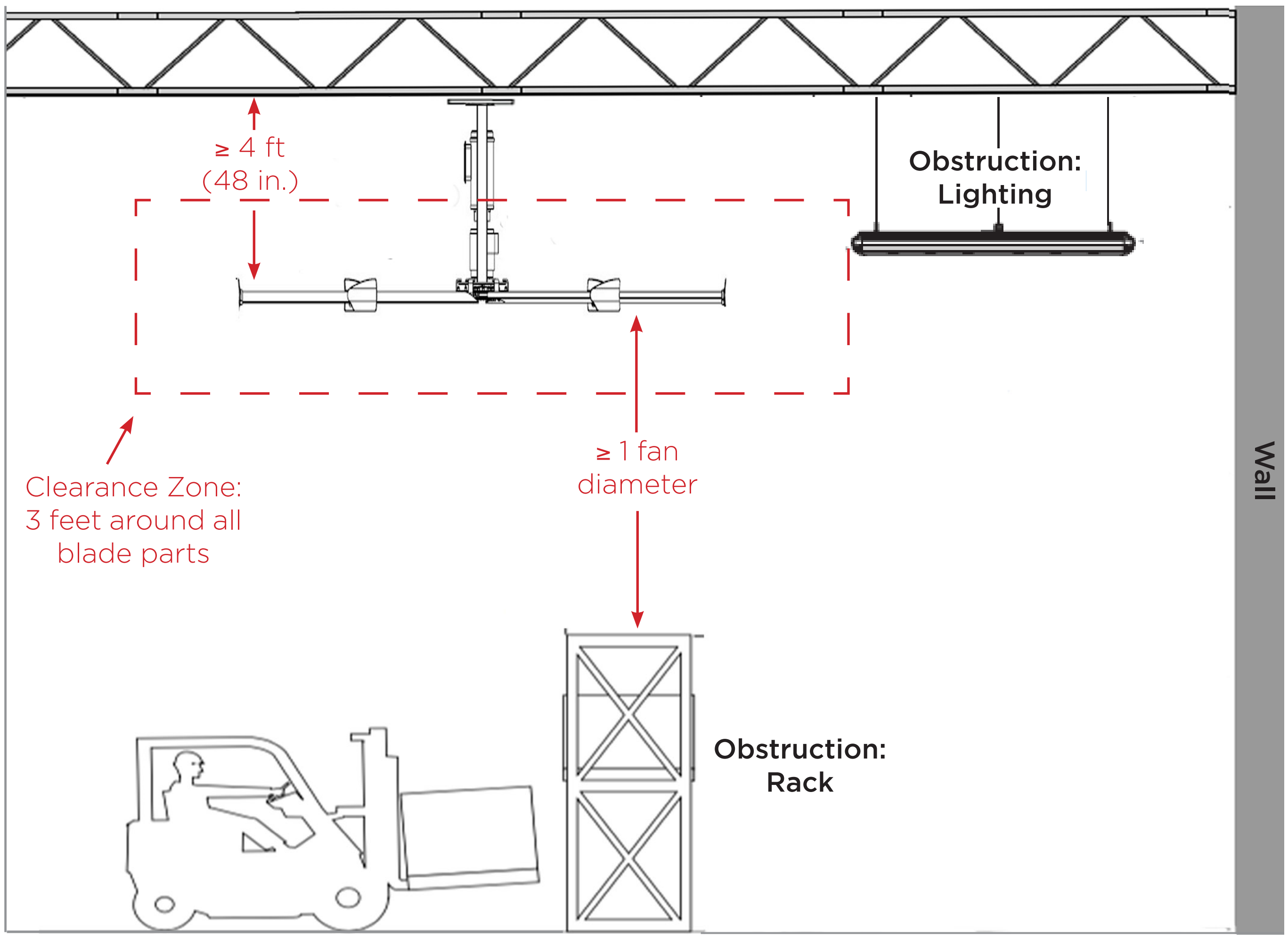


Sources: Big Ass Solutions, 2014 (b), Big Ass Solutions, 2016 (b), Entrematic Fans, 2016 (a) Entrematic Fans, 2016 (b)
Image Source: Big Ass Solutions. 2016 (b)

OBSTRUCTIONS: AIRFOIL BLADE HVLS FAN

Below are the obstruction guidelines for HVLS ceiling fans that are of vertical orientation. Such guidelines include minimum distances from floor equipment as well as overhead items, sitting above the fan on the ceiling. The guidelines featured in the below image are further explained in the following page.

Vertical Obstruction Guidelines



Sources: Big Ass Solutions, 2014 (b), Big Ass Solutions, 2016 (b), Entrematic Fans, 2016 (a), Entrematic Fans, 2016 (b)
Image Source: Big Ass Solutions, 2016 (b)

OBSTRUCTIONS: AIRFOIL BLADE HVLS FANS

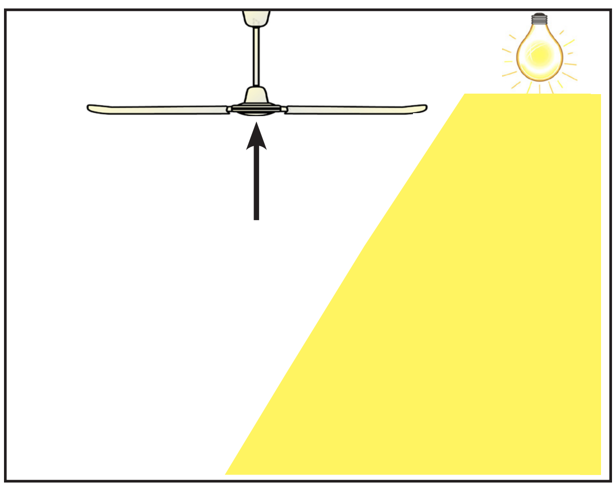
General Guidelines:	• All sized HVLS fan blade parts should allow for a minimum clearance distance of 3 feet (36”) from obstructions such as light fixtures, cables, fire sprinklers and other building components. • All sized HVLS fans should allow for a minimum clearance distance of 4 feet (48”) between the fan blades and the ceiling. • All sized HVLS fans should allow for a distance of 1 fan diameter from the center of the fan to any wall.
Guidelines for Specific Obstructions:	**Fire Sprinklers:** The NFPA 13, 2013 Edition provides a set of design and installation rules based on performed testing. They are listed below: • HVLS fans need to be centered between four adjacent sprinklers. • HVLS fan blades need to be positioned at least 3 feet away from the sprinkler deflector so that the blades do not interfere with sprinkler activation. • HVLS fans must be all programmed to shut down immediately upon 90 seconds of activation of a water flow signal from the fire alarm system. Fans must also shut off after the activation of smoke and heat detection devices. **Lighting:** As noted in the general guidelines above, when a ceiling fan is installed into a room with existing light fixtures and/or panels, a minimum clearance of 36 inches (3 feet) is recommended. Placing a ceiling fan too close to lighting can cause a strobe effect, where light perpetually dims and brightens as it penetrates through a moving fan. To minimize this effect, it is important to maximize the horizontal and vertical distance between the blade and the light panel. When a complete separation is not possible, it is best to minimize the light and fan overlap, as the frequency of the strobe effect increases when the fan and light grow closer. **HVAC:** For HVLS ceiling fans situated near HVAC equipment such as diffusers, exhaust fans and radiant heaters, the fan must allow for a certain cleared distance. • HVLS fans located at or above HVAC equipment should allow for a minimum clearance distance that is equal than or equal to 1 fan diameter. • HVLS fans located below HVAC equipment should allow for a minimum clearance distance that is greater than or equal to 2 fan diameters. **Equipment (Racks, Walls, etc) Below:** For HVLS ceiling fans installed above solid equipment, such as racks, walls or storage, the fan must allow for a minimum clearance distance. • HVLS fans located above solid equipment must allow for a minimum vertical clearance greater than or equal to 1 fan diameter, and less than or equal to a 1/4 fan diameter inside the fan blade’s arc to allow the air column to wash over it, rather than be obstructed by it.

Sources: MacroAir Fans, 2016. Krell, 2016, Klaus Bruckner, 2011, Allianz, 2012

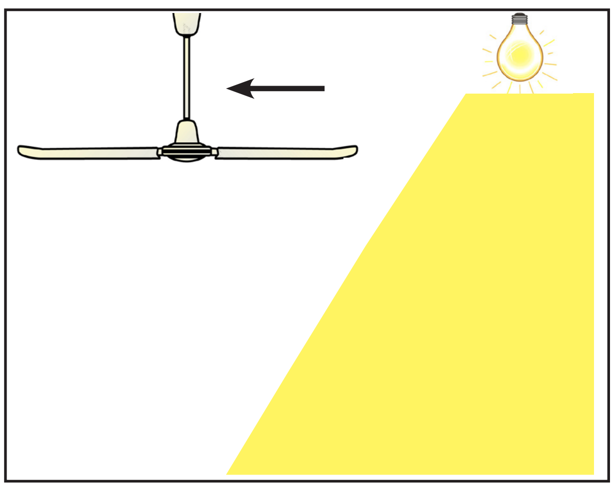
LIGHTING OBSTRUCTIONS: STROBE EFFECT

Ceiling fans are often installed in rooms with existing light fixtures and if the fan is placed too closely to a light panel or fixture, a strobe or flicker effect may occur. A strobe effect is when light perpetually brightens and dims as it penetrates and passes through a moving ceiling fan, causing dizziness and confusion for occupants. While no exact distance guidelines exist to minimize potential strobe effects with standards of HVLS ceiling fans, industry recommends that the horizontal and vertical distance between the light and the fan be maximized between the light fixture and the ceiling fan. Additionally, if a complete separation between the fan and the light panel is not possible, it is best to minimize overlap since the frequency of the strobe effect increases with the amount of overlap. When the light panel is outside of the perimeter of the fan, three recommendations exist: (1) the fan should be moved up far enough so that light does not penetrate through, which can be done by shortening the downrod (2) the fan should be moved away from the light so that light does not penetrate through, or (3) the light's angle of dispersion or the field angle should be reduced so that light does not penetrate through.

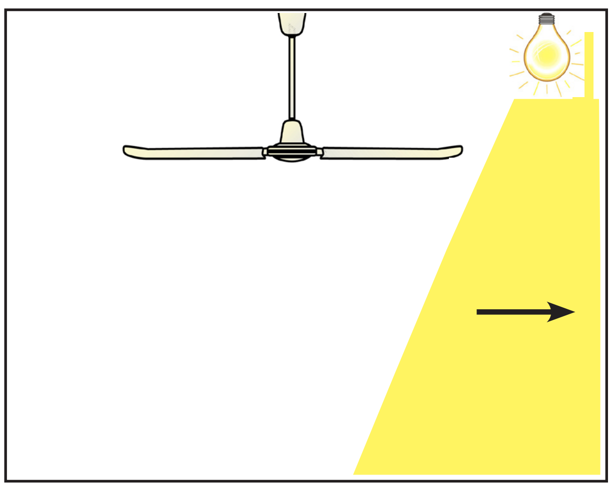
Recommendation #1:
Move Ceiling Fan Up



Recommendation #2:
Move Ceiling Fan Away From Light



Recommendation #3:
Reduce Light's Angle of Dispersion



Sources: MacroAir Fans, 2016, EM Reno Blog, 2012
Image Sources: EM Reno Blog, 2012, Radiant, n.d.

5

Operations

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ENERGY COMPARISON WITH AIR CONDITIONING

Ceiling fans are often compared to air conditioning (AC) as both technologies aim to increase occupant comfort but through different mechanisms and at different building scales. Ceiling fans provide a perception of cooling by increasing air movement while AC provides cooling by actually altering the air temperature and humidity. Another key difference is that ceiling fans and window AC units operate on a room level, while one central AC system can cool an entire building. Therefore, many window AC and ceiling fans are required to achieve the same coverage as central AC.

Cooling an indoor space, using a central AC, a window AC or a ceiling fan has different power requirements. For example, a typical 3 ton central AC used to cool a 1600 feet[2] residential application would consume 3,000 watts per hour while a window AC unit would consume 1200 watts per hour. An average ceiling fan consumes 60 watts per hour or 2% of the central AC system and 5% of the window AC units. In other words, 50 ceiling fans would be required to achieve the same power draw as a central AC unit and 20 ceiling fans would be required to achieve the equivalent power draw of a window AC unit. Thus, with air conditioning installed in almost two-thirds of homes, ceiling fans can provide significant energy savings by reducing AC operating hours, retrofitting AC systems to be smaller or eliminating them altogether.

The large range in power consumption between AC and ceiling fans translates into a significant cost differential. “The Energy Information Administration has found that fewer than 4 percent of households with central air turn it off during the workday when no one is home1”. As an edge example, the energy required to run a window AC in Hawaii all year round would cost $2,716 to operate while a ceiling fan’s would cost $175.

