Incorporation of natural ventilation in a commercial HVAC system using temperature as a comfort parameter

Rahul Subhash Pendse

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A Thesis

Entitled

Incorporation of Natural Ventilation in a Commercial HVAC System

Using Temperature as a Comfort Parameter

By

Rahul S. Pendse

Submitted as partial fulfillment of the requirements for

the degree Master of Science in Civil Engineering

Advisor: Dr. Ashok Kumar

Graduate School

The University of Toledo

May 2004
Researchers are assessing the possibility of using natural ventilation for a certain period of day to reduce the energy consumption due to HVAC systems. There is a need to develop hybrid systems involving both conventional HVAC systems and natural ventilation as a viable solution to energy consumption issues. This thesis is an effort to develop a hybrid HVAC system with natural night ventilation serving as an energy efficient component of the system. This research is targeted for commercial buildings, especially a manufacturing plant (e.g. metal fabricator plant) and a small office located at the plant. Night cooling times are
calculated on a monthly basis for both the manufacturing plant as well as for the office separately.

The first step is the development of a model for the calculation of indoor temperature after night cooling. This is done with the aim of using internal room temperature as a comfort index for the occupants. Accordingly, the models are developed for calculating final indoor temperature by incorporating the heat gains and losses observed in a plant as well as in an office building unit separately. The effect of changes in moisture content on indoor temperature at designed relative humidity has been taken into consideration. It is also assumed that the designed relative humidity is remaining constant throughout the cooling period. Both of the models involve a complex equation for the calculation of final indoor temperature, which makes the process time-consuming.

To facilitate the calculations, a spreadsheet tool used is composed of five sheets, wherein inputs concerning wall details, window details, lighting details, motor details, heat emitted during different activities by human beings, and outdoor temperature calculations are obtained from the ASHRAE Handbook of Fundamentals 2001; moisture contents at different temperatures at designed relative humidity are obtained from Mark’s Handbook for Mechanical Engineers. Variation of the temperature with respect to internal mass, air change rate, start time, change in relative humidity, duration, and change in load and shifts is studied for five cities, each belonging to one of the five climatic zones into which the United States is divided by the Department of Energy. Based on the pattern of the variation of indoor temperature and comfort ranges of indoor temperature developed from an ASHRAE
study, recommendations are made for night cooling in the cities on a monthly basis. The recommendations are made in two sets, one conservative set assuming a low tolerance for temperature fluctuation and a liberal set of recommendations for building occupants having higher degree of adaptability to varying indoor temperatures. In warm regions like Texas, night cooling can be carried out for almost all months of the year. In a city like Raleigh, NC, it is possible to reduce usage of conventional systems in a manufacturing plant by approximately 1500 hours per year and for an office building by approximately 1400 hours per year. In a comparatively colder city like Minnesota, MN, it is possible to reduce usage of conventional systems in a manufacturing plant by approximately 1300 hours per year and for an office building by approximately 1200 hours per year.
Dedicated to

My Parents

without whom, I would have been nowhere.
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<td>Btu/h ft²</td>
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**$E_t$**  Total irradiance (Btu/h ft$^2$)

**$F_{lm}$**  Motor load factor

**$F_g$**  Area of fenestration/window (ft$^2$)

**$F_{sa}$**  Lighting special allowance factor

**$F_{ul}$**  Lighting use factor

**$F_{um}$**  Motor use factor

**$F_w$**  Area of exposed wall (ft$^2$)

**$H$**  Hour angle (solar hour)

**$h_o$**  Coefficient of heat transfer at outer surface (Btu/h ft$^2.oF$)

**$L$**  Latitude of location (degrees)

**$LON$**  Longitude of location (degrees)

**$LSM$**  Local Standard Time Meridian (degrees)

**$M_a$**  Mass of air (lbs)

**$M_f$**  Mass of furniture/internal mass (lbs)

**$n$**  Number of air changes (ach$^{-1}$)

**$Q_1$**  Heat gain through window due to difference in internal and external temperatures (Btu/h)

**$Q_2$**  Total heat gain due to solar activity (Btu/h)

**$Q_f$**  Heat gain due to internal mass (Btu/h)

**$Q_g$**  Total heat gain due to window (Btu/h)

**$Q_w$**  Heat gain due to walls (Btu/h)

**$Q_v$**  Heat gain due to cooling (Btu/h)

**$q_b$**  Direct beam solar heat gain (Btu/h)
\( q_d \) Diffuse solar heat gain (Btu/h)

\( P \) Motor power rating, (hp)

\( \text{SHGC}_D \) Diffuse solar heat gain coefficient

\( \text{SHGC}_\theta \) Solar heat gain coefficient for incidence angle \( \theta \)

\( T_1 \) Indoor temperature before night cooling (\(^\circ\)F)

