# Thermal Comfort: Designing for People

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Based on a presentation by Julie M. Ferguson

Figure 1: Barton Springs in Austin, TX, a popular spot in summer because it offers many options for adjusting thermal comfort

## Introduction

Understanding thermal comfort is important to architecture, since it not only lays the foundation for building design, but also affects the field of sustainable design. Contemporary models of thermal comfort recommend that a narrow temperature range be applied equally across all building types, climatic zones, and populations. This method casts the building occupants as passive recipients of thermal applications, leading to thermal comfort standards that require energy-intensive environmental control strategies. Often this can result in an exaggerated need for air conditioning. Yet, new research and innovative Heating, Ventilating, and Air Conditioning (HVAC) design systems are challenging the accepted notions of universal thermal comfort parameters on the basis that they overlook important cultural, climatic, and contextual factors of comfort.

Declining energy resources and an awakening environmental consciousness have created an interest in climate-responsive, energy-conserving designs and innovative mechanical strategies that allow for more personal control of thermal comfort. The increased interest in replacing the current traditional comfort standards with variable indoor temperature standards to has resulted in wider scale employment of psychrometrics in HVAC design. Adopting a revised model of thermal comfort puts us one step further toward increasing energy-efficiency in building design and linking indoor temperatures more directly to the occupants and their activities inside the building, as well as to the larger climatic context of the building.

This paper addresses the broad field of thermal comfort, dehumidification and building air conditioning systems, attempting to answer the following questions: What is thermal comfort? Why and how do thermal comfort conditions impact energy consumption? What does the history of comfort and space conditioning teach us? What is psychrometrics and why should we use it? In traditional building design, a trade-off usually exists between capital expenditures, operating costs, and occupant thermal comfort. With proper HVAC design using psychrometrics, building energy consumption can be reduced while still achieving thermal comfort.

## Thermal comfort defined

Thermal comfort is a condition of mind that expresses satisfaction with the thermal environment. Due to its subjectivity, thermal comfort is different for every individual. It is maintained when the heat generated by the human metabolism is allowed to dissipate at a rate that maintains thermal equilibrium in the body. Any heat gain or loss beyond this generates substantial discomfort. Essentially, to maintain Thermal comfort, heat produced must equal heat lost.

It has been long recognized that the sensation of feeling hot or cold is dependent on more than just air temperature. In fact, there are six primary Thermal comfort variables:

- Ambient temperature (air temperature)
- Radiant temperature (the temperature of the surfaces around us)
- Relative humidity (measurement of the water vapor in an air -water mixture)
- Air motion (the rate at which air moves around and touches skin)
- Metabolic rate (amount of energy expended)
- Clothing insulation (materials used to retain or remove body heat)

Understanding these six variables, is essential to making informed decisions when planning and designing a building air conditioning system. However, it is equally important to understand how these systems impact a building's energy load.

## Thermal Comfort Conditions and Energy Consumption

Almost half of the energy used in our society is consumed by the building sector - the design, construction, and operation, and demolition of our built environment.[1] Much of that energy is used to cool and/or heat buildings. Air conditioning accounts for 44% of a building's energy consumption. Knowing this, designers can help reduce the energy consumption patterns of a building by improving air conditioning systems.[2]

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (AHSRAE) Standard 55, Thermal Environmental Comfort for Human Occupancy, specifies "the combination of indoor thermal environmental factors and personal factors acceptable to a majority of occupants."[3] There are two approaches to deciding what this combination of factors should be:

- Analytical: People are put in a temperature-controlled environment and their responses are monitored. This method favors highly controlled environments and the results are used to develop a model that can be used to predict optimum comfort.
- Behavioral: People are monitored in their normal environments and their responses are related to the conditions they experience. The results are analyzed statistically to develop an understanding of the interaction between people and buildings.

These two approaches produce different results, especially in variable conditions. The analytical approach uses computer software programs that control conditions to make the most people happy. In the behavioral approach, a psychrometric chart is applied. Prior to discussing this latter application in more depth, it is important to consider the history of heating and cooling systems, and what we can learn from our past.