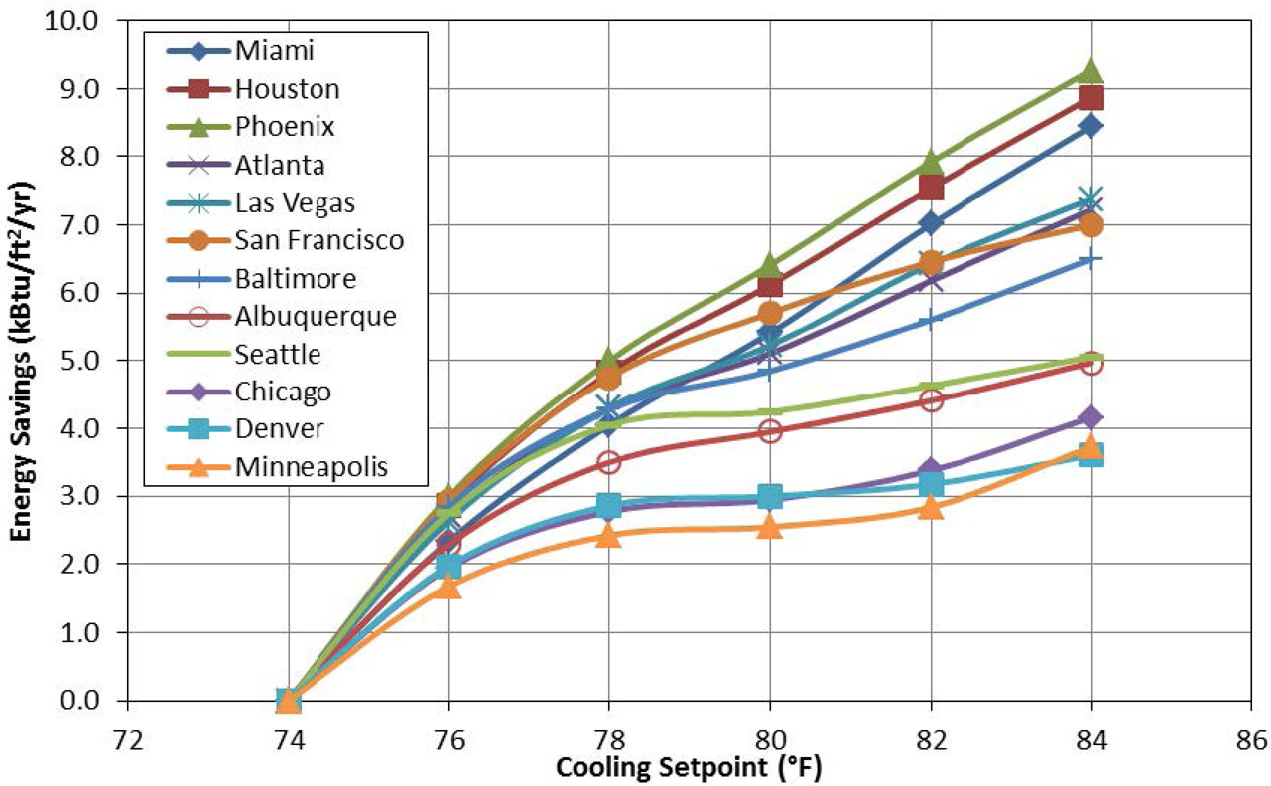
	Avg Power (Watts)	**Avg Hourly Cost in HI[3]**	**Average Annual Cost in HI[4]**
Central Air Conditioner	3,000	$0.78	$6,833
Window Air Conditioner	1,200	$0.31	$2,716
Ceiling Fan	60	$0.02	$175

Sources: 1. Tortorello 2011. Schauer, 2012; In Table: 3. Energy Information Administration, 2017. 4: 8760 hours in a year

CEILING FAN INDIRECT ENERGY SAVINGS

Ceiling fans do not save energy directly but rather indirectly through HVAC energy reduction. Air movement provided from ceiling fans keeps occupants comfortable even though HVAC setpoints are relaxed. The National Renewable Energy Laboratory used energy models to estimate total energy savings in medium office building by incrementally changing setpoints from 74°F to 84°F in 12 U.S. cities. Moving the cooling setpoint from 74°F to 84°F resulted in a 3-9% total energy savings as seen below. Cities in hotter climates (e.g. Phoenix, Houston, Miami) had larger total energy savings.

Key Takeaway: Relaxing cooling setpoints by 10°F can save 3-9% in total energy use

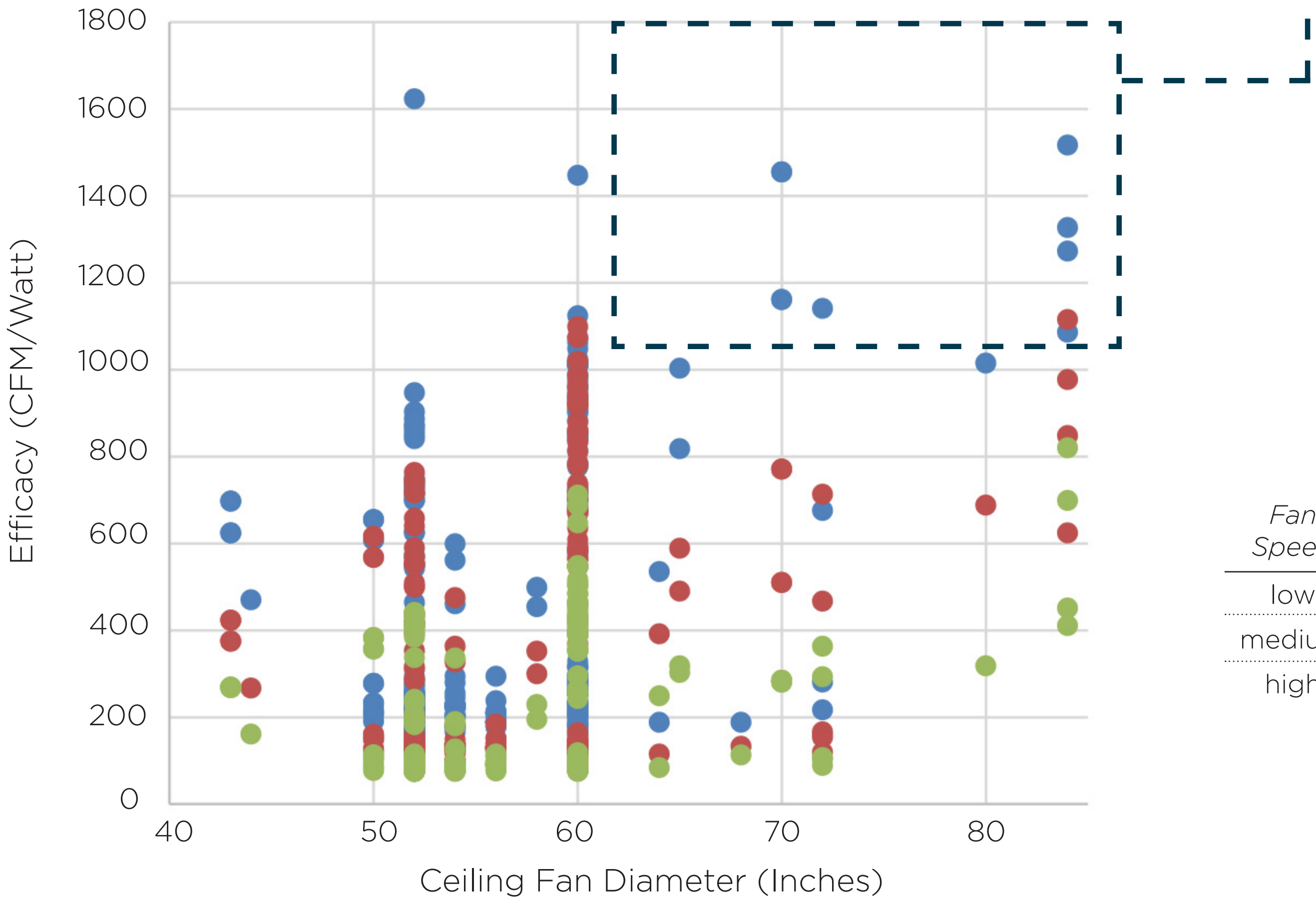


Source: Kiatreungwattana 2016
Image Source: Kiatreungwattana 2016

PERFORMANCE METRICS

ENERGY STAR has promoted energy efficiency of ceiling fans by providing minimum airflow and efficacy requirements, with efficacy measured as CFM/Watt. Currently there are over 100 available models (14% of market) meeting those requirements. The following chart shows the range of efficacies for ENERGY STAR ceiling fans based on ceiling fan diameter. Efficacy is measured on three fan speeds (i.e., low, medium, high). The conclusions are that lower fan speeds and larger ceiling fan diameters have higher efficacies.

Key Takeaway: Lower fan speeds and larger diameters have higher efficiencies



Fan Speed	*Minimum Airflow*	*Minimum Efficacy Requirement*
low	1,250 CFM	155 CFM/watt
medium	3,000 CFM	100 CFM/watt
high	5,000 CFM	75 CFM/watt

Source: ENERGY STAR, 2016
Image Source: ENERGY STAR, 2016

LIFE CYCLE COSTS & SIMPLE PAYBACK

Life Cycle Cost (LCC) and simple payback calculations are good cost-benefit tools for evaluating alternatives. As part of DOE's analysis to amend the ceiling fan energy conservation standard for more stringency (effective March 2020), they conducted LCC analyses and simple payback calculations to understand the economic impacts to consumers of higher efficiency ceiling fans. More specifically, the initial cost of a ceiling fan with higher efficiency will likely increase but consumers will benefit from a reduction in operational costs.

In both LCC and simple payback calculations, lower values are preferred. Mathematically, LCC calculations add the total customer expense (i.e. installation, first cost, sales tax) and discounts future operational costs (i.e. maintenance, repair, operations) across the product's lifespan to time of purchase. A simple payback calculation gives the amount of time, in years, before a consumer breaks even. Simple payback is the ratio of incremental change in initial investment from a high efficiency product to a baseline divided by the change in first year operating expenses.

Key factors and results from the LCC and Simple Payback calculations used by the DOE are summarized on the subsequent pages and will likely be useful for future cost benefit analysis.

Factors	Average Value
Sales Tax	7.16%
Operating Hours	Standard Fans: 6.45 hrs/day; Large-diameter fans: 12 hrs/day
Product Lifetime	Mean: 13.8 years; Median: 13 years
Discount Rate	Residential: 5% for replacement, 3% for new installation; Commercial/Industrial: 5%

Source: U.S. Department of Energy, 2016 (c)

LIFE CYCLE COSTS & SIMPLE PAYBACK (CONT'D)

Key LCC and payback findings from the average standard fan and large diameter fan product types conducted by the DOE are organized below. Four efficiency levels above the baseline are included to show the range of results within each product type. For all efficiency levels, standard fans and large diameter fans have simple paybacks of less than 5 years with lower efficacy levels paying back in less than 1 year. The equations used to calculate Life Cycle Cost and Simple Payback are provided on the following page. The equations are based on Standard Fans with Efficiency Level 4 (EL4).

Standard Fans (blade span of 44,52 & 60 inches)

Efficiency Level (EL)	Efficacy (CFM/W)	Avg Installed Cost (2015$)	Avg First Year's Operating Cost (2015$)	Avg Lifetime Operating Cost (2015$)	Avg Life Cycle Cost (2015$)	Simple Payback (years)
Baseline[1]	44	$113.49	$16.99	$190.29	$303.79	--
1	58	$113.49	$12.75	$144.06	$257.55	<1 yr
2	64	$113.49	$11.48	$130.20	$243.70	<1 yr
3	72	$124.95	$10.33	$117.58	$242.53	1.7 yr
4	110	$158.01	$5.86	$75.92	$233.93	4 yr

[1] baseline: = flat, wood blades with an AC motor and pull chain control sizes

Large Diameter Fans (blade span of 8,12 & 20 feet)

Efficiency Level (EL)	Efficacy (CFM/W)	Avg Installed Cost (2015$)	Avg First Year's Operating Cost (2015$)	Avg Lifetime Operating Cost (2015$)	Avg Life Cycle Cost (2015$)	Simple Payback (years)
Baseline[2]	83	$4119.72	$292.21	$2921.38	$7041.10	--
1	92	$4119.72	$262.99	$2632.90	$6752.62	<1 yr
2	101	$4261.44	$239.08	$2396.87	$6658.31	2.7 yr
3	115	$4458.32	$210.14	$2110.93	$6569.25	4.1 yr
4	156	$4706.71	$156.42	$1624.11	$6330.82	4.3 yr

[2] baseline = curved aluminium blades and 3-phase induction motors

Source: U.S. Department of Energy, 2016 (c)

LIFE CYCLE COSTS & SIMPLE PAYBACK EXAMPLES

To provide information on the method that the DOE used to arrive at Average Life Cycle Cost (LCC) and Simple Payback estimates, equations and example calculations performed for a Standard Fan at an efficiency level of 4 (EL 4) are provided below.