\( T_2 \) Indoor temperature after night cooling (\(^\circ\)F)

\( T_f \) Temperature of the furniture/internal mass (\(^\circ\)F)

\( T_i(t) \) Indoor temperature at time \( t \) (\(^\circ\)F)

\( T_o \) Outdoor temperature (\(^\circ\)F)

\( T_o(t) \) Outdoor temperature at time \( t \) (\(^\circ\)F)

\( T_{sa} \) Sol-air temperature (\(^\circ\)F)

\( T_{sa}(t) \) Sol-air temperature at time \( t \) (\(^\circ\)F)

\( T_{we} \) Temperature of wall at external face (\(^\circ\)F)

\( T_{wi} \) Temperature of wall at internal face (\(^\circ\)F)

\( t \) Time

\( t_1 \) Time at beginning of cooling

\( t_2 \) Time at end of cooling

\( U_g \) Thermal conductivity of fenestration (Btu/h \( ft^{2}\circ\)F)

\( U_w \) Thermal conductivity of walls (Btu/h \( ft^{2}\circ\)F)

\( W \) Total light wattage

\( Y \) Sky diffuse factor
Greek Symbols

α  Absorptance of surface for solar radiation
β  Solar altitude (degrees)
γ  Surface-solar azimuth (degrees)
δ  Solar declination (degrees)
ε  Hemispherical emittance of surface
θ  Incidence angle (degrees)
ρg  Ground reflectivity
Φ  Solar azimuth (degrees)
ψ  Surface azimuth (degrees)
ψn  Relational factor in Ogulata’s model
ω1, ωn  Frequency
Σ  Surface tilt from horizontal (degrees)
ΔR  Difference between Long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature (Btu/h·ft²)
Δt  time interval
CHAPTER ONE

INTRODUCTION

1.1. Overview

Achieving good indoor air quality in large residential and commercial buildings continues to be of top priority for designers, owners, as well as for occupants. Maintaining good indoor air quality, which enables the occupants to get maximum comfort, is a great challenge and this challenge is greater today because of many new materials, furnishings, processes and products used in the construction which might increase the release of air contaminants.

Ventilation, air filtration, and source control are the common methods for achieving required indoor air quality. Of these methods, ventilation is most commonly used. Basically, ventilation is the process of replacing stale air from the enclosed place by outdoor air. In ancient times, human beings were dependent only on natural ventilation. This didn’t prove to be a sustainable solution (i.e. environment friendly solution that can be used for many years), for many parts of the world which experienced severe climatic changes. In order to develop the sustainable solution for maintaining good indoor air quality, mechanical ventilation was introduced. Mechanical ventilation is costly as the outside air has to be heated in winter and has to be cooled in summer. Today many mechanical ventilation devices are available
and Heating Ventilating and Air conditioning (HVAC) systems are the most popular ones, especially for commercial buildings.

HVAC systems are a major consumer of energy in the residential as well as commercial buildings. Issues such as global warming, the California energy crisis, and the blackout on Aug 15, 2003 in the U.S. and Canada, have again diverted a focus on a major rethink of energy consumption by conventional systems. Researchers are trying to find energy efficient solutions to replace the conventional systems without compromising indoor air quality. The possible solution could be the use of alternate modes, like natural and mixed ventilation, which are more energy efficient and environmentally friendly. The application of these systems is growing very rapidly in the United States.

Even though natural ventilation is energy efficient, it cannot remedy all the issues related to indoor comfort especially in severe climatic zones. Therefore, consideration should be made for the system which combines benefits of both natural and mechanical systems with minimized drawbacks. This new system can be referred as a “Hybrid HVAC system”. This system would not be as energy efficient as natural ventilation, but would provide better control over usage which helps the user to customize his/her environment and also results in energy conservation.

1.2. Problem Statement

The objectives of this effort are:

1. Develop ideal times for natural ventilation to work, based on thermal mass, rate of ventilation, effect of difference in the indoor and outdoor moisture contents on temperature, effect of latent heat emitted by various sources and thermal comfort range,
and optimized cooling times by use of indoor temperature as an index assuming constant relative humidity over a period of natural cooling.

2. Develop a software package that aids a designer with a ventilation system to achieve the above objectives.
CHAPTER 2
LITERATURE REVIEW

2.1 Ventilation

Ventilation is the process of supplying or removing air to or from a place by natural or mechanical means in order to maintain the air quality within the comfort zone. Generally, outside air is used for ventilation. Apart from natural or mechanical means of ventilation, an unintentional type also exists, referred as infiltration or air leakage.