## Historical Perspective

Prior to the development of mechanical air conditioning systems, societies used natural heating and cooling methods – such as shading, thermal mass, and natural ventilation – to achieve thermal comfort. Such methods have been used for thousands of years. For example, the ancient Babylonians used evaporative cooling to condition their dwellings as far back as 2,000 BC. Individuals would spray water onto exposed surfaces at night; the combined evaporation and drop in night time temperatures provided a simple and effective method to get relief from the heat.[4] Ancient Indians would hang wet grass mats on the windward side of their homes to achieve a cooler indoor temperature.[5]

Society moved away from these methods when mechanical cooling became available in the early 1900s. In 1902, the first mechanical cooling system was built.[6] Four years later, the first office building was designed for air conditioning.[7] In 1929, the first room cooler went on the market and 1931 marked the first time that year-round central air systems became available for homes.[8] By 1947, the window air conditioning unit was being mass-produced and after World War II mechanical systems flourished with the large-scale and rapid development of homes.[9] Due to these achievements over the course of the 20th century, the mechanical air conditioning industry led the market in growth in energy use in buildings.

While the advent of air conditioning made it

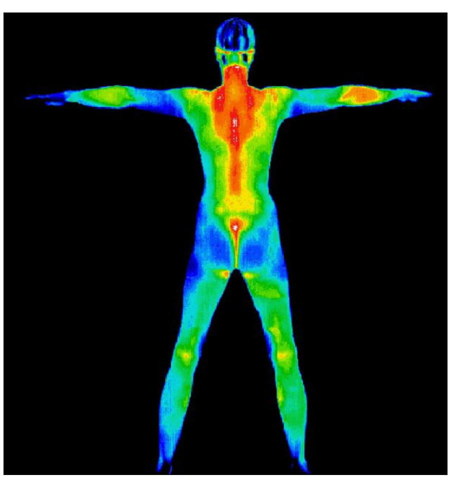

Figure 2: A thermographic scan of the human body

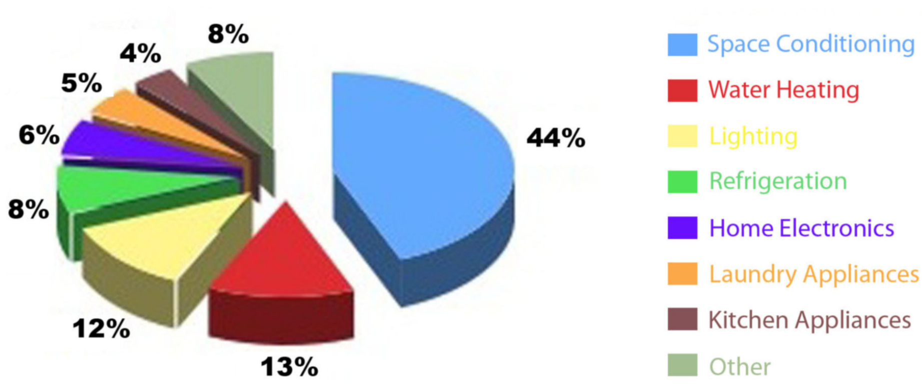


Figure 3: Building energy consumption by type

possible to have a comfortable indoor environment in any climate, it also led to design that completely ignored varying climatic conditions. For example, New York-style town-homes were built in New Orleans. This caused buildings that had functioned efficiently in one environment to consume excessive amounts of energy in another.  Essentially, we began to build less efficient buildings that used more energy.

Before the 1970s energy crisis, occupants accepted and expected the experience of occasional high humidity periods. This variation in humidity rarely factored into building material choices, which have a huge impact on overall structure and indoor air quality. During this time, buildings were constructed loosely, with poor insulation. This construction resulted in an added sensible load, keeping the AC units running frequently.