Life Cycle Cost Equation: $LCC = IC + \sum_{t=1}^{N} OC_t / (1+r)^t$

Average Life Cycle Cost Equation*: $Avg\ LCC = Avg\ IC + Avg\ OC$

IC: Total installed cost (in dollars)
$\sum$: Summation over a lifetime, from year 0 to year N
N: Lifetime of product (in years)
OC: Operating cost (in dollars)
r: Discount rate
t: Year for which the operating cost is being determined

Simple Payback Equation: $PBP = \Delta IC / \Delta OC$

PBP: Payback period (in years)
ΔIC: Increase in the total installed cost between the more efficient equipment (EL 1, 2, 3, 4) and the baseline efficiency equipment
ΔOC: Decrease in first-year annual operating cost

Example Calculation:
Average Life Cycle Cost (Standard Fans, EL 4)

Average Life Cycle Cost Equation: $Avg\ LCC = Avg\ IC + Avg\ OC$

$$Avg\ LCC = \$158.01 + \$75.92$$

$$Avg\ LCC = \$233.93$$

*As Avg OC includes OC at each year discounted and summed over the lifetime of the product, the above Avg LCC equation is simply summing Avg IC and Avg OC together

Example Calculation:
Simple Payback Equation (Standard Fans, EL 4)

Simple Payback Equation: $PBP = \Delta IC / \Delta OC$

$$PBP = \frac{(Avg\ IC^{EL4} - Avg\ IC^{Baseline})}{\left|(Avg\ FY^*\ OC^{EL4} - Avg\ FY^*\ OC^{Baseline})\right|}$$

$$PBP = \frac{(\$158.01 - \$113.49)}{\left|(\$5.86 - \$16.99)\right|} = 4.04 \text{ years}$$

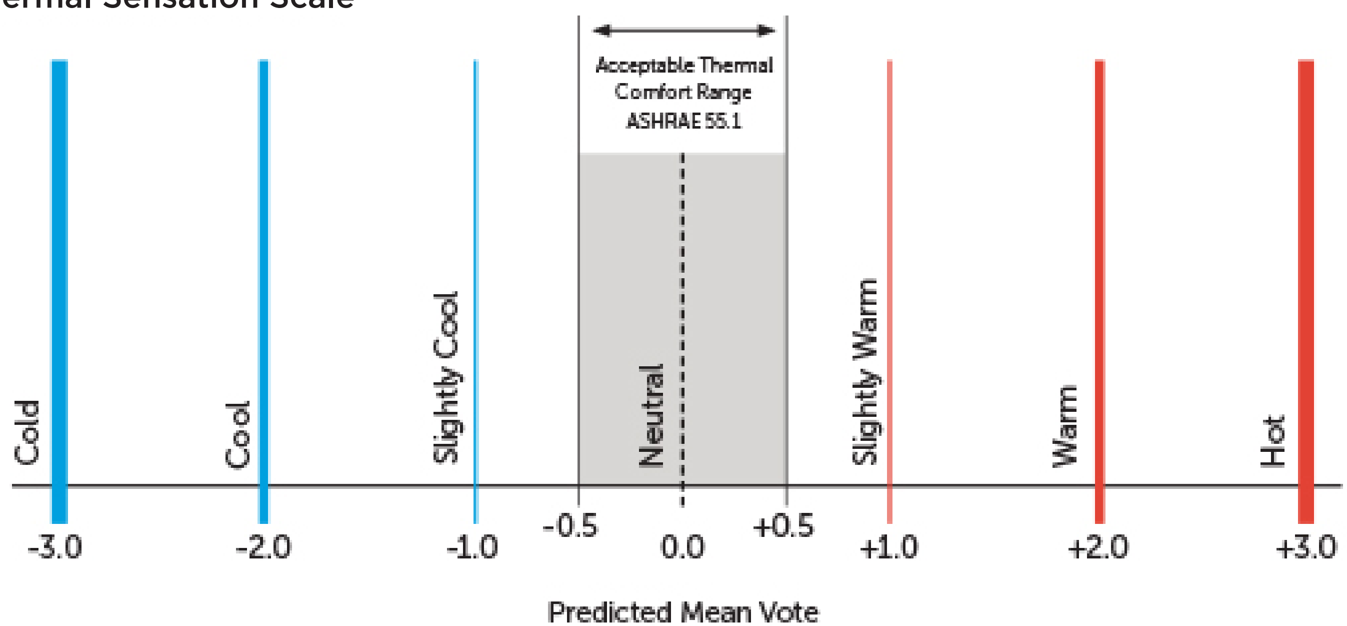
*FY: First Year

Source: U.S. Department of Energy, 2016 (c)

Thermal comfort is defined in the EN (ISO) 7730 Standard as "the mental condition that expresses satisfaction with the surrounding environment". Thermal comfort is assessed using Predicted Mean Vote (PMV), a thermal sensation scale that predicts the average value of occupants' thermal comfort ratings in a given environment.

The **six** main influencing factors involved in thermal comfort are: (1) air temperature, (2) relative humidity, (3) mean radiant temperature, (4) air speed, (5) clothing value, (6) metabolic rate. In surveys, occupant's thermal sensation ratings are recorded using a seven point-scale that ranges from cold to neutral to hot, as is shown below. The acceptable thermal comfort range denoted by ASHRAE-55 Standards falls between -0.5 and +0.5. This range represents 80% thermal occupant acceptability, where 80% of occupants are satisfied with their thermal conditions.

Thermal Sensation Scale

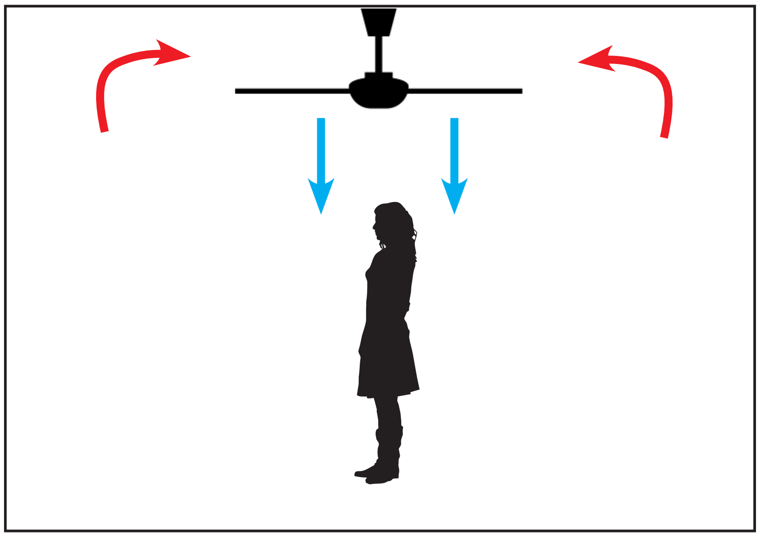


Source: Oliveira, 2012. ASHRAE, 2008
Image Source: Payette, n.d.

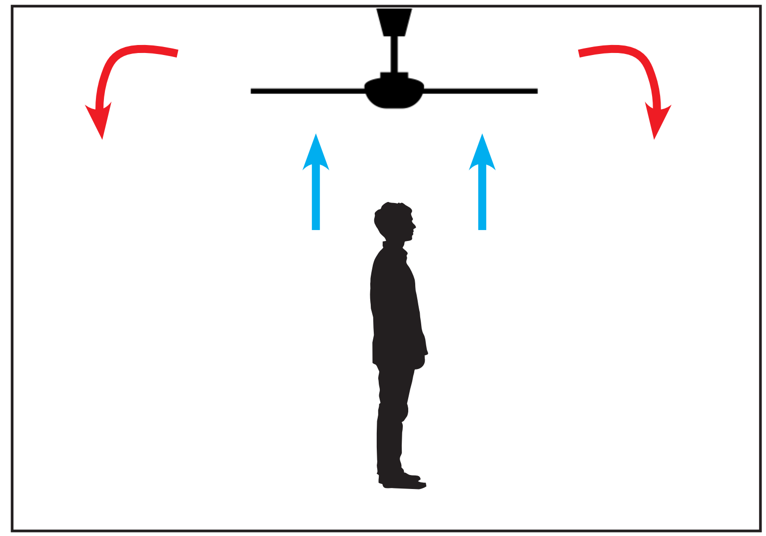
SEASONAL COMFORT OPERATIONS

Ceiling fans are intended to be used year-round, day and night. In the summer or in warm climates, fans primarily provide perceived cooling by pushing down cooler air and providing increased air movement. In the winter, the fan directs the airflow upward to circulate the warm air that has risen to the ceiling down to the occupant level.

Summer



Winter

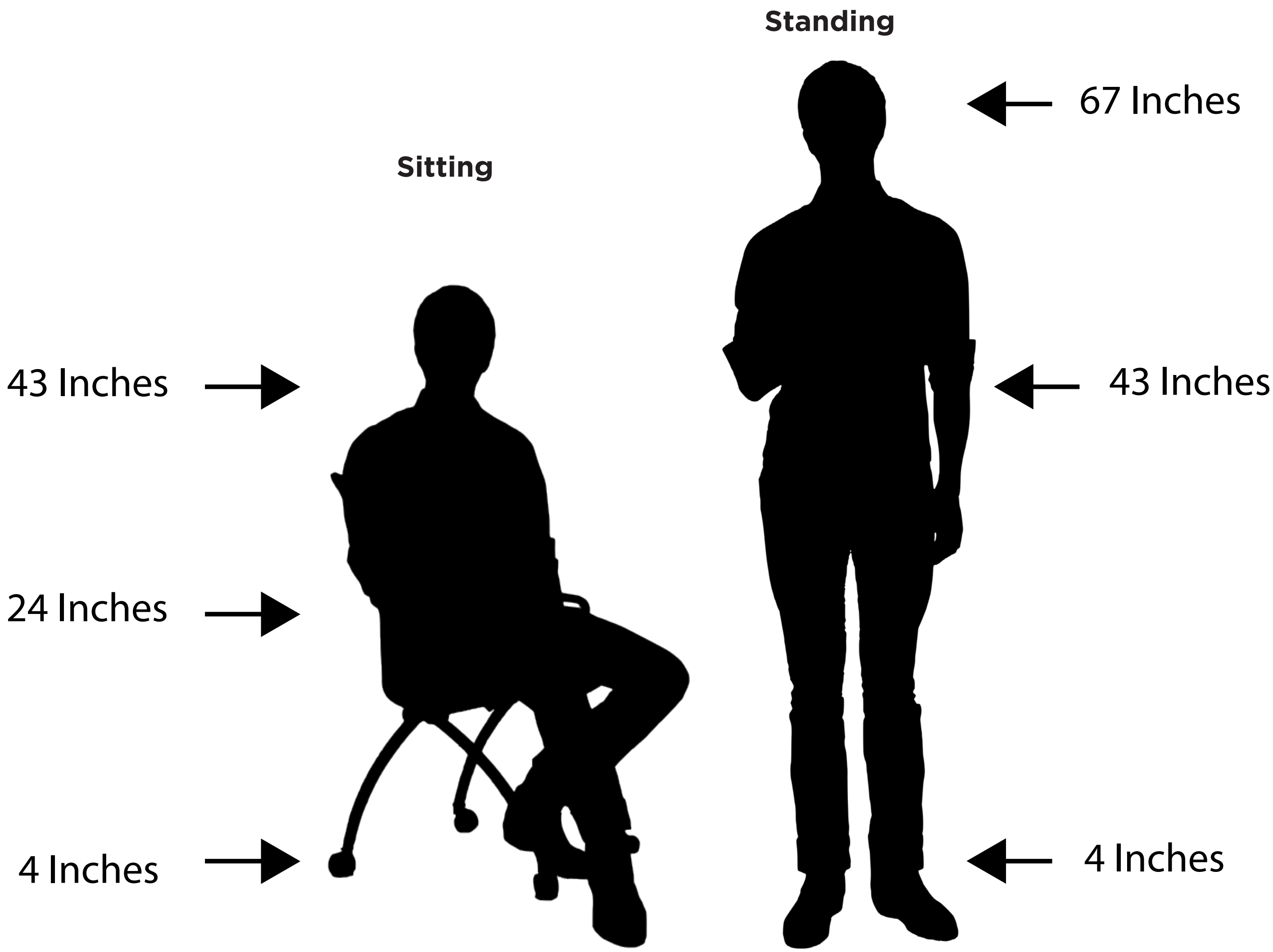


Perceived Comfort	Cooler	Warmer
Mechanism	Convection and evaporation	Air mixing which reduces vertical air stratification
Fan Speed	Varies (but often high)	Low
Fan Rotation	Forward or counterclockwise	Reverse or clockwise
Energy Impact	Increase cooling HVAC set-point temperatures (e.g. from 74°F to 78°F) which can save energy by reducing how often the cooling system is on and possibly alter the required size of the HVAC system	Reduce heating HVAC set-point temperatures (e.g. from 68°F to 65°F) which can save energy by reducing how often the heating system is on

Source: Bermudez, 2013 (b)

AIR MEASUREMENT LOCATIONS

Air temperature and average speed shall be measured at the 4 inch, 24 inch and 43 inch levels for seated occupants and at the 4 inch, 43 inch and 67 inch levels for standing occupants. These variables are measured at 3 different heights because of the stratification in air velocity and temperatures within a space. When calculating thermal comfort, the most extreme observed values should be taken.