Ventilation is required to control the concentration of objectionable contaminants (e.g., carbon dioxide, formaldehyde), which can produce bad health effects and/or objectionable odors. Ventilation helps in improving the occupational environment and in regulating heat and moisture (Shaw, 2000). Ventilation requirements depend on occupancy and building use and usually involve significant expenditure. There are two popular types of ventilation (i.e. local ventilation and dilution ventilation). In a manufacturing plant, local as well as dilution ventilation is used depending on the type of products produced. Control of odors, carbon dioxide and oxygen levels etc. are the other purposes of providing adequate ventilation.

Ventilation of building spaces induces air movement within the spaces. This movement can be influenced by wind factors and/or thermal buoyancy. An illustration that would serve the purpose would be the movement of warm air in the bottom of the
building to colder areas near or at the roof of the building or the movement of cold air in the top of the building to the warmer area at the bottom. This is known as the “stack effect”. These types of air movements can lead to a very dangerous situation in commercial buildings like hospitals where control of pollution migration is considered of prime importance or manufacturing plants where hazardous materials are the byproducts of the different processes. Proper design of ventilation systems requires the understanding of both wind and stack-driven pressurization. In general, air change rate, interzonal airflow, and air leakage characteristics are the important parameters that affect ventilation design and measurement.

2.2 Need for a Hybrid Ventilation System

Natural ventilation has made a comeback as energy consumption has become a central concern for policy makers worldwide, particularly since energy demands are expected to increase further in the near future. The idea of reducing human’s impact on the environment is definitely gaining ground. Use of fossil fuel has also become a major concern. If the per capita rate of fossil fuel consumption by developed nations is projected to apply to the world population, the carbon dioxide content of the atmosphere and the rate of consumption of fossil fuels will increase by a factor of 10 which is not sustainable (Fordham, 2000). Surveys performed by Jones and West (2001), have shown that the energy cost of air-conditioned buildings is 40% more than for non-air-conditioned buildings and, moreover, air conditioning is not considered a sustainable solution for lowering the temperature as heat is made to go
from a cold place to a hot place. As much as a 25% reduction in cooling energy is possible for lightweight structures using natural ventilation.

However, all occupant needs that pertain to indoor comfort cannot be fulfilled only by natural ventilation. So, in spite of all the arguments in favor of natural ventilation, mechanical ventilation still has its uses. Air conditioning is preferred in certain rooms like offices where a personal computer is used at every desk or in hospital’s intensive care units where total control over indoor environment is required. Specific conditions exist in extreme climates where using only natural ventilation may result in occupant dissatisfaction. Hence, channeling the advantages of both the disparate systems into a hybrid system will give flexibility for use of systems under varying situations (Elovitz, 2002, Fordham, 2000, Kosik, 2001 and Wright, 2000).

2.3 Factors Affecting Ventilation and Energy Use

The main factors affecting the performance and energy efficiency of a ventilation system are air distribution, air leakage, and contamination sources (Shaw, 2000). Ideally all the occupants should be benefited equally from the ventilation air being circulated to a space, i.e., air should reach all the occupied spaces of the building. This is not always the case. The air gets distributed inside the units depending upon the pressure inside each unit, which depends upon temperature, wind, or both.

Air leakage is the infiltration of air through the building envelope. The amount of leakage depends on the amount of air tightness of the building envelop and
the pressure difference across it caused mainly by wind and stack effect. Cold drafts are usually a good indication that air leakage is occurring. When this is the case, sealing cracks and openings in the exterior walls and around the windows improves air tightness.

When powerful sources of contamination are present inside the building, leading to occupants complaints, increasing the ventilation to speed up the dilution process becomes an option. Institute for Research in Construction, National Research Council, Canada (2000) showed that this can’t be a sustainable solution even when energy use is not a concern.

2.4 Energy Efficient Control of Ventilation

In order to reduce the ventilation energy use, two strategies have been used viz. shutdown of the ventilation system during non occupied periods and carbon dioxide demand controlled ventilation. ASHRAE recommends ventilation rates for buildings based on the maximum number of occupants. For commercial buildings, where the number of occupants varies significantly with time, it may be possible to control the ventilation rates based on number of occupants at a given time. A demand controlled ventilation system using the occupant generated carbon dioxide as an index can also be used. Promoting natural ventilation can also be a good option.

An important consideration in favor of natural ventilation is the prospect of night-time ventilation. The use of night-time ventilation causes cool night air to lower the mass temperature of a building. This method of pre-cooling can lower peak and overall electric demands bringing about substantial indirect savings. Natural
ventilation can also result in improved environmental quality and occupant satisfaction (Kolokotroni, 2001). A majority of occupants prefer provision of good daylight and ventilation by openings in walls, so that they can get rid of the feeling of being enclosed in the conditioned place. When a building is sealed shut and people do not have a sense of the outdoor conditions, they become more intolerant of temperature swings that they cannot control. The above observation also agrees with the notion that a person’s comfort level will largely be dependent on individual perceptions and expectations. Today, entire malls are being designed using natural ventilation principles (Fordham, 2000, Jones and West, 2001, and Thomas, 2002).