After the 1970s energy crisis, stringent building codes began to arise through the Energy Policy Act to improve building efficiency. ASHRAE Standard 90 Energy Standard for Buildings addressed energy efficiency, Standard 62 Ventilation for Acceptable Indoor Air Quality addressed ventilation, and Standard 55 addressed issues of thermal comfort.[10] These more stringent codes also required that mechanical equipment become more energy efficient. With these codes in place, an unintended consequence was that equipment continued to be optimized for sensible cooling, but still ignored the moisture load.

The following factors emerged from these developed standards and changes made to the manner in which we designed and constructed our buildings:

- The sensible load in a building was reduced, however, the moisture level stayed the same. This caused relative humidity problems. Though the changes in standards after the 1970s energy crisis made buildings and equipment more efficient, the focus on sensible loads (temperature) meant that humidity was often ignored in system design.
- With increased ventilation requirements more moisture was added with ventilated air .
- With increased indoor air  quality awareness drier conditions were expected by the occupants.

Because of the emergent standards, indoor air quality conditions decreased as a result of unaddressed moisture loads. While the energy crisis resulted in more energy efficient buildings and equipment, we were left with less dehumidification. This is problematic from an indoor air  quality standpoint as increased moisture can cause mold or mildew to grow inside the building, which is a health hazard for occupants and detrimental to the life of building materials.

As a result of these changes, one important lesson emerged: we should design to control humidity and not just temperature. Peak dehumidification load is different from the peak temperature load, but it is not often accounted for in mechanical design. Peak temperature load only occurs 2% of the year. When designing for this maximum peak dehumidification and part load conditions are often not considered.

While air conditioning systems had previously been designed for a specific building, over time they became standardized. Now, we are witnessing a desire to return to using passive systems, often in tandem with specifically designed mechanical systems. New energy efficient methods that consider the occupants in a space, rather than designing the building and air conditioning  system without thought for who is using the space (or how it is used), are being employed more frequently. Additionally, these systems are adapted to the local climatic context of the building, accounting for both temperature and humidity not only peak