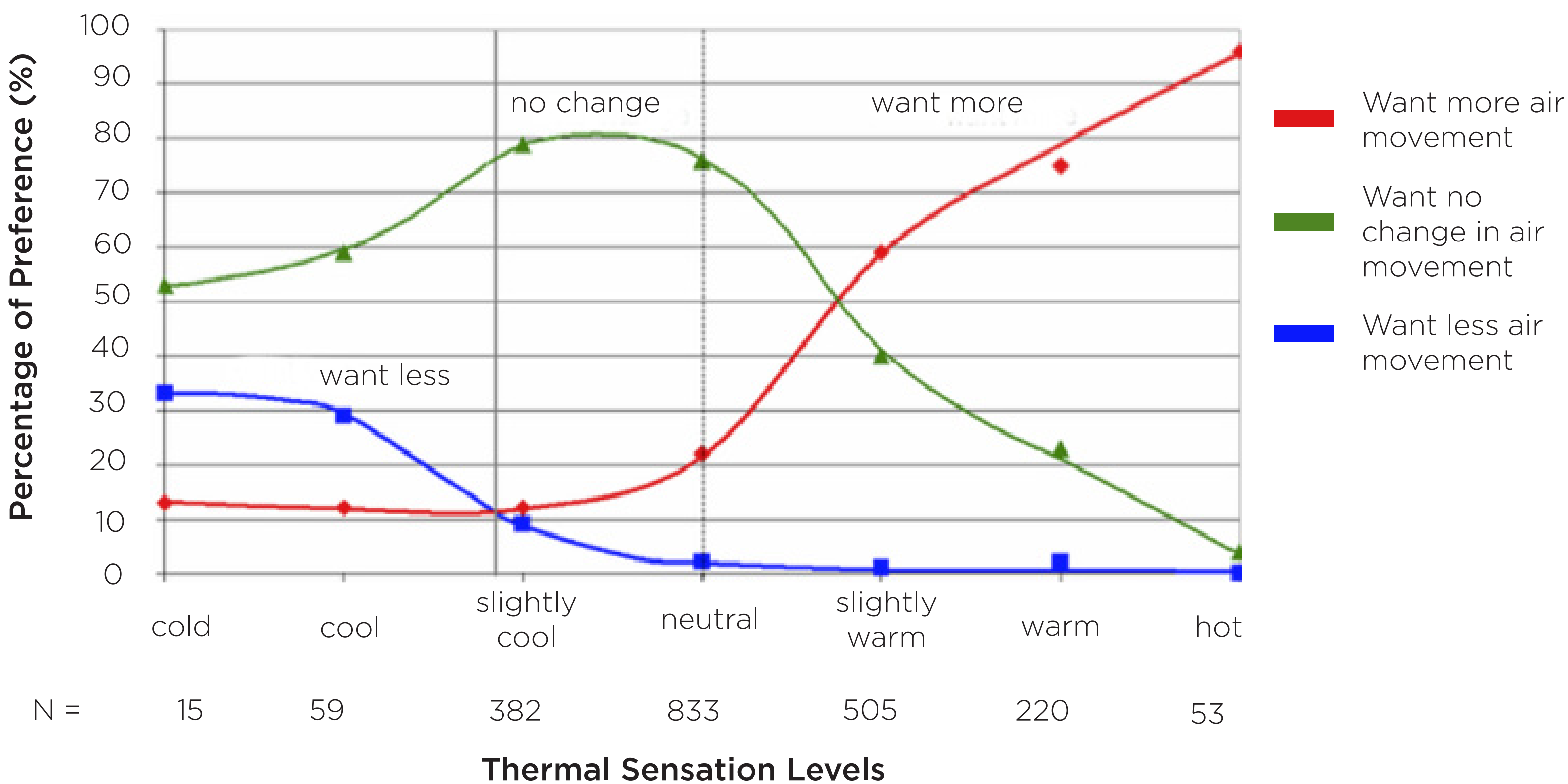
Source: ASHRAE, 2013

AIR SPEED DEMAND

Air speed, or rate of air movement is important for the comfort of occupants in indoor environments. Research has shown that there exists a need for increased air movement, especially when occupant sensation falls within the range of neutral to hot. Arens (2012) created the graphic below to understand air movement preferences by thermal sensation level. This study's findings suggest that when an environment is perceived as either neutral, slightly warm, warm or hot on the thermal sensation scale, there is a clear increasing trend or preference for more air movement.

Key Takeaway: A need for increased air movement exists in warm indoor environments

Air Movement Preference by Thermal Sensation Level



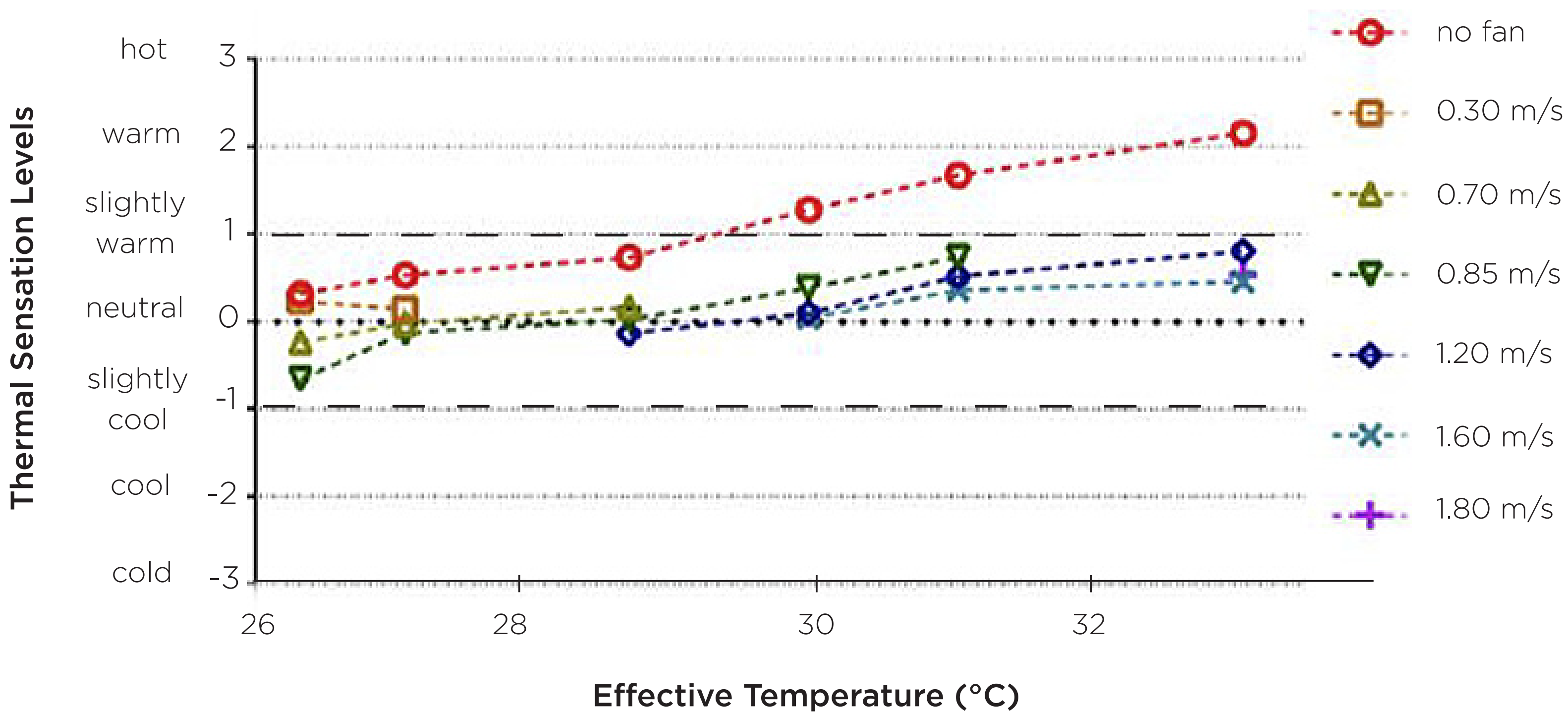
Source: Arens, 2012
Image Source: Arens, 2012

AIR SPEED IMPACT

As ceiling fans circulate air and create perceived cooling for occupants in warm indoor conditions, they are solutions for the existing need for more air movement. Tests performed in warm temperature conditions of 28°C and 30°C (82.4°F and 86°F) at all speeds and at 26°C (78.8°F) at high speeds provide evidence that air movement from ceiling fans improves thermal sensation. The figure below from Arens, et al (2013) demonstrates that the use of ceiling fans maintains thermal sensation ratings within a comfort range of 1 (slightly warm) to -1 (slightly cool) while the no fan scenario results in higher levels of reported warm sensations at each temperature condition.

Key Takeaway: Ceiling fans can improve thermal sensation ratings in warm temperature conditions

Effect of Air Movement (via fan) on Thermal Sensation

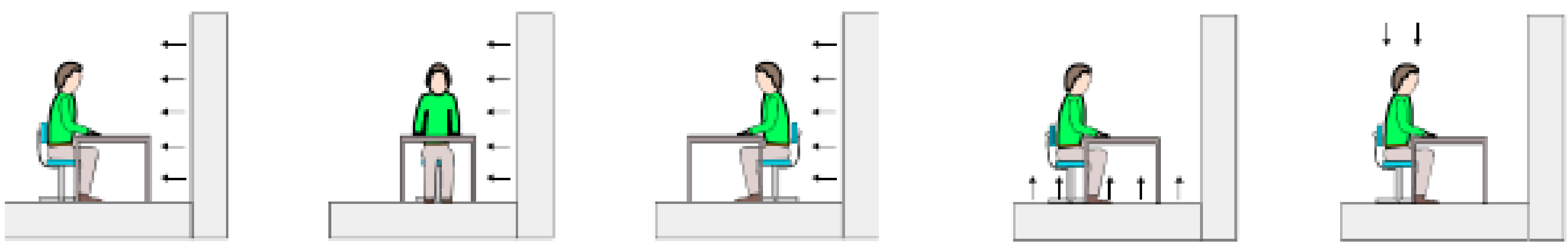


Source: Arens, et al, 2013, (k)
Image Source: Arens, et al, 2013, (k)

AIR DIRECTION

The air movement direction can differ by the type of ceiling fan used. As opposed to standard ceiling fans positioned perpendicular to the floor, dual-head ceiling fans have two opposing head fixtures that are oriented diagonally. This difference in orientation alters which part of body receives the most air movement. Airflow directed towards occupants from the front, side, back, bottom and top can be used to increase perceived cooling when focused at regions of exposed skin (e.g. face, neck, ankles, and hands). Since clothing choice varies by day and activity, optimizing the room air direction for maximum cooling is likely not practical. Furthermore, room air speed and temperature have a bigger influence on overall comfort.

Front **Side** **Back** **Bottom** **Top**



Sources: Toftum, et al, 1997. Todde, 2000, Arens, 2013 (g), Arens, 2013 (h)
Image Source: Toftum, et al., 1997

AIR INTERMITTENCY

Airflow intermittency has the possibility of increasing comfort for occupants. Intermittency can be separated into either speed or fan head oscillation. Academic studies have compared constant speed, fixed fans to speed pulse and x-axis oscillation fans, which are each defined below. There is no consensus regarding whether constant or oscillating airflow provides better thermal comfort for occupants. The table below contains findings from the experiments.

Key Takeaway: Constant fans are preferred to x-axis oscillation fans and speed-pulsing fans are preferred to constant fans, however since these three configurations have not been tested together, no definitive conclusions can be made on which configuration is best for optimizing thermal comfort

Constant: Airflow is occurring continuously in one direction and one speed setting over a period of time
Speed Pulse: Airflow is focused in one direction and cycles through multiple speed settings
X-Axis Oscillation: Airflow remains at one speed setting and the fan head moves horizontally

Article Name	Experiment Configuration	Year	Constant	Speed Pulse	X-Axis Oscill.	Findings
Enabling Energy-efficient Approaches to Thermal Comfort Using Room Air Motion	• 16 college student subjects • 11 different fan settings and air direction configurations • Surveyed rating thermal comfort and thermal sensation	2014	X		X	• No statistical differences between the 'no-fan' and X-axis oscillating fan configurations • Statistical significance found between 'no-fan' and constant fan configurations
Effects of Air Temperature, Humidity, and Air Movement on Thermal Comfort under Hot and Humid Conditions	• 64 college aged students • 7 different air movement patterns: constant, pulse, random • Surveyed rating thermal sensation	1994	X	X		• Statistically significant results show pulsing air speeds provides more perceived cooling than constant air velocity
A Study of Occupant Cooling by Personally Controlled Air Movement	• 119 subjects • Range of warm temperatures and air movements • Surveyed preferences regarding air movement	1998	X		X	• Statistically significant results show that constant mode cools better than X-axis oscillation mode at the same mean wind speed

Sources: Pasut, et al, 2014. Tanabe, et al, 1994. Arens, et al, 1998, Arens, 2013 (i)

ALLIESTHESIA

Alliesthesia is the phenomenon that describes pleasure as a result of changes in body temperature. Different types of alliesthesia exist, and those most related to thermal comfort are spatial and thermal alliesthesia, both of which are explained below. With the emergence of new ceiling fan capabilities such as oscillating fans and intermittent speed settings, ceiling fans are increasingly capable of inducing alliesthesia or pleasurable sensastions for occupants within a space.

Thermal alliesthesia describes the sensation that results from a new stimulus such as air movement and a subject's temperature state. For positive thermal alliesthesia to take place, two things need to occur: (1) the body needs to be in a non-neutral state, at minimum a slightly warm or slightly cool state, and (2) the stimulus needs to restore the body in the direction of its neutral state. For instance, if a subject's current temperature is warm or higher than their neutral state temperature, introducing a ceiling fan will cause a positive sensation or a 'pleasant breeze' as it will restore the body to its neutral state. However, if a subject's current temperature is cool, or lower than their neutral state temperature, introducing a ceiling fan will now cause thermal displeasure or an 'unpleasant draft', as it makes the occupant even colder.

Spatial alliesthesia is the pleasure that arises from differences in temperature across the skin's surface. Just as with thermal alliesthesia, positive sensations occur when the heating or cooling stimulus is in the opposite direction of the initial body state and closer to the neutral state. Recent studies have found that small variations in skin temperature created with localized stimuli can result in positive pleasure sensation, therefore targeting certain body parts simultaneously with personalized heating or cooling systems such as desk or ceiling fans can create pleasurable sensations. An example of spatial alliesthesia is a pleasure that arises from a wind breeze on the face during a hot day.