2.5 Night Ventilation (Kolokotroni M. and Aronis A., 1999)

Cooling energy requirements can be reduced by using low energy technologies. Such use is particularly suited to commercial buildings as the number of occupants is usually less at night. Night ventilation works by using natural or mechanical ventilation to cool the surfaces of the building fabric at night and is more effective for a building with a high thermal mass. Night ventilation is a popular choice as buildings are comparatively less occupied at night. Night ventilation can affect internal conditions during the day in the following ways:

1. Reducing peak air temperatures
2. Reducing air temperature during the day, especially the morning hours
3. Reducing slab temperatures
4. Creating a time lag between internal and external temperatures
The research in Europe showed that night ventilation combined with thermal mass is one of the most appropriate techniques for hot as well as cold climates in reducing the need for air conditioning and improving the internal thermal conditions. Kolokotroni (2001) used night ventilation strategies to effectively reduce energy consumption without compromising indoor thermal comfort and showed that 5 to 15% energy can be saved using this method depending upon the various building parameters.

2.6 Deployment of Natural Ventilation Systems

Designers of HVAC systems tend to favor mechanical systems, as they need to conform to standards such as ASHRAE Standard 55 (1992) or the ISO 7730 (1994). These standards tend to favor rigid interpretations of thermal comfort and do not consider the possible stretching of thermal comfort ranges that are possible for human beings in naturally ventilated buildings (Thomas, 2002). The study carried out by Brager and Dear (2000), has shown that occupants exposed to natural ventilation can adapt to a larger variation in temperature when compared with occupants exposed to mechanical ventilation, which implies that people in naturally ventilated buildings preferred conditions that more closely reflected outdoor patterns. It can also be concluded that occupants in HVAC buildings develop high expectations of the indoor climate, which might affect the productivity when the indoor climate varies. The factors affecting natural ventilation efficiency are given as follows (Brager and Dear, 2000, Fordham, 2000 and Jones and West, 2001):

- Direction of wind
- Internal and external temperatures
- Geometry of building structure
- Extent and amount of infiltration in the building envelope
- Flow of air within the building as per interior layout

Site characteristics such as vegetation, urban building layout, or nearby landforms can divert the wind or reduce its speed, which changes the natural ventilation. Climate characteristics, especially temperature and relative humidity play a major role in setting the comfort levels.

The Hybrid HVAC system indicated in this study is assumed to have the facility of providing natural ventilation. Certain applications in the building like storage places of hazardous materials require total control over the environment, which are preferred to be ventilated mechanically, and other places where variation in indoor climate is allowed can be ventilated naturally for certain durations as long as the resulting indoor climate stays within the comfort zone as given by Brager (2000).

Fordham (2000) suggested ventilation control on the basis of occupant control, indoor air quality, and temperature. It is seen that the satisfaction of the occupants reflects in the production capabilities. More comfort reflects more production. Good indoor quality includes adequate temperature and relative humidity. Indoor air quality ensures that occupants are not exposed to harmful pollutants that are released during the production process. These pollutants can lead to health hazards if certain quantities are present for more than a certain time.

2.7 Past Studies Using Temperature as an Index for Determining Comfort.
The basic criterion for a control requirement in a space is a heating/cooling system based on temperature, which can be said to be the most common parameter for a ventilation system. For occupants, temperature and relative humidity are the most important indices of comfort inside a room. Hence, it is necessary to maintain the temperature and relative humidity within the comfort limits in order to achieve desirable productivity. Conduction (steady or unsteady states), convection, and radiation are the main causes of temperature variation inside a room (Thomas S., 2002). Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole. Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it. Radiation is heat transferred in the form of electromagnetic waves even in vacuum.

In an ASHRAE Journal article, “A Standard for Natural Ventilation,” Brager and Dear (2000), suggest that “Occupants of naturally ventilated buildings appear tolerant of—and, in fact, prefer—a wider range of temperatures,” when compared to occupants in mechanically conditioned buildings. The temperature range for naturally ventilated buildings “may extend well beyond the comfort zones published in ANSI/ASHRAE Standard 55-1992[2], and may more closely reflect the local patterns of outdoor climate change.” This may suggest that the application of natural ventilation in the U.S. climate zones may be more feasible than perceived (Thomas, 2002).

Ogulata (2000) studied the variation of indoor temperature due to heat transfer in the various components of a building. In this investigation, variation of indoor
temperature has been analyzed considering the variation of the heat gain by convection, radiation, infiltration, heat capacity of the materials used in the building, and the ambient temperature. He used Fourier series to express the changes in indoor temperature, outdoor temperature, and various heat gains.