Figure 4: Environmental Factors affecting Thermal Comfort

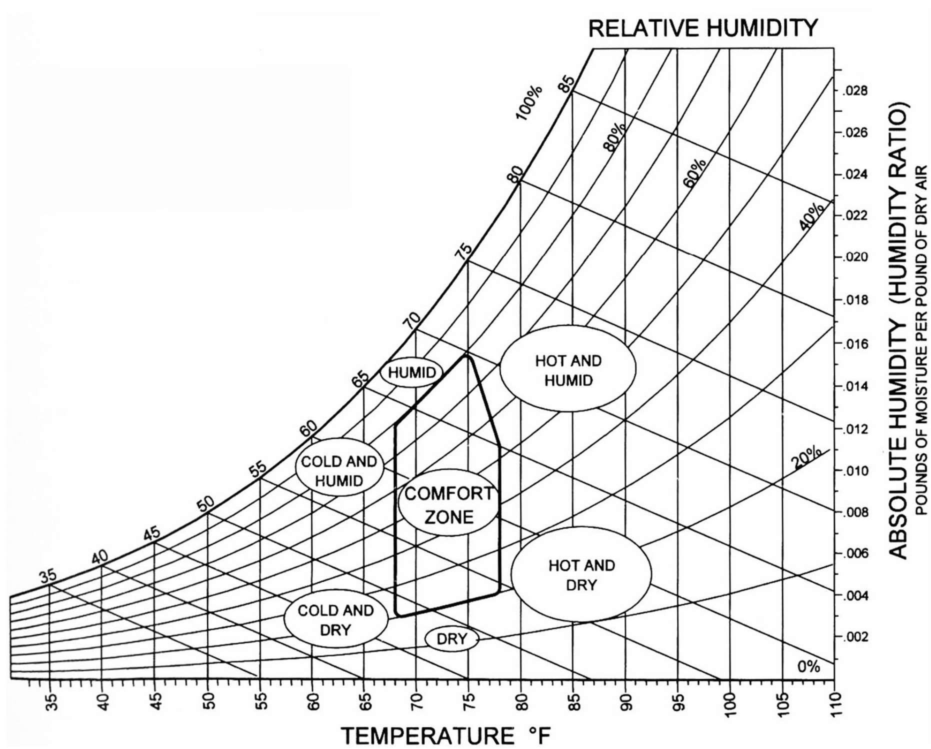


Figure 5: The psychrometric chart

temperature but peak humidity and part load conditions as well. One method with which to properly design an HVAC system is to apply the concept of psychrometrics to system design, since psychrometrics considers the factors of local climate, human occupancy and comfort, and varying temperature and humidity controls.

## Psychrometrics

Before defining and applying the concept of psychrometrics, it is important to understand what an air conditioning system is, and what it's inputs/outputs are. Psychrometrics is the study of the physical and thermodynamic properties of air-water vapor mixtures and according to Willis Carrier, inventor of modern air conditioning, it is "the control of the humidity of the air by either increasing or decreasing its moisture content. Added to the control of humidity is the control of the temperature by either heating or cooling the air, the purification of the air by washing or filtering the air, and the control of air motion and ventilation."[11] In order to improve our air conditioning systems, we must examine all the variables involved in thermal comfort: humidity, temperature, air purification, air motion and ventilation.

Psychrometrics is used to help select the proper air conditioning equipment and determine the environmental conditions that affect human thermal comfort. It is also useful to help understand : a building's regional climatic context and better address , human occupancy and use, and structural considerations.The study and analysis of psychrometric properties is especially important in applications where moisture and heat transfer in air are critical.

Most of psychrometrics is embodied in the psychrometric chart (Figure 5). An understanding of how to apply the psychrometric chart will help to diagnose air temperature and humidity concerns. The chart is a tool for visualizing the airconditioning process and helps inform climate-specific designs. It uses three main categories: temperature, moisture, and relative humidity, to inform the design of energy efficient and properly sized HVAC systems.[12]

Understanding the chart helps with visualizing environmental control concepts such as how hot air can hold more moisture, and conversely, how cooling moist air to its dewpoint will produce condensation.

The three principal boundaries of the psychrometric chart (Figure 5) are a dry-bulb temperature scale on the horizontal axis, a humidity ratio (moisture content) scale on the vertical axis, and an upper curved boundary which represents saturated air, or 100 percent relative humidity. The chart also shows other important properties such as enthalpy (the energy content of an air-water mixture, expressed in BTUs per pound of dry air) and specific volume (the space occupied by a given mass of air). The versatility of the chart lies in the fact that knowing any two of these properties fixes a point on the chart from which all the other properties can be determined. The use of the chart is simple and the following sections discuss its applications by dissecting the components of the graph piece by piece.