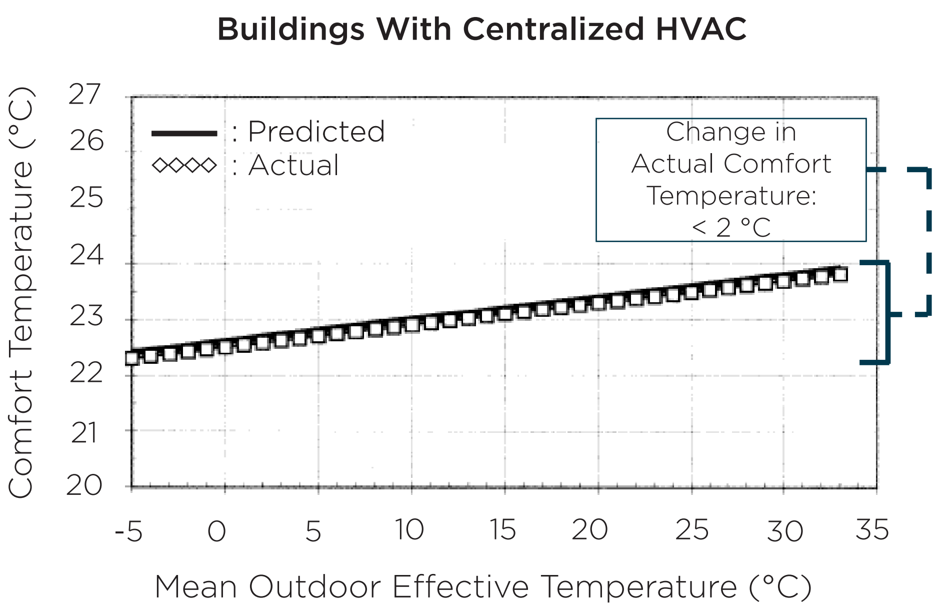
In practice, designing for spatial alliesthesia is more appealing than for thermal alliesthesia as it does not necessitate intentionally creating an uncomfortable situation which is then to be corrected for, and rather is based on assessing the benefits of stimulus directed at specific body parts.

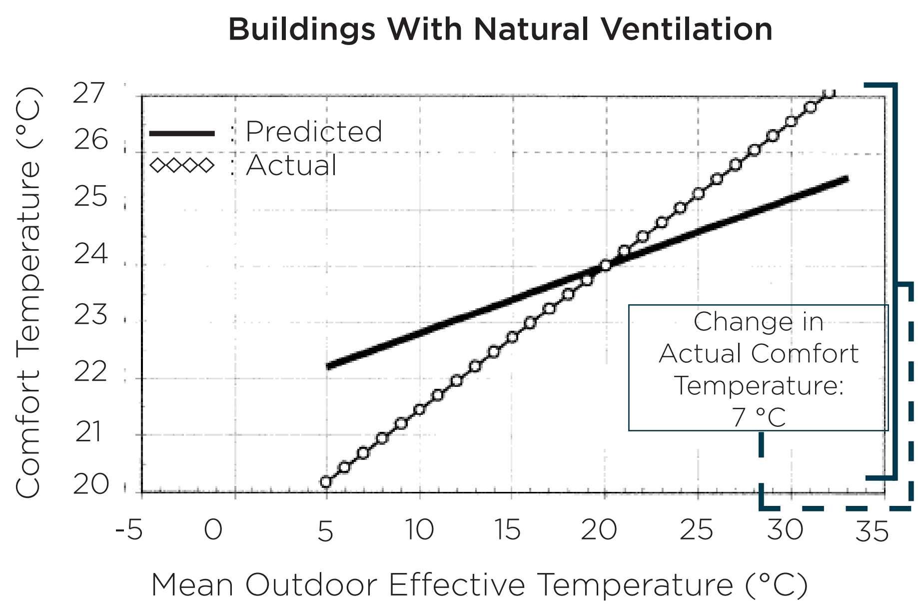
Sources: De Dear, 2015. Parkinson, et al, 2012. De Dear, n.d. Parkinson, et al, 2016 (a). De Dear, 2011. Parkinson, et al, 2014. De Dear, et al, 1998. De Dear, 2009. Brager, et al, 2015

FIXED VS. DYNAMIC INDOOR ENVIRONMENTS

Alliesthesia can occur when a variable stimulus, such as air movement interrupts an occupant's static environment. Ceiling fans provide opportunities for creating dynamic environments as they are capable of providing intermittent air movement. Newer control modes such as the Haiku Whoosh mode automatically alters speeds at different times throughout the day to simulate natural breezes and create variability in air movement. Moreover, findings from a research study (shown below) seeking to understand comfort in fixed or dynamic environments suggests that occupants in naturally ventilated buildings are able to tolerate a wider comfort temperature range than occupants in buildings with centralized, HVAC systems. The likely explanation is that the wider range of adaptive opportunities provided with natural ventilation systems, such as variability and dynamic stimulus from vents and operable windows leads to greater comfort even with warmer temperatures. Therefore, providing intermittent air movement with ceiling fans as a way to replicate natural breezes may increase how often pleasurable sensations are felt, which can improve the overall thermal comfort level of occupants.

Key Takeaway: Occupants in variable and dynamic indoor environments are able to remain comfortable in warmer temperatures





Source: De Dear, et al, 1998
Image Source: De Dear, et al, 1998

6

Literature Review

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LITERATURE REVIEW INTRODUCTION

Compiled in the following pages is a literature review that contains all the sources and articles read in support of Subtask 1a and Subtask 1b research. The intent of the literature review is to provide an overview and transparency into the types of sources used so others may build off the knowledge assembled.

The literature review is comprised of three main parts. First, the source diversity and content diversity summaries provide a snapshot into the range of sources and topics covered to quickly convey the scale of research. Second, there is an bibliography separated into articles, images and personal conversations with manufacturers and industry professionals. Some of the article references are specifically cited in the report while others were used for context only. Lastly, an acronym list is included for easy referral.

Also, there is a literature review containing a comprehensive summary of all the articles reviewed including a brief abstract and key takeaways from each article. This information is available in a excel and not included in this report due to its size.

SOURCE DIVERSITY

Diversity of sources used for Subtask 1a, Market Assessment and Subtask 1b, Technical Assessment research.

Source Type	Unique Sources	Reference Count
Government [e.g. EPA, DOE, NREL, CARB]	13	18
Academia [e.g. CBE]	36	61
Manufacturers [e.g. BAF, Del Mar]	20	50
Other [e.g. trade organizations]	49	66
Total	**118**	**195**

ARTICLE CONTENT DIVERSITY

Diversity of article content used for Subtask 1a, Market Assessment and Subtask 1b, Technical Assessment. Articles can include information across many content areas.

Source Type	Reference Count	Content Category: Design Product	Design Application	Thermal Comfort	Energy
Government [e.g. EPA, DOE, NREL, CARB]	18	5	9	4	9
Academia [e.g. CBE]	61	8	24	49	8
Manufacturers [e.g. BAF, Del Mar]	50	27	28	1	0
Other [e.g. trade organizations]	66	29	31	10	10
Total	195	**69**	**92**	**64**	**27**

ARTICLE BIBLIOGRAPHY

Acer Trading Group (2017) Universal 3-Speed Ceiling Fan Control. Acer Trading Group. Retrieved from https://www.acertrading.com/collections/electrical-supplies-main/products/ceiling-fan-control-variable-speed-downdraft

Adeeb, Maqsood, Mushtaq (2015) Effect of Number of Blades on Performance of Ceiling Fans. National University of Sciences & Technology.

Adeeb, Maqsood, Sohn (2016). Parametric Study and Optimization of Ceiling Fan Blades for Improved Aerodynamic Performance. National University of Sciences and Technology, Islamaba

Allianz Risk Consulting (2012) High Volume Low Speed Fans in Sprinklered Buildings. Retrieved from http://www.agcs.allianz.com/assets/PDFs/ARC/Tech%20Talks/TTVol3-HVLSFansinSprinkleredBuildings_English.pdf

American Lighting Association (2014) Stay Cool with a Ceiling Fan as Stylish as it is Functional. Retrieved from http://blog.americanlightingassoc.com/stay-cool-with-a-ceiling-fan-as-stylish-as-it-is-functional/?doing_wp_cron=1502396903.9460790157318115234375

American Lighting Association (2016) Stay Cool for Next to Nothing. Retrieved from https://www.americanlightingassoc.com/About-ALA/Press-Releases/National-Ceiling-Fan-Day.aspx

Arens, Edward, Xu, Tengfang. Miura, Katsuhiro, Hui, Zhang. Fountain, Marc, Bauman, Fred (1998) A Study Of Occupant Cooling by Personally Controlled Air Movement. Energy and Buildings

Arens, Edwards (2012) Assessment of Indoor Environments. Center for the Built Environment. Retrieved from https://www.researchgate.net/profile/Edward_Arens/publication/228755012_Assessment_of_Indoor_Environments/links/56ec782e08aed17d09f64a84/Assessment-of-Indoor-Environments.pdf

Arens, Edwards (2013, a) Analysis of Energy Savings Enabled By Use of Fans. Center for the Built Environment

Arens, Edwards (2013, b) Ceiling-integrated Fan Mockups. Center for the Built Environment

Arens, Edwards (2013, c) Comparison With Whole-body Heat Balance Models Under Airflow (desk fans). Center for the Built Environment

Arens, Edwards (2013, d) Evaluating HeatTransfer Performance of Radiant Slab Systems with Acoustical Panels and Integrated Fans. Center for the Built Environment

Arens, Edwards (2013, e) Fan Velocity Performance Evaluation. Center for the Built Environment

ARTICLE BIBLIOGRAPHY

Arens, Edwards (2013, f) Field Studies of Naturally Ventilated or Mixed Mode Office Buildings with Ceiling Fans. Center for the Built Environment

Arens, Edwards (2013, g) Human Comfort and Perceived Air Quality in Hot And Humid Conditions With Horizontal Airflow. Center for the Built Environment

Arens, Edwards (2013, h) Human Comfort and Perceived Air Quality in Hot and Humid Conditions with Vertical Airflow. Center for the Built Environment

Arens, Edwards (2013, i) Human Comfort and Perceived Air Quality with an Oscillating Ceiling Fan. Center for the Built Environment

Arens, Edwards (2013, j) Oakland School Classrooms With Ceiling Fans. Center for the Built Environment

Arens, Edwards., Turner, S., Zhang, H., Paliaga, G. (2009). Moving Air For Comfort. ASHRAE journal, 51(5), 18.

Arens, Edwards, Zhang, Hui, Pasut, Wilmer, Zhai, Yongchao, Hoyt, Tyler, Huang, Li (2013, k) Air Movement As An Energy Efficient Means Toward Occupant Comfort. Center for the Built Environment. Retrieved from https://www.arb.ca.gov/research/apr/past/10-308.pdf

ASHRAE (2008) ASHRAE Standard: Proposed Addendum d to Standard 55-2004, Thermal Environmental Conditions for Human Occupancy. Retrieved from https://osr.ashrae.org/Public%20Review%20Draft%20Standards%20Lib/Add-55-2004-d-PPR1-Draft%20(chair-approved).pdf

ASHRAE (2013) Standard 55 -- Thermal Environmental Conditions for Human Occupancy. Retrieved from https://www.ashrae.org/resources--publications/bookstore/standard-55-and-user-s-manual

ASHRAE (2017) Titles, Purposes and Scopes, July 2017. Retrieved from https://www.ashrae.org/standards-research--technology/standards--guidelines/titles-purposes-and-scopes#spc216p

Attiaa, S. & Carluccib, S. (2015). Impact of Different Thermal Comfort Models On Zero Energy Residential Buildings in Hot Climate. Energy and Buildings 102, 117–128

Aynsley. R., (2008). The Thrust of ANSI/AMCA 230-07. AMCA International Engineering Conference, Las Vegas, NV

Bangaleea, M.Z.I., Lina, S.Y., Miau, J.J. (2012). Wind Driven Natural Ventilation Through Multiple Windows of Building: A Computational Approach. Energy and Buildings 45, 317–325.

ARTICLE BIBLIOGRAPHY

Baskaya, S. & Eken, E. (2003). Investigation Of Room Air Flow Regarding Effects of Occupants, Inlet/Outlet Locations, Inlet Velocity, and Winter/Summer Conditions. Int Comm. Heat Mass Transfer, Vol. 30, No.8, 1147-1156.

Bassiouny, R., Korah, N.S. (2011). Studying The Features of Air Flow Induced by a Room Ceiling Fan. Energy and Buildings 43, 1913–1918.