Thomas and Kumar (2002) studied the factors affecting the indoor temperature changes and developed a model for determining duration of night time cooling hours for residential building. This study was carried out for five zones of the United States as divided by the US Department of Energy. One city representing each zone was considered for analysis. Analysis was carried out considering various factors like building material, properties of window material, internal mass of a building etc.

2.8 Scope for Natural Ventilation in the United States

Jones and West (2001) state, “In the United States, the reliance on mechanical ventilation is reinforced by standards such as ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*. This standard is on continuous maintenance. However, the language in the commonly used 1989 version is biased toward mechanical ventilation and the prescriptive specification of minimum outdoor air ventilation rates per person. While natural ventilation strategies might be developed and implemented using the indoor air quality procedure of this standard, few system designers are willing to take on this challenge or risk. Partly as a consequence, few U.S. buildings are designed for natural ventilation”. Research is going on in the United States for promoting natural ventilation. It can be seen that,
especially in some cities of the southern part of US, night time cooling can be implemented throughout the year with variations in duration. Attempts to implement natural ventilation are being carried out on buildings with high heat masses.

Kosik (October 2001) noted that although the United States has not yet embraced natural ventilation into mainstream design, sufficient research exists to propel the thrust in that direction. Kosik also recommends more U.S.-based research and application will be needed to popularize the idea.

2.9 Summary

The literature review can be summarized in the following points:

1. In order to reduce the energy consumption due to HVAC systems, natural ventilation can be adopted for a suitable time period.

2. Rather than depending totally upon one type of ventilation (i.e., natural or mechanical), a different system should be designed which will accommodate the benefits due to both the types.

3. The indoor temperature varies with the heat gains/losses due to various components of a building unit, as well as, with the changes in the moisture contents of indoor and outdoor air.

4. Thermal comfort is one of the top priorities of occupants. In order to maintain the thermal comfort, changes in indoor temperature should be studied carefully.
Night ventilation is not only a power-saving measure for the time during which it is implemented, but also influences the consumption of energy in the daytime.

The literature review clearly indicates that night cooling can be a viable option for energy conservation because of its ease of use and economy. It is necessary to develop a hybrid HVAC system which will give users the choice of using natural or mechanical ventilation with adjustable air changes per hour.

This research aims to help in designing such a hybrid ventilation system. This study expands the work done by Thomas and Kumar (2002), which was targeted for mainly residential buildings. While developing the models in this study, additional heat gains/losses parameters are considered (e.g., heat gains/losses due to motors, heat gains/losses due to human beings, and heat gains/losses due to lighting), as well as the effect of difference in indoor and outdoor moisture contents on indoor temperature is also considered. The duration for night ventilation is decided on the basis of indoor temperature and a software tool is offered as a design aid.
CHAPTER 3

HOURLY TEMPERATURE VARIATION IN A COMMERCIAL BUILDING

In a building, outside climatic conditions affect heat gains by heat transfer processes. The whole concept behind developing this model is to calculate the time during night for which total dependence on natural ventilation is possible. Inside temperature depends on the cooling, heat gains from various aspects like windows, people working inside the plant, lighting, and motors as well as the properties of the walls and roof. The temperature difference between outside and inside temperatures is used to promote the natural ventilation which results in savings in electricity usage.

This chapter combines the cooling load calculation in ‘Mark’s Standard Handbook for Mechanical Engineers’ (1987 and 1996), the equations available in the ASHRAE Handbook of Fundamentals (2001), and the research from various other sources (Lu et. al., 2002, Incropera et. al., 2002, and Lucas, Frank et. al., 2002) to arrive at a suitable equation for indoor air temperature at a specific time after night time cooling. Integrating the equation over a time interval for which the natural cooling is used, gives the resultant indoor temperature at the end of natural cooling.
3.1 Calculations of Heat Gains for a Manufacturing Plant

This section presents the equations of heat gain from various components of a manufacturing plant.

3.1.1 Heat Gains Through Walls and Roof

Exterior walls are in contact with two different thermal environments, i.e., outside and inside air. The outside air temperature is independent of the building parameters and is mainly determined by the seasonal variation in a given climate. The inside air temperature, however, is functionally dependent on various parameters such as outside air temperature, building materials, sensible heats (i.e. the heat energy stored in a substance as a result of an increase in its temperature) and latent heats (i.e. the heat energy which flows to or from the substance without change in temperature) due to internal loads like people, lights and motors, heating and cooling control strategy, radiation heat transfer and convection coefficients, and the difference between the moisture content of inside and outside air.

Exterior walls are usually characterized by a dominant heat transfer component through the wall. This implies that of all the heat transferred from one environment to the wall is transferred through the wall, when only part, and in some cases, none of the heat is released back to the same environment. Figure 3.1 shows the heat transfer through the wall when outside temperature is less than the inside temperature.