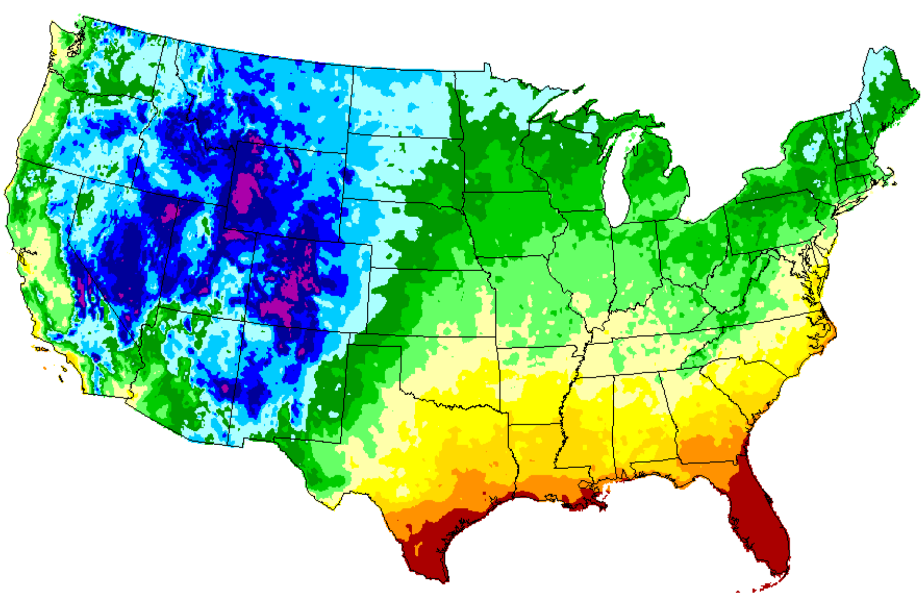

Figure 6: Mean daily average dew point temperature, October

### Temperature

There are two main sources of building heat: internal and external. Internal sources include people, lights, appliances, equipment; external sources include solar load, conduction, ventilation, and infiltration. Temperature increases from cold to hot along the x-axis of the psychrometric chart. The temperature measured in this case is the 'dry bulb' temperature, which is that of an air sample as determined by an ordinary thermometer. It is called "dry-bulb" since the sensing tip of the thermometer is dry and does not take the moisture content of the air into account.

### Moisture

Moisture in the air is an important consideration of air conditioning system design, and thus an integral element of the psychrometric chart. Like temperature, there are also two main sources of moisture: internal and external. Internal includes evaporation, desorption, and people (breath, clothes); external includes ventilation, infiltration, and permeation. Internal moisture sources are as important to consider as outside moisture sources, since each person emits 0.25 pounds of moisture per hour, therefore100 people at a moderate activity level produce three gallons of water per hour.[13] Moisture is measured through a humidity ratio measurement, which is found on the y-axis, with lines of constant humidity ratio running horizontally across the chart. The humidity ratio is the weight of water per unit of dry air. This is often expressed as grains of moisture per pound of dry air, with 7,000 grains of moisture per pound of water.[14,15]

### Humidity

The ASHRAE user's manual states that HVAC systems that have dehumidification must be designed to control relative humidity when analyzed for either of the following design conditions:

1. At the peak outdoor dewpoint design conditions and the concurrent (simultaneous) indoor design latent load, or,

2. At the lowest space sensible heat ratio expected to occur at the concurrent (simultaneous) outdoor condition.

Relative humidity provides an indication of how close the air is to its saturation point. It compares the amount of water in the air to the amount of water that the air could potentially hold at that temperature. This affects the perceived temperature of an environment, as well as mold growth and stability of building materials. On the psychrometric chart, lines of constant relative humidity are represented by the curved lines sweeping up from the bottom left and to the top right of the chart.

Wet-bulb temperature is determined by circulating air past a wetted sensor tip, which is affected by air saturation. In practice, this is the reading of a thermometer whose sensing bulb is covered with a wet sock evaporating into a rapid stream of the sample air. (Note: WBT will be the same as DBT when the air sample is saturated with water, since no water can evaporate in those conditions.)

The line for 100 percent relative humidity, or saturation, is the upper, left boundary of the chart. This is also the dew point temperature. Dew point temperature indicates the temperature at which water will begin to condense out of moist air. A rule of thumb is that the annual night time temperature for a given region is that area's dew point temperature. See Figure 6 for a map of the daily average dew point temperature for October in the continental United States. High levels are represented by the red areas and range down through the spectrum to low levels in the purple and blue areas.

There are different ways to remove moisture from the air in a building: cooling below the air's dewpoint, desiccants that adsorb or absorb water, and compression to condense water out of the air. Which ever method is used it is important to analyze both it's performance and annual energy use at all of the building loads.