Begg, George (2012) Trust and Quality in CFD. The University of Manchester. Retrieved from http://cfd.mace.manchester.ac.uk/twiki/pub/Main/TimCraftNotes_All_Access/cfd2-trust-quality.pdf

Bermudez, Mara (2013, a) What Are the Best Types of Fans for a Home? Del Mar Fans & Lighting. Retrieved from http://www.delmarfans.com/educate/basics/best-types-of-fans-for-a-home/

Bermudez, Mara (2013, b) What is the Proper Ceiling Fan Direction? Del Mar Fans & Lighting. Retrieved from http://www.delmarfans.com/educate/basics/what-is-the-proper-ceiling-fan-direction/

Bermudez, Mara (2014) Smart, Automated and Modern: the Haiku SenseME. Del Mar Fans & Lighting. Retrieved from http://www.delmarfans.com/educate/basics/what-size-downrod-do-i-need/

Bermudez, Mara (2016, a) Ceiling Fan Size Guide - How to Measure and Size a Fan for Any Room. Retrieved from http://www.delmarfans.com/educate/basics/what-size-ceiling-fan-do-i-need/

Bermudez, Mara (2016, b) What Size Ceiling Fan Downrod Do I Need? Del Mar Fans & Lighting. Retrieved from http://www.delmarfans.com/educate/basics/what-size-downrod-do-i-need/

Best Ceiling Fans (n.d.) Low Ceilings? There is a Ceiling Fan For That. Retrieved from http://bestceilingfans.info/articles/ceiling-fans-for-low-ceilings/

Big Ass Solutions (2013, a) Haiku Installation Guide. Retrieved from http://docs.bigassfans.com/haiku/Haiku-Install-Guide-S1-SG-MY.pdf

Big Ass Solutions (2013, b) Haiku® Wall Control Kit. Retrieved from http://www.bigassfans.com/images/Haiku-Wireless-Wall-Control-Installation.pdf

Big Ass Solutions (2014, a) Big Ass Fans Introduces the World's First Smart Ceiling Fan. Retrieved from http://www.bigassfans.com/big-ass-fans-introduces-worlds-first-smart-ceiling-fan/

Big Ass Solutions (2014, b) Big Ass Fan 4900 Installation Guide. Retrieved from http://www.homedepot.com/catalog/pdfImages/c4/c49ba7fb-979b-4791-b532-82655a0bba00.pdf

Big Ass Solutions (2016, a) BAF Works - Technical Specifications. Retrieved from http://docs.bigassfans.com/tech-specs/BAFWorks-Spec-Sheet.pdf?_ga=2.25787390.25398060.1500324010-1192055596.1499383574

Big Ass Solutions (2016, b) Fan Distance Guidelines.

Big Ass Solutions (2016, c) Haiku Wall Control with SenseME Technology - Technical Specifications. Retrieved from https://cdn.haikuhome.com/media/pdf/HaikuHome_CutSheet_HaikuWallControl.pdf?pdf=Cut-Sheet&_ga=2.224840346.1266234368.1500309494-1192055596.1499383574

Big Ass Solutions (2016, d) Smart Sense - Technical Specifications. Retrieved from http://docs.bigassfans.com/tech-specs/SmartSense-Specs.pdf?_ga=2.99655261.25398060.1500324010-1192055596.1499383574

Big Ass Solutions (n.d., a) Haiku H Series Fans Technical Specifications. Retrieved from https://www.haikuhome.com/media/pdf/HaikuHome_CutSheet_HSeries_Haiku52.pdf?_ga=2.99363607.824702709.1499706433-1192055596.1499383574

Big Ass Solutions (n.d., b) Haiku Wall Control Specifications. Retrieved from http://docs.bigassfans.com/haiku/Haiku-Wall-Control.pdf

BladeTec Fans (n.d.) High Volume, Low Speed Fans (HVLS). Retrieved from http://www.bladetecfans.com/uploads/BladeTec_Brochure_June2012.pdf

Blogbyusha (2015) Ceiling Fan Buying Guide. USHA. Retrieved from https://blogbyusha.com/2015/02/28/buying-guide-of-ceiling-fans/

Blue Giant (2017) Airflow HVLS Fans - Climate Control for Commercial and Industrial Facilities. Retrieved from http://www.bluegiant.com/Files/Brochures/HVLS-Fans/HVLS_Fans_SelectionGuide_WEB.aspx

Bodine Electric Company (2003) Small Motor, Gearmotor and Control Handbook. Retrieved from http://www.et.byu.edu/~chasek/ME%20472/Motors/Bodine%20Handbook/bodine_chap03.pdf

Brager, Gail; Zhang, Hui; Arens, Edward (2015) Evolving Opportunities for Providing Thermal Comfort. Center for the Built Environment. Retrieved from http://escholarship.org/uc/item/77c0q85j#page-1

CaptiveAire (n.d.) Fan Calculator: How to Calculate the Number of Fans. Retrieved from https://www.captiveaire.com/CatalogContent/Fans/HVLS/HVLS_FanCalculator.asp?catId=444&Model=CA%2DHVLS

ARTICLE BIBLIOGRAPHY

Casablanca Fan Company (2014) Tribeca: Owner's Guide and Installation Manual. Retrieved from https://content.abt.com/documents/77202/HTRC59505_manual.pdf

Ceiling Fan Select (2017) Buying the Right Size Ceiling Fan. Retrieved from http://www.ceilingfansselect.com/buying-right-size-ceiling-fan/

CeilingFan.com (2017) Ceiling Fans Blade Pitch. Retrieved from https://www.ceilingfan.com/Ceiling-Fans-Blade-Pitch-s/1618.htm

CeilingFan.com (n.d., a) Choose the Right Ceiling Fan Downrod Length. Retrieved from https://www.ceilingfan.com/Choose-Ceiling-Fan-Downrod-Length-s/1709.htm

CeilingFan.com (n.d., b) Choose The Right Size Ceiling fan for YOUR Room. Retrieved from https://www.ceilingfan.com/Choose-the-Right-Size-Ceiling-Fan-s/1710.htm"

CeilingFan.Org (2000) How to Buy a Ceiling Fan: Part Three. Retrieved from http://www.ceilingfan.org/how-to-buy-a-ceiling-fan-part-three/

Cham (n.d.) Introduction to Computational Fluid Dynamics. Retrieved from http://www.cham.co.uk/phoenics/d_polis/d_info/cfdintro.htm#target2

Chen, Qingyan (Yan) (n.d.) How to correctly use CFD as a tool for ventilation design? American Industrial Hygiene Association (AIHA). Retrieved from https://www.aiha.org/aihce06/handouts/d2chen.pdf

Cheng, Yong, Zhang Lin, and Alan M.I. Fong (2015) Effects of Temperature and Supply Airflow Rate on Thermal Comfort in a Stratum-ventilated Room. Building and Environment 92: 269-77

Chester (2016) Hunter SIMPLEconnect Bluetooth Remote Control Pack Review. Retrieved from http://thegadget.reviews/hunter-fan-simpleconnect-bluetooth-remote-control/

City of Colorado Springs (n.d.) Plans Reviewed by Fire. Retrieved from https://www.springsgov.com/units/fire/Prevent/PlansReview/FPS_20121152-SP-1.asp?Print=True

CLEAR: Comfortable Low Energy Architecture (n.d.) Adaptive Opportunity Retrieved from https://www.new-learn.info/packages/clear/thermal/people/introduction/adaptive_opportunity.html

Davis Energy Group, Energy Solutions. (2004). Analysis of Standards Options for Ceiling Fans

ARTICLE BIBLIOGRAPHY

De Dear, Richard (2009) Thermal Comfort in Natural Ventilation - A Neurophysiological Hypothesis. University of Sydney, Australia. Retrieved from http://anzasca.net/wp-content/uploads/2015/12/ANZAScA_2009_deDear.pdf

De Dear, Richard (2011) Revisiting an Old Hypothesis of human Thermal Perception: Alliesthesia. Building Research and Information. Retrieved from https://www.researchgate.net/profile/Richard_De_Dear/publication/239789766_Revisiting_an_old_hypothesis_of_human_thermal_perception_Alliesthesia/links/0a85e53b2096bdc660000000/Revisiting-an-old-hypothesis-of-human-thermal-perception-Alliesthesia.pdf

De Dear, Richard (2015) Urban Thermal Comfort: Counterpoint and Alliesthesia. The Chinese University of Hong Kong. Presentation. Retrieved from http://web5.arch.cuhk.edu.hk/asi2015/en/Sources/lecture/ASI%202%20-%20Richard%20de%20Dear%20-%20Part%202.pdf

De Dear, Richard; Brager, G. S (1998) Developing an Adapative Model of Thermal Comfort and Preference Center for the Built Environment. Retrieved from http://escholarship.org/uc/item/4qq2p9c6#page-1

Department of Safety & Professional Services (DSPS) - Wisconsin (n.d.) NFPA 13R / 13D. Presentation. Retrieved from http://www.dsps.wi.gov/Documents/Industry%20Services/Forms/Commercial%20Buildings/13R%20vs.%2013D%20Sprinkler%20Systems.pdf

Duke, Bob (2002) HOME OFFICE : Knowing Electrical Limits Can Keep You From Blowing a Fuse. Retrieved from http://articles.latimes.com/1992-08-01/home/hm-4199_1_home-office

E3T: Energy Efficiency Emerging Technologies (n.d) High-Volume, Low-Speed Fans. Retrieved from http://e3tnw.org/ItemDetail.aspx?id=620

EM Reno Blog (2012) Preventing 'Strobing' Effect From Ceiling Fans. Retrieved from https://emrenoblog.wordpress.com/2012/02/02/preventing-strobing-effect-from-ceiling-fans/

Energy Information Administration (2017) Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector. <https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a> Accessed August 2017

ENERGY STAR (2012-2015) ENERGY STAR Unit Shipment and Market Penetration Report

ENERGY STAR (2016) ENERGY STAR® Ceiling Fan Product Specification Review February 2016. Retrieved from https://www.energystar.gov/sites/default/files/asset/document/Ceiling%20Fan%202016%20Product%20Review.pdf

Engineered Air Solutions (2017) HVLS 101. Retrieved from http://engineeredairsolutions.com/lines/hvls-101/

English, Trevor (2017) A Look at the History of Computational Fluid Dynamics. The Short Sleeve and Tie Club. Retrieved from http://shortsleeveandtieclub.com/a-look-at-the-history-of-computational-fluid-dynamics/

Entrematic Fans (2014) Wave HVLS Fans Specifications. Retrieved from http://kelleyentrematic.com/assets/KCB-FHVLS-0414_w.pdf

Entrematic Fans (2016, a) Industrial HVLS Fan User's Manual. Retrieved from http://entrematicfans.com/assets/6015653H_Industrial_Industrial_HVLS-FAN-USER-MANUAL_January2017.pdf

Entrematic Fans (2016, b) White Paper - HVLS Industrial Fans Evaluation Guide: 7 Defining Application Design Factors That Will Add Up to a Smart Investment. Retrieved from http://entrematicfans.com/assets/HVLS-Industrial-Fans-Evaluation-Guide_Entrematic-Fans.pdf

EnviroFan (n.d., a) Envirofan Adjustable Speed Controls Installation and Operating Instructions. Retrieved from http://www.envirofan.com/Documents/scall4one.pdf

EnviroFan (n.d., b) Recommended Fan Spacing for Various Ceiling Heights. Retrieved from http://www.envirofan.com/documents/efspace.pdf

Eubanks, Brent, Friedman, Glenn (2014) Climate- Adapted Design for California School. ASHRAE Journal

Fanimation (n.d., a) Fanimation Caruso FP7000** Ceiling Fan Specifications. Retrieved from http://www.fanimation.com/files/3414/5240/6201/Caruso_FP7000_Spec_Sheet.pdf

Fanimation (n.d., b) SPITFIRE TMMA6721** Ceiling Fan Specifications. Retrieved from http://www.fanimation.com/files/6714/8847/8437/MA6721_Spitfire_Spec_Sheet_03_02_17.pdf

Faninfl, Buckeye (2017) Residential Pendent Sprinkler Head Spacing With Surface Mounted Lights and Ceiling Fans. The Fire Sprinkler Designer. Retrieved from http://thefiresprinklerdesigner.com/residential-pendent-sprinkler-head-spacing-with-surface-mounted-lights-and-ceiling-fans/

Franke, Jörg; Hellsten, Antti; Schlünzen, Heinke; Carissimo, Bertrand (2007) Best Practice Guideline For the CFD Simulation of Flows in the Urban Environment. Retrieved from http://theairshed.com/pdf/COST%20732%20Best%20Practice%20Guideline%20May%202007.pdf

Fulpagare, Togesh S., and Neeraj Agrawal (2013) Experimental Investigation on Room Air Flow Pattern & Thermal Comfort Quantification.Technological University Lonere, India. International Journal of Engineering Sciences & Emerging Technologies 6.1. 120-32.

ARTICLE BIBLIOGRAPHY

Gescan (2013) Industrial Ceiling Fan Controls. Retrieved from https://cdn.gescan.com/media/product-specifications/CAWFRMC5/o9k6mt-canarm-frmc5-specification.pdf

Gossamer Wind (n.d) What is So Special About These Fans? Retrieved from http://www.gossamerwind.com/content/what-so-special-about-these-fans-0

Gromicko, Nick (n.d.) Ceiling Fan Inspection. International Association of Certified Home Inspection (IACHI). Retrieved from https://www.nachi.org/ceiling-fan-inspection.htm

Gungor, Kemal (2015) Sources of errors for indoor air CFD simulations. Norman Disney & Young. Retrieved from http://www.ndy.com/sites/default/files/CFD_paper_Part1.pdf

Haiku Home (2015) Haiku Home Owner's Manual. Haiku Home. Retrieved from https://www.haikuhome.com/media/pdf/Haiku-H-and-I-Series-Owners-Manual.pdf

Haiku Home (2017) Haiku Remote Control. Haiku Home. Retrieved from https://www.haikuhome.com/haikuremotecontrol

Hansen Wholesale (n.d., a) Dual Head Ceiling Fan. Retrieved from http://www.hansenwholesale.com/ceiling-fans/shop-by-type/dual-head

Hansen Wholesale (n.d., b) How to Position 2 Ceiling Fans in a Single Room. Retrieved from http://www.hansenwholesale.com/ceiling-fans/multiple-ceiling-fan-positioning

Hawaii State Energy Office (n.d.) Ceiling Fans. Retrieved from https://energy.hawaii.gov/wp-content/uploads/2016/07/Ceiling-Fans-Factsheet_final.pdf

Henley Fan (2013) DC vs AC Ceiling Fans. Retrieved from https://www.henleyfan.com/blog/dc-vs-ac-ceiling-fans/

Ho, S. H., Rosario, L., Rahman, M.M. (2009). Thermal Comfort Enhancement by Using a Ceiling Fan. Energy and Buildings 117, 246–259.