The technique for calculating the heat gains through exterior roofs and walls involves the concept of sol-air temperature. Sol-air temperature is that temperature of
the outdoor air, which in absence of all radiation exchanges, would give the same rate of heat

![Figure 3.1: Heat transfer through a Wall](image)

entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange with the outdoor surroundings, and convective heat exchange with the outdoor air.

Heat flux through walls and roof, $Q_w$ may be defined using the equation given below.

$$Q_w = \Sigma (A_w \cdot U_w) \cdot [T_{sa}(t) - T_i(t)] \quad (1)$$

Where,

$A_w$ is the area of the walls and roof, ft$^2$

$U_w$ is the thermal conductivity of walls/roof, $\frac{Btu}{hr \cdot ft^2 \cdot ^\circ F}$

$T_{sa}(t)$ is the sol-air temperature at time $t$, °F

$T_i(t)$ is the internal temperature of the room at time $t$, °F

### 3.1.2 Heat Gain Through a Window
Heat gain through a window is to be computed in two parts. The first part $Q_1$ is the simple heat transfer due to the difference in temperature between internal and external temperatures and is given as follows:

$$Q_1 = U_g * A_g * [T_o(t) - T_i(t)] \quad (2)$$

Where,

$U_g$ is the thermal conductivity of window, $\frac{Btu}{hr.\cdot ft^2 \cdot \circ F}$

$A_g$ is the area of a glass panel of the window, $\text{ft}^2$

$T_o(t)$ is the outdoor temperature at time $t$, $^\circ \text{F}$

The second part, $Q_2$ is the heat transfer due to solar heat gains given as:

$$Q_2 = q_b + q_d \quad (3)$$

The figure 4.2 shows the heat transfer through a window due to radiation. Resultant radiation consists of direct radiation, diffused radiation and ground reflected radiation.

![Figure 3.2: Heat transfer through a Window](image-url)
Both parts of $Q_2$ are explained below.

The first part is the direct beam solar heat gain is $q_b$ given as:

$$q_b = \text{SHGC}_\theta \cdot A_g \cdot E_D$$  \hspace{1cm} (4)

Where,

- $\text{SHGC}_\theta$ is the solar heat gain coefficient for incidence angle $\theta$
- $E_D$ is the surface direct irradiance.

The second part is the diffused solar heat gain $q_d$, given as:

$$q_d = \text{SHGC}_D \cdot A_g \cdot (E_r + E_d)$$  \hspace{1cm} (5)

Where,

- $\text{SHGC}_D$ is the diffused solar heat gain coefficient
- $E_r$ is the ground reflected irradiance and
- $E_d$ is the diffuse irradiance.

The SHGC values depend on type of window and can be computed from table 13 of Chapter 30 of ASHRAE Handbook of Fundamentals, 2001.

Hence,

$$Q_g = \sum (Q_2 + U_g \cdot A_g \cdot [T_o(t) - T_i(t)])$$  \hspace{1cm} (6)

Where,

- $Q_g$ = Total heat transfer through window, Btu /hr

### 3.1.3 Heat Gain Due To Employees

In the different states of activity, human beings give off heat and moisture. This heat consists of sensible as well as latent heat. Often these heat gains constitute a
large fraction of the total load. Even for the short term occupancy, the extra heat and moisture brought in by the employees may be significant.

The conversion of sensible heat gain from employees to space cooling load is affected by the thermal storage characteristics of that space, since some percentage of the sensible load is radiant energy. Latent heat gains are considered instantaneous. For representative rates at which moisture and heat are given off by human beings in the different states of activity, refer ASHRAE Fundamentals Handbook (2001), Chapter 29, Table 1. The heat gain due to employees is given by

$$Q_p = \text{Heat gain due to employees working inside, Btu/hr}$$ (7)

### 3.1.4 Heat Gain Due To Lights

Lighting is often a major component of space cooling load. Various factors have to be considered for the calculation of cooling load due to lights. Where lighting is installed below ceilings or in ceilings which are not part of return air plenums, all of the light heat is allocated as space heat gain. When the return air plenums are utilized, there are two potential conditions that must be evaluated by the designer:

- With unventilated lights, 15-20% of the light heat is absorbed by the return air passing over the light and will not contribute to the space heat gain.

- For ventilated lights, 40-60% of the heat will be absorbed by the return air passing through the light and will not contribute to the space heat gain.

The primary source of heat from lighting comes from light-emitting elements, or lamps, although significant additional heat may be generated from associated
appurtenances in the light fixtures that house such lamps. In this model development, only instantaneous heat gain from lights is considered. It is assumed that lighting is installed below ceilings. The instantaneous rate of heat gain from electric lighting may be calculated as:

\[ Q_{cl} = 3.41 \times W \times F_{ul} \times F_{sa} \]  

(8)

Where,

\( Q_{cl} \) = Heat gain in Btu/h

\( W \) = total light wattage

\( F_{ul} \) = lighting use factor, decimal fraction <= 1.0

\( F_{sa} \) = lighting special allowance factor.