Another way to remember the inputs for proper HVAC design is to remember to consider both the sensible and latent heat of a given building. Sensible heat refers to the temperature load of a given space. Latent heat is basically the moisture load of the building. It is the energy given up or taken up by the air as water changes phase, such as vapor condensing into liquid. It considers the moisture content, which engineers often forget about when designing and sizing HVAC systems. The latent load is crucial because it is a significant load and also accounts for the outdoor moisture at peak and part load conditions as well as moisture from the people in the room (Indoor and outdoor moisture loads). If latent load is not considered it may lead to increased moisture in the space that could create higher relative humidity, discomfort and building deterioration. Combining the latent and sensible heat gives the total heat load.

## Conclusion

It is important to mention that these heating and cooling systems do not operate in a vacuum. Aside from understanding a building's potential moisture content, another issue arises with proper building site orientation. Proper orientation, materials, and design affects heat gain and loss of a building, as well as ventilation and cooling loads. Therefore, it is important to also consider the location and orientation of a given building on a given site in addition to the proper sizing of an HVAC system.

Looking back at history provides a broader understanding of how various building cultures designed for their climates, considering proper orientation with regard to air flow and other thermal comfort conditions. Today, maintaining thermal comfort for building occupants is one of the most important goals of building design engineers. While we can employ adaptive strategies to cope with our changing thermal environment (removing clothing, unconsciously changing posture, moving to cooler locations away from heat sources), problems arise when this choice (to remove jacket, or move away from heat source) is not available, and people are not able to adapt. Therefore, we need to consider the following factors in building design and construction:

- The role of cooling in comfort, productivity and energy use for different climates
- Strategies for reducing reliance on AC and reduction of its energy use
- Adaptive behavior in buildings: mechanical cooling and passive controls
- Standards for comfort and energy use in buildings
- Thermal comfort in the context of energy performance regulations
- Improving building simulations
- Improving building envelope, design and materials to reduce loads
- The role of renewable energy in cool buildings
- Impacts of climate change, urban heat islands and rising fuel costs
- Practical issues for low or zero carbon cooling

Current best practices in building design and construction result in homes that conserve much more energy than average new homes. Constructing homes in smart ways results in the use of minimal resources to cool and heat the house as the seasons change. Employing these methods can significantly reduce energy costs. Some of these best practices and guides include:

- Passive houses: using the sun's energy for heating and cooling living spaces, the building itself, or some element of it, taking advantage of the natural energy potential of materials and air that have been exposed to the sun.[16]
- Superinsulation: an approach to solving thermal envelope problems through design, construction, and retrofitting. A superinsulated house can include thick insulation and/or an air tight envelope.
- Windows and lighting: Utilization of properly designed and installed high efficiency windows and lighting.
- Self-sufficient homes: also known as off-grid, where the building generates and consumes its own power/energy.
- Zero energy buildings: produce on average as much energy as they consume; designed to use zero net energy from the utility grid.
- Earthships: passive solar houses built out of recycled tires and usually built into the ground.[17]
- MIT Design Advisor: computer modeling to improve indoor comfort and energy performance of conceptual building designs.[18]

Maintaining thermal comfort for building occupants is one of the most important goals of HVAC design engineers. If we can understand the variables of thermal comfort in our regional climatic contexts, and the mechanisms by which they operate in relation to human physiology, then we can design buildings that provide comfort in more rich and economical ways than a standard HVAC solution. The psychrometric chart offers much insight into the integration of physiological properties, the properties of the local climate context, and other factors which allow us to design comfortable environments in a holistic manner.

## Glossary of Terms

*Air conditioning*: The cooling and dehumidification of indoor air for thermal comfort. It also refers to the modification of the air, i.e., cleaning.

*Ambient Temperature*: Refers to the temperature surrounding a body or unit.

*ANSI*:The American National Standards Institute.

*ASHRAE:* The American Society of Heating, Refrigerating, and Air Conditioning Engineers.

*Conduction:* The transfer of heat from molecule to molecule within a substance.

*Convection:* The transfer of heat by a moving fluid.

*Desorption:* Changing from an adsorbed state on a surface to a gaseous or liquid state.

*Dessicant*: A substance that creates or maintains a state of dryness. Dessicant wheels can be added to HVAC systems to provide for extra humidity control.