Hollist, Jonathan (2017) How To Test Fan Performance (AMCA 230-15). MacroAir Fans. Retrieved From https://macroairfans.com/blog/how-to-test-fan-performance/

Home Depot (2015) Hunter Fan: SimpleConnect - Add-On Receiver Model 99106 Installation Guide. Retrieved from http://www.homedepot.com/catalog/pdfImages/2c/2cbb3ab8-cabd-4937-bc31-f66ad7925a06.pdf

ARTICLE BIBLIOGRAPHY

Home Depot (n.d.) How to Buy Electric Panels. Retrieved from http://www.homedepot.com/c/which_breaker_box_is_right_for_your_home_HT_BG_EL

Home Depot (n.d.) Universal 3-Speed Ceiling Fan Control. Home Depot. Retrieved from http://www.homedepot.com/p/Universal-3-Speed-Ceiling-Fan-Control-99110/203689999

Home Depot (n.d.) Universal On and Off Ceiling Fan Remote Control. Home Depot. Retrieved from http://www.homedepot.com/p/Universal-On-and-Off-Ceiling-Fan-Remote-Control-99112/203689998

Hunter Fan (2002) Installation Instructions for Hunter Original Ceiling Fans. Retrieved from http://www.hunterfan.com/supportdocuments/ownersmanuals/41569.pdf

Hunter Fan (2013) How to Properly Install Multiple Remote-Controlled Fans. Retrieved from http://www.hunterfan.com/getattachment/937ef4aa-e948-45fe-9cac-80c29c392ecc/MultiplePlatformRemotesEnglish.pdf

Hunter Fan (2015) SimpleConnect Programmable Control Model 99107 Installation and Setup Guide. Retrieved from http://www.hunterfan.com/HunterFan/media/SiteDocuments/SimpleConnect-Installation-and-Setup-Guide-99107.pdf

Hunter Fan (2016) Hunter Fan: Installation and Operation Manual. Retrieved from http://www.hunterfan.com/SupportDocuments/OwnersManuals/M3514-01.pdf

Hunter Fan (n.d.) MIDDLEBURYTM Owner's Manual. Retrieved from http://www.hunterfan.com/SupportDocuments/OwnersManuals/Middlebury_v4.pdf

Hunter Fan Store (n.d.) Model 22394 Original Multiple Fan Speed Control Specifications. Retrieved from https://www.hunterceilingfanstore.com/139649-2875-Model-22394-Original-Multiple-Fan-Speed-Control

Jameson, Antony (n.d.) Computational Fluid Dynamics Past, Present and Future. Stanford University. Retrieved from http://aero-comlab.stanford.edu/Papers/NASA_Presentation_20121030.pdf

Judkoff, R. Neymark, J (2006) Model Validation and Testing: The Methodological Foundation of ASHRAE Standard 140. National Renewable Energy Laboratory (NREL). Retrieved from http://www.nrel.gov/docs/fy06osti/40360.pdf

Kabanshi, Alan, Hans Wigo, and Mats Sandberg (2016) Experimental Evaluation of an Intermittent Air Supply System Part 1: Thermal Comfort and Ventilation Efficiency Measurements. Building and Environment 95: 240-50.

ARTICLE BIBLIOGRAPHY

Kabanshi, Alan, Hans Wigo, Robert Ljung, and Patrik Sorqvist. (2016) Experimental Evaluation of an Intermittent Air Supply System Part 2: Occupant Perception of Thermal Climate. Building and Environment 108: 99-109

Kammel D.W., M.E, Raabe, J. J. Kappelman (n.d.) Design of High Volume Low Speed Fan Supplemental Cooling System in Dairy Free Stall Barns. Wisconsin Public Service. Retrieved from http://www.wisconsinpublicservice.com/business/pdf/efficient_equipment_uwstudy.pdf

Kiatreungwattana, K., Deru, M., Degraw, J. (2016) GSA Green Proving Ground Smart Ceiling Fan White Paper. National Renewable Energy Laboratory

Kinnear, David; MA, Atherton; MW, Collins, Dokhan, J, TG, Karayiannis (2006) Colour in Visualisation for Computational Fluid Dynamics. Brunel University London. Retrieved from http://bura.brunel.ac.uk/bitstream/2438/2322/1/Colour%20in%20visualisation%20for%20computational%20fluid%20dynamics.pdf

Klaus Bruckner & Associates (2011) Do HVLS Fans Risk Fire Safety? Retrieved from http://www.klausbruckner.com/blog/do-hvls-fans-risk-fire-safety/

Knoop, Aphrodite (n.d.) Higher Performance and Lower Costs with HVLS Fans. Hanley Wood University. Retrieved from http://www.hanleywooduniversity.com/media/course/4252/story_content/external_files/HWU_AR_Entrematic_June_ADV16-DIGITAL.pdf

KnowTheFlo (n.d.) Industrial Ceiling Fans 101 – Everything you need to know. Retrieved from http://www.knowtheflo.com/industrial-ceiling-fans-101/

Kostora, Nick (2017) High-efficiency Air Movement Options Remain in High Demand. Air Conditioning Heating & Refrigeration News

Krell, Jaylin (2016) Stay Cool and See Clearly: HVLS Fans & LED Lights Unite. MacroAir Fans. Retrieved from https://macroairfans.com/blog/stay-cool-see-clearly-hvls-fans-led-lights/

Kuzmin, Dmitri (n.d.) Introduction to Computational Fluid Dynamics. Institute of Applied Mathematics University of Dortmund. Retrieved from http://www.mathematik.uni-dortmund.de/~kuzmin/cfdintro/lecture1.pdf

Kwok, Alison, Jessup, Britini, Rajkovich, Nicolas (2009) Orinda City Hall Case Study. American Institute of Architects

Leading Edge: Marley Engineered Products (1999) Technical Guide: Commercial Industry & Special Application Ceiling Fan. Retrieved from http://repesa.com/manufac/qmark/specs/ZDA-LEFTG.pdf

Littman Bros Lighting (2017) Interior Design Center - Inspiration, Resources, Trends. Retrieved from http://blog.littmanbros.com/ceiling-fans/

Liu, S., Yin, L., Ho, W. K., Ling, K. V., & Schiavon, S. (2017). A Tracking Cooling Fan Using Geofence and Camera-based Indoor Localization. Building and Environment, 114, 36-44.

Lumen Light and Living (2017) Fan Buyer's Guide - Ceiling Fan Blade Pitch. Retrieved from https://www.lumens.com/fan-buyers-guide/fan-blade-pitch.html

Macro Air Fans (2011) Function Over Flash: How HVLS Technology Works. Retrieved from https://macroairfans.com/wp-content/uploads/2012/02/wpgeneric.pdf

MacroAir Fans (2012) Engineering and Design Guide. Retrieved from https://macroairfans.com/wp-content/uploads/2012/02/MacroAir_Retrofit_052512.pdf

MacroAir Fans (2016) Introduction to Specifying HVLS Fans. Retrieved from http://www.esmagazine.com/ext/resources/ES/White_Papers/Files/PDF/introduction-to-specifiying-hvls-fans-02021632.pdf

Manley, Nada (2013) The Advantages of DC Motors Explained. Del Mar Fans & Lighting. Retrieved from http://www.delmarfans.com/educate/basics/how-does-dc-motor-work/

Marley Engineered Products (2016) Adjustable Speed Controls. Retrieved from https://www.marleymep.com/system/files/node/file/field-file/5200-2405-003_12.pdf

Maxim Integrated (2011) Fan Speed Control Is Cool! Retrieved from https://www.maximintegrated.com/en/app-notes/index.mvp/id/1784

Mishra, A.K., Loomans, M.G.L.C., Hensen, J.L.M. (2016). Thermal Comfort of Heterogeneous and Dynamic Indoor Conditions — An Overview. Building and Environment 109, 82-100

MyFan (n.d.) Odyn Fan Specification. Retrieved from https://www.myfan.com.au/media/assets/pdf/Odyn-FO48-Specification-Sheet.pdf

NASA (n.d.) Overview of CFD Verification and Validation. Retrieved from https://www.grc.nasa.gov/www/wind/valid/tutorial/overview.html

National Fire Protection Association (NFPA) (2014) National Fire Protection Association Report 13 Revision. Retrieved from http://www.nfpa.org/Assets/files/AboutTheCodes/13/13_AUT-SSI_A2015_SD_SRStatements.pdf

Occupational Safety and Health Standards (OSHA) (n.d.) Standard 1910.212 General Requirements for All Machines. Retrieved from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9836

Omer, A. M. (2008). Renewable Building Energy Systems and Passive Human Comfort Solutions. Renewable and Sustainable Energy Reviews 12, 1562–1587.

Parker, D., Callahan, M., Sonne, J., Su, G., (1999). Development of a High Efficiency Ceiling Fan, 'The Gossamer Wind', Florida Energy Office, Department of Community Affairs, Tallahassee, FL.

Parkinson, Thomas, de Dear, Richard, Candido, Christhina (2012) Perception of Transient Thermal Environments: Pleasure and Alliesthesia. Network for Comfort and Energy Use in Buildings. Retrieved from http://nceub.org.uk/w2012/pdfs/session8/W1220%20Parkinson.pdf

Parkinson, Thomas, de Dear, Richard (2014) Thermal Pleasure in the Built Environment: Physiology of Alliesthesia. Building Research and Information. Retrieved from https://www.researchgate.net/publication/280027621_Thermal_pleasure_in_built_environments_Alliesthesia_in_different_thermoregulatory_zones

Parkinson, Thomas, de Dear, Richard (2016) Thermal Pleasure in Built Environments: Spatial Alliesthesia from Air Movement. Building Research & Information. Retrieved from https://www.researchgate.net/publication/297608797_Thermal_pleasure_in_built_environments_spatial_alliesthesia_from_air_movement

Parkinson, Thomas; de Dear, Richard (2016) Thermal Pleasure and Alliesthesia in the Built Environment. Network for Comfort and Energy Use in Buildings

Pasut, W., Aren, E.,, Zhang H. & Zhai, Y. (2014). Enabling Energy-Efficient Approaches to Thermal Comfort Using Room Air Motion. Building and Environment 79, 13-19.

Payette (n.d.) Thermal Comfort and Glazing. Retrieved from http://www.payette.com/research/thermal-comfort-and-glazing/

Pelonis, Sam (2014) Comparing the Advantages and Disadvantages of AC Fans and DC Fans. PTI Pelonis Technologies. Retrieved from http://www.pelonistechnologies.com/blog/advantages-and-disadvantages-of-ac-fans-and-dc-fans

Rackes, A., Melo, A.P., Lamberts, R. (2016). Naturally Comfortable and Sustainable: Informed Design Guidance and Performance Labeling for Passive Commercial Buildings in Hot Climates. Applied Energy 174 (2016) 256–274.

Rite Hite Fans (n.d.) Revolution SP Fan Planner. Retrieved from http://www.canadonacan.com/content/literature/1243.pdf

Rohles, F. H., S. A. Konz, and B. W. Jones (1983) Ceiling Fan Extenders of the Summer Comfort Envelope. ASHRAE Trans 89: 245-263.

Sali, Sagar (2016) Evaluation of Ceiling Fan Blade Angle Performance using CFD. College Of Engineering, and Technology, Bambhori.

Sathaye, N., Phadke, A., Shah, N., Letscher, V. (2012). Potential Global Benefits of Improved Ceiling Fan Energy Efficiency.

Sawyers, Harry (2011) What's Inside Your Ceiling Fan? Popular Mechanics. Retrieved from What's Inside Your Ceiling Fan? Popular Mechanics

Schauer, G. (2012) The Cost of Ceiling Fans Versus Air Conditioning: Whats The Difference? <http://blog.ceilingfan.com/the-cost-of-ceiling-fans-vs-air-conditioning-whats-the-difference/>. Accessed August 2017

Schiavon, Stefano, and Arsen K. Melikov (2008) Energy Saving and Improved Comfort by Increased Air Movement. Energy and Buildings 40.10: 1954-960

Schweikera, M., Wagnera, A. (2016). The Effect of Occupancy on Perceived Control, Neutral Temperature, and Behavioral Patterns. Energy and Buildings 117, 246–259.

Shah, Nihar, Nakul Sathaye, Amol Phadke, and Virginie Letschert (2014) Efficiency Improvement Opportunities for Ceiling Fans. Energy Efficiency 8.1): 37-50.