### 3.1.5 Heat Gain Due To Motors

The amount of heat that actually contributes to the heat gain of a space is dependent on the motor and load arrangements. When both the motor and the driven equipment are in the conditioned space, the instantaneous heat gain due to the equipment is given by,

\[ Q_{em1} = 2545 \times (P_1/E_m) \times F_{um} \times F_{lm} \]  

(9)

Where,

\( Q_{em1} \) = Heat equivalent of equipment operation, Btu/h

\( P_1 \) = Motor power rating

\( E_m \) = Motor efficiency, decimal fraction < 1.0

\( F_{um} \) = Motor use factor, 1.0 or decimal fraction < 1.0

\( F_{lm} \) = Motor load factor, 1.0 or decimal fraction < 1.0
When the motor is placed outside the conditioned space, but the driven machine is inside, the instantaneous heat gain is given by:

$$Q_{em2} = 2545\times P_1^2 \times F_{um} \times F_{lm}$$  \hspace{1cm} (10)$$

When the motor is inside the conditioned space, but the driven machine is outside, the instantaneous heat gain is given by:

$$Q_{em3} = 2545\times P_3\times [(1- E_m)/E_m] \times F_{um} \times F_{lm}$$  \hspace{1cm} (11)$$

Hence, the total instantaneous heat gain is given by:

$$Q_{em} = Q_{em1} + Q_{em2} + Q_{em3}$$

For the average efficiencies and related data representative of typical electric motors, refer to the ASHRAE Handbook of Fundamentals (Chapter 29, Table 3A).

$$Q_{em} = 2545\times (P_1/E_m) \times F_{um} \times F_{lm} + 2545\times P_2 \times F_{um} \times F_{lm} + 2545\times P_3 \times [(1- E_m)/E_m] \times F_{um} \times F_{lm}$$  \hspace{1cm} (12)$$

### 3.1.6 Load due to Cooling by Natural Ventilation

The external nighttime temperatures are generally lower than the indoor room temperatures. When the interiors of a building are exposed to natural ventilation, heat transfer results in a slow lowering of indoor temperature. The change in temperature depends on the difference in temperature, the rate of air changes and the volume of air being exposed. The rate of air change is affected by the wind speed, area of openings and the orientation of the openings.

Thus the cooling load is given as:

$$Q_v = M_a \times C_a \times n_a \times (T_o(t) - T_i(t))$$  \hspace{1cm} (13)$$

Where,
\( n_a \) is number of air changes per hour

\( M_a \) is air mass inside the building, which is the product of volume of air inside the building unit and the density of air, lb

\( C_a \) is the coefficient of heat transfer of air

### 3.1.7 Load Due to the Difference Between Moisture Contents of Inside and Outside Air.

Moisture as a cooling load is a latent heat gain expressed in BTU per hour and is computed with the following equation.

\[
Q_m = 0.68 \times \text{Air flow} \times (M_o - M_i) \quad (14)
\]

Where,

\( Q_m \) = Latent heat gain due to moisture expressed in BTU/hr

\( M_o \) = Outdoor moisture content at design wet bulb temperature in gr/lb

\( M_i \) = Outdoor moisture content at design wet bulb temperature in gr/lb

Air flow is to be measured in ft\(^3\)/min.

### 3.2 Derivation of Internal Temperature Change with Respect to Time for a Manufacturing Plant Model

The indoor temperature in the building exposed to natural ventilation will depend on outdoor temperature, different sources of heat available inside and heat transfer characteristics of the outer covering of the building. The heat balance equation for inside air can be written as given below:

\[
M_a C_a \frac{dT_i}{dt} = Q_w + Q_g + Q_p + Q_{el} + Q_{em} + Q_v + Q_m \quad (15)
\]
Substituting the values for different heat gains from equations (1), (6), (7), (8), (12), (13), and (14) in the equation (15):

\[ M_a C_a (dT_i/dt) = \Sigma(A_w * U_w) * [T_{sa(t)} - T_i(t)] + \Sigma(SHG C_\theta * A_g * E_D + SHG C_D * A_g * (E_r + E_d) + U_g * A_g [T_o(t) - T_i(t)]) + Q_p + 3.41 * W * F_{ul} * F_{sa} + 2545 * (P_1/E_m) * F_{um} * F_{lm} + 2545 * P_2 * F_{um} * F_{lm} + 2545 * P_3 * [(1 - E_m) / E_m] * F_{um} * F_{lm} + M \frac{C_a}{n_a} (T_o(t) - T_i(t)) + 0.68 * \text{Air flow} \times (M_o - M_i) \]  