*Dewpoint:* The temperature to which the air can be cooled before it reaches saturation, at constant barometric pressure. It is an absolute measure of how much water vapor is in the air (how humid it is). The condensed water is called dew. A relative humidity of 100% indicates that the dew point is equal to the current temperature (and the air is maximally saturated with water).

*Dry Bulb Temperature:* Temperature read with an ordinary thermometer.

*Evaporative Cooling*: The cooling effect caused by the evaporation of a liquid.

*Humidity Ratio:* (also known as moisture content or specific humidity) - The proportion of mass of water vapor per unit mass of dry air at the given conditions.

*HVAC:* Heating, Ventilating, and Air Conditioning.

*Latent Heat*: Heat that produces a change of state without a change in temperature; for example, from water to steam at 212º F. Latent heat is measured in British Thermal Units (BTU).

*Latent Cooling Load:* In HVAC design, this refers to the wet bulb temperature of the building. Factors that influence the latent cooling load of a building are those which introduce moisture into a structure: people, equipment and appliances, air filtration through cracks in the buildings, doors, and windows.

*Peak Load:* The maximum energy requirement for heating and/or cooling at one time. This often determines the size of HVAC systems though peak load only occurs for a small percentage of the time.

*Psychrometric Chart*: A chart on which can be found the properties of air under varying conditions of temperature, dew point, humidity, volume ethermal comfort.

*Radiant Temperature:* The energy being emitted from a surface of an object due to that object's temperature.

*Relative Humidity:* The percentage of water vapor present in a given quantity of air compared to the amount it could hold at that temperature.

*Sensible Heat* - Heat that can be measured or felt. Sensible heat always causes a rise in temperature and is measured in degrees (C, F or K).

*Sensible Cooling Load*: In HVAC design, this refers to the dry bulb temperature of the building. The factors which influence the sensible load of a structure include: insolation, glass windows and doors, roofs and floors, air infiltration, people, appliances and lights, among others.

*Solar Load*: The largest component of heat gain for building exterior surfaces.

*Thermal Comfort*: The state of mind that expresses satisfaction with the surrounding environment.

*Ventilation:* The intentional movement of air from the outside to the inside of a building.

*Wet Bulb Temperature*: Temperature read with a thermometer whose bulb is encased in a wetted wick.

## Notes

1. Ed Mazria, Architecture 2030, http://www.architecture2030.org/

2. However, true reduction comes from the application of several energy conservation strategies; single application strategies are not effective in isolation.

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14. Ibid; p. 29

15. Since the humidity ratio of moist air is not dependent on temperature, it is easier to use in calculations

16. http://www.greenbuilder.com/sourcebook/PassiveSol.html

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## Figures

Figure 1: http://5minuteswithmolly.files.wordpress.com/2008/07img_2551.jpg

Figure 2: http://www.physioimaging.com/index.php?id=48

Figure 3: ?

Figure 4: Julie Raish

Figure 5: Lechner, Norbert. (2000) Heating Cooling and Lighting: Design Methods for Architects 2nd Ed. (New Jersey: John Wiley & Sons).

Figure 6: http://www.climatesource.com/us/fact_sheets/td_us.gif

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## Biography


Julie M. Ferguson is the President of Applied Dehumidification, Inc., an HVAC design and consulting firm based in Miami, Florida which began operation in 1997. Since then, Applied Dehumidification, Inc. has developed into one of the premier HVAC representatives in western Florida. Ms Ferguson's focus is on the cutting edge of system technology, extremely critical in today's energy conscious market. Applied Dehumidification, Inc. has built a sales force that provides extensive knowledge in both product and system applications. Julie Ferguson is an active member of ASHRAE and IAQA. Her monthly involvement in ASHRAE meetings, attendance at yearly industry events and continual relationship with industry leaders allows her to maintain an astute understanding of the importance of both the industry standards and market needs for building Air conditioning systems.