SkyBlade Fans (2017, b) SkyBlade Fan Company Controllers. Retrieved from http://www.skybladefans.com/wpcontent/uploads/LTSSBC.0617_SkyBlade-Controllers-Spec-Sheet-1.pdf?5ff437

SkyBlade Fans (n.d., a) Calculating the Number of Fans Required for your Building. Retrieved from https://skybladefans.com.au/wp-content/uploads/2017/01/Design-Guide.pdf

SkyBlade Fans (n.d., b) Radar Multi-Fan Controller Specifications. Retrieved from http://www.skybladefans.com/wp-content/uploads/LTSRC.0617_Radar-Fan-Control-Spec-Sheet-3.pdf?5ff437

Smith, Richard (2008) Origins of the Commercial CFD Industry. Symscape: Computational Fluid Dynamics Software for All. Retrieved from http://www.symscape.com/blog/origins-of-the-commercial-cfd-industry

Srebric, Jelena; Chen, Qingyan (Yan) (2002) An Example of Verification, Validation, and Reporting of Indoor Environment CFD Analyses (RP-1133). Retrieved from https://engineering.purdue.edu/~yanchen/paper/2002-6.pdf

ARTICLE BIBLIOGRAPHY

Stephens, Gus (n.d.) How Low Should You Hang a Ceiling Fan? SF Gate. Retrieved from http://homeguides.sfgate.com/low-should-hang-ceiling-fan-68754.html

Swaroop, M P (2017) Optimisation of Fan Blade Angle. Jyothi Engineering College.

Tanabe, Shin-ichi. Kimura Ken-ichi (1994) Effects of Air Temperature, Humidity, and Air Movement on Thermal Comfort under Hot and Humid Conditions

Tauqeera, T., Ansaria M.A., Hasan, A. (2017). Realization for Low Cost and Energy Efficient Ceiling Fans in the Developing Countries. Renewable and Sustainable Energy Reviews 76, 193–201.

Todde, Valentino (2000) Perception and Sensitivity to Horizontal Turbulent Air Flows at the Head Region. International Journal of Indoor Environments and Health

Toftum J, Zhou G, Melikov A, (1997) Effect of Airflow Direction on Human Perception of Draught. Technical University of Denmark

Tortorello, M. (2011). Bringing in the Big Fans. The New York Times. Retrieved from <http://www.nytimes.com/2011/06/16/garden/bringing-in-the-big-fans.html>. Accessed August 2017

U.S. Department of Energy (2016, a) 2016-07-25 Energy Conservation Program: Test Procedures for Ceiling Fans; Final rule

U.S. Department of Energy (1989). Improving Fan System Performance a sourcebook for industry

U.S. Department of Energy (2016, b). Energy Conservation Program: Energy Conservation Standards for Ceiling Fans

U.S. Department of Energy (2016, c). Methodology Of Calculating Values As Required By The FTC EnergyGuide Based On Measurements Taken In Accordance With Appendix U To Subpart B Of 10 CFR Part 430—Uniform Test Method For Measuring The Energy Consumption Of Ceiling Fans

U.S. Environmental Protection Agency. (2011). ENERGY STAR Laboratory Guidance Manual: Building a Testing Facility and Performing the Solid State Test Method for Energy Star Qualification of Ceiling Fans

Ullman, David G. (2013) Redesigning the Ceiling Fan at the Florida Solar Energy Center: A Case Study for The Mechanical Design Process. Retrieved from http://www.davidullman.com/images/MechEngPDFs/SFEC.pdf

Wayfair (n.d.) Ceiling Fan Buying Guide. Retrieved from https://www.wayfair.com/ideas-and-advice/ceiling-fan-buying-guide-S4502.html

ARTICLE BIBLIOGRAPHY

Westinghouse Lighting Latin America (n.d.) How to Choose a Ceiling Fan? Retrieved from http://www.wl-la.com/FansA.pdf

Whalenado Fans (2015) Whalenado HVLS Fans Ordering Guidelines 2014-2015 Edition. Retrieved from http://www.cisco-eagle.com/uploads/Nordock/Whalenado%20Order%20Guidelines.pdf"

Wong, N.h, J. Song, and A.d. Istiadji (2006). A Study of the Effectiveness of Mechanical Ventilation Systems of a Hawker Center in Singapore Using CFD Simulations. Building and Environment 41.6 : 726-33.

Y - Lighting (n.d.) Multiple Fan Control (3-5 Fans). Retrieved from http://www.ylighting.com/mod-mf009b.html

Yang, L., & Ye, M. (2014). CFD Simulation Research on Residential Indoor Air Quality. Science of the Total Environment, 472, 1137-1144.

Zhai, Y., Elsworth, C., Arens, E. Zhang, H., Zhang, Y., Zhao, L. (2015, a). Using Air Movement for Comfort During Moderate Exercise. Building and Environment 94 (2015) 344-352.

Zhai, Y., H. Zhang, Y. Zhang, W. Pasut, E. Arens, and Q. Meng. (2013). Comfort Under Personally Controlled Air Movement in Warm and Humid Environments. Retrieved from http://www.escholarship.org/uc/item/9s12q89q

Zhai, Yongchao, Yufeng Zhang, Hui Zhang, Wilmer Pasut, Edward Arens, and Qinglin Meng (2015, b) Human Comfort and Perceived Air Quality in Warm and Humid Environments with Ceiling Fans. Building and Environment 90: 178-85.

Zhang, H., Arens, E., Fard, S. A., Huizenga, C., Paliaga, G., Brager, G., & Zagreus, L. (2007). Air Movement Preferences Observed in Office Buildings. International Journal of Biometeorology, 51(5), 349-360.

Zhu, Yingxin, Maohui Luo, Qin Ouyang, Li Huang, and Bin Cao (2015) Dynamic Characteristics and Comfort Assessment of Airflows in Indoor Environments: A Review. Building and Environment 91: 5-14.

IMAGE BIBLIOGRAPHY

Acer Trading Group (2017) Universal 3-Speed Ceiling Fan Control. Acer Trading Group. Retrieved from https://www.acertrading.com/collections/electrical-supplies-main/products/ceiling-fan-control-variable-speed-downdraft

Arcat (n.d.) MacroAir Technologies, Inc. BIM content
Retrieved from https://www.arcat.com/bim/macroair/Fans.shtml

Arens, Edwards (2012) Assessment of Indoor Environments. Center for the Built Environment

Arens, Edwards, Zhang, Hui, Pasut, Wilmer, Zhai, Yongchao, Hoyt, Tyler, Huang, Li (2013) Air Movement as an Energy Efficient Means Toward Occupant Comfort. Center for the Built Environment.

Aynsley. R., (2008). The Thrust of ANSI/AMCA 230-07. AMCA International Engineering Conference, Las Vegas, NV

Big Ass Solutions (2016, b) Fan Distance Guidelines.

de Dear, Richard; Brager, G. S (1998) Developing an Adaptive Model of Thermal Comfort and Preference. Center for the Built Environment. Retrieved from http://escholarship.org/uc/item/4qq2p9c6#page-1

ENERGY STAR (2016) ENERGY STAR® Ceiling Fan Product Specification Review. Retrieved from https://www.energystar.gov/sites/default/files/asset/document/Ceiling%20Fan%202016%20Product%20Review.pdf

Google Patents (2011) Ceiling Fan Housing US D635236 S1. Google. Retrieved from https://www.google.com/patents/USD635236#forward-citations

Gromol Niy (2014) Ceiling Fans – Lighting, Home Lighting Fixtures, Outdoor Lighting Retrieved from http://gromolniy.com/bronze-outdoor-ceiling-fan/”

Haiku Home (2017) Haiku Remote Control. Haiku Home. Retrieved from https://www.haikuhome.com/haikuremotecontrol

Home Depot (n.d., b) Universal On and Off Ceiling Fan Remote Control. Home Depot. Retrieved from http://www.homedepot.com/p/Universal-On-and-Off-Ceiling-Fan-Remote-Control-99112/203689998

Home Depot (n.d., c) Universal 3-Speed Ceiling Fan Control. Home Depot. Retrieved from http://www.homedepot.com/p/Universal-3-Speed-Ceiling-Fan-Control-99110/203689999

Home Depot (n.d., d) Ceiling Fans. http://www.homedepot.com/b/Lighting-Ceiling-Fans-Ceiling-Fans-Accessories-Ceiling-Fans/N-5yc1vZbvlq

Hunter Fan (n.d.) SIMPLEConnect Overview. Retrieved from http://www.hunterfan.com/SimpleConnectControl

Kiatreungwattana, K., Deru, M., Degraw, J. (2016) GSA Green Proving Ground Smart Ceiling Fan White Paper. National Renewable Energy Laboratory

Knoop, Aphrodite (n.d.) Higher Performance and Lower Costs with HVLS Fans. Hanley Wood University. Retrieved from http://www.hanleywooduniversity.com/media/course/4252/story_content/external_files/HWU_AR_Entrematic_June_ADV16-DIGITAL.pdf

Lavars, Nick (2014) Haiku Smart Ceiling Fan Knows When To Go For a Spin. Retrieved from http://newatlas.com/haiku-senseme-smart-ceiling-fan/32430/

Lowe's (n.d.) Harbor Breeze 42-in White Downrod or Close Mount Indoor Residential Ceiling Fan with Light Kit. Retrieved from https://www.lowes.com/pd/Harbor-Breeze-42-in-White-Downrod-or-Close-Mount-Indoor-Residential-Ceiling-Fan-with-Light-Kit/50057271

Lumens (n.d) Flushmount Ceiling Fans. Retrieved from https://www.lumens.com/flushmount-ceiling-fans/

Make Use Of (2016) The Different Types of Ceiling Fans. Retrieved from http://www.makeuseof.com/tag/simple-ways-automate-ceiling-fan/

Nyuk Hien, Wong, et al. (2006) A Study of the Effectiveness of Mechanical Ventilation Systems of a Hawker Center in Singapore Using CFD Simulations. National University of Singapore

Orientalmotor (n.d.) AC or DC? Brushed DC or Brushless DC Motor? Retrieved from http://www.orientalmotor.com/brushless-dc-motors/technology/AC-brushless-brushed-motors.html

Parker, D., Callahan, M., Sonne, J., Su, G., (1999). Development of a High Efficiency Ceiling Fan, 'The Gossamer Wind', Florida Energy Office, Department of Community Affairs, Tallahassee, FL.

Parkinson, Thomas, de Dear, Richard (2016) Thermal Pleasure in Built Environments: Spatial Alliesthesia from Air Movement. Building Research & Information. Retrieved from https://www.researchgate.net/publication/297608797_Thermal_pleasure_in_built_environments_spatial_alliesthesia_from_air_movement

Payette (n.d.) Thermal Comfort and Glazing. Retrieved from http://www.payette.com/research/thermal-comfort-and-glazing/

Pinterest (n.d.) Fanimation-FP7000AB-Caruso-Antique-Brass-Dual-52-0. Retrieved from https://www.pinterest.com/pin/292452569531125172/

IMAGE BIBLIOGRAPHY

Radiant (n.d.) Production Pictures. Retrieved from https://radiant.co.za/Prod_pics/Draw/JX12.gif
Science Buddies (n.d.) Retrieved from https://www.sciencebuddies.org/Files/5103/5/angle-of-attack-definition_img.jpg

Singh, Ajay (2014) Why Do Ceiling Fans Have 3 Blades? ZigZag Science. Retrieved from http://zigzagscience.blogspot.com/2015/06/why-do-ceiling-fans-have-3-blades.html

Tanger Ecole (n.d) Ceiling Fans Remote Control Transmitter. Retrieved from http://www.tangerecoles.com/ceiling-fans-remote-control-transmitter/

Toftum J, Zhou G, Melikov A, (1997) Effect of Airflow Direction on Human Perception of Draught. Technical University of Denmark

Westinghouse Lighting Latin America (n.d.) How to Choose a Ceiling Fan? Retrieved from http://www.wl-la.com/FansA.pdf

PERSONAL COMMUNICATIONS

Big Ass Solutions (2017) Personal Interview

Dave (2017) Crestron. Personal Interview

Frank Xiong (2017) Big Ass Solutions. Personal Interview

Hunter Fan (2017) Personal Interview

Lutron (2017) Personal Interview

MacroAir Fans (2017) Personal Interview

Paliaga, Gwelen (2017, July 24) TRC Solutions. Personal interview.

SkyBlade (2017) Personal Interview

ACRONYMS

Below contains a list of acronyms relevant to this report.

AC	Alternating Current
AC	Air Conditioning
AIAA	American Institute of Aeronautics and Astro nautics
AMCA	Air Movement and Control Association
ANSI	American National Standards Institute
APRISES	Asia Pacific Research Initiative for Sustainable Energy Systems
ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BAF	Big Ass Fans
BLDC	Brush Less Direct Current
CARB	California Air Resource Board
CBE	Center for the Built Environment
CFD	Computational Fluid Dynamics
CFM	Cubic Feet Per Minute
CFR	Code of Federal Regulations
DC	Direct Current
DOE	Department of Energy
EPCA	Energy Policy and Conservation Act
FPM	Feet Per Minute
FSEC	Florida Solar Energy Center
HVAC	Heating Ventilation and Air Conditioning
HVLS	High-Volume Low-Speed
InterNACHI	International Association of Certified Home Inspectors
LCC	Life Cycle Cost
NEC	National Electric Code
NFPA	National Fire Protection Agency
PMDC	Permanent Magnet Direct Current
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
VFD	Variable Frequency Drive
V&V	Validation & Verification

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