(16)

To reduce the complexity of the equation, constants will be assigned to values which will remain fixed at an instance of time, t.

\[ \Sigma(A_w * U_w) = A \]  

(17)

\[ \Sigma(SHG C_\theta * A_g * E_D + SHG C_D * A_g * (E_r + E_d)) = B \]  

(18)

\[ \Sigma U_g A_g = C \]  

(19)

\[ M_a C_a n_a = D \]  

(20)

\[ Q_p = E \]  

(21)

\[ 3.41 * W * F_{ul} * F_{sa} = F \]  

(22)

\[ 2545 * (P_1/E_m) * F_{um} * F_{lm} + 2545 * P_2 * F_{um} * F_{lm} + 2545 * P_3 * [(1 - E_m) / E_m] * F_{um} * F_{lm} = G \]  

(23)

\[ 0.68 * \text{Air flow} \times (M_o - M_i) = J \]  

(24)

\[ M_a C_a = X \]  

(25)

Equations (17) to (25) can be used to simplify equation (16) to

\[ X * (dT_i/dt) = A[T_{sa(t)} - T_i(t)] + B + C[T_o(t) - T_i(t)] + D(T_o(t) - T_i(t)) + E + F + G + J \]
\[ = A \ T_{sa}(t) - A \ T_i(t) + B + C \ T_0(t) - C \ T_i(t) - DT_i(t) + D \ T_0(t) + E + F + G + J \]
\[ = \{ A \ T_{sa}(t) + B + C \ T_0(t) + D \ T_0(t) + E + F + G + J\} - \{A + C + D\} T_i(t) \]
(26)

Again, assigning single terms to multiple fixed values in equation 26:

\[ X \cdot (dT_i/dt) = (Y - Z \ T_i) \]
\[ = - Z \ (T_i - (Y/Z)) \]  
(27)

Where,

\[ Y = \{ A \ T_{sa}(t) + B + C \ T_0(t) + D \ T_0(t) + E + F + G + J\} \]
(28)

\[ Z = (A + C + D) \]  
(29)

The equation (18) can now be written as:

\[ dT_i/(T_i - (Y/Z)) = (-Z/X)dt \]  
(30)

Integrating equation (30) between the limits of internal temperature \( T_1 \) at time \( t_1 \) and \( T_2 \) at time \( t_2 \),

\[ \int_{T_1}^{T_2} \frac{dT_i}{T_i - (Y/Z)} = \int_{t_1}^{t_2} \frac{-Zdt}{X} \]

\[ \log(T_2 - (Y/Z)) - \log(T_1 - (Y/Z)) = (-Z/X) \cdot (t_2 - t_1) \]  
(31)

Simplifying equation (31),

\[ \log((T_2 - (Y/Z))/(T_1 - (Y/Z))) = (-Z/X) \cdot (\Delta t) \]
\[
\frac{(T_2 - (Y/Z))}{(T_1 - (Y/Z))} = e^{(-Z/X) \cdot (\Delta t)}
\] (32)

Multiplying both sides of equation (32) by \((T_1 - (Y/Z))\) we get,

\[
T_2 - (Y/Z) = (T_1 - (Y/Z)) \cdot e^{(-Z/X) \cdot (\Delta t)}
\] (33)

Hence, the final equation for indoor air temperature at time \(t_2\) when the night cooling inside the manufacturing plant is stopped will read as:

\[
T_2 = \left( \frac{Y}{Z} \right) + (T_1 - \left( \frac{Y}{Z} \right)) \cdot e^{(-Z/X) \cdot (\Delta t)}
\] (34)

Refer to previous equations for values of the variables. This equation is same as obtained by Thomas and Kumar (2002), however, the parameter forming \(X\), \(Y\), and \(Z\) are different as the model studies residential buildings. This model does not consider the heat loss or gain due to lighting and people.

3.3 Limitations of the Manufacturing Plant Model

The model for indoor temperature as shown in equation (34) has the following limitations:

1. It is highly dependent on the data and equations in the ASHRAE Handbook (2001) and Mark’s Standard Handbook for Mechanical Engineers (1996). This would necessitate the availability of both books for design.

2. The current model assumes that the relative humidity is stagnant over the period of cooling time. This model will give more reliable results where variation in humidity is less.
3. The current model assumes the entire manufacturing plant unit as a single compartment. Internal partitions and resulting internal temperature flows are not considered in the model. It is assumed that the temperature varies uniformly in the manufacturing plant, which indicates no internal temperature differences and consequently no heat transfer across internal partitions.

3.4 Calculations of Heat Gains for an Office located at a Manufacturing Plant

This section presents the equations of heat gain from various components of the office located at the manufacturing plant.

The sources of heat gains for the manufacturing plant model and the office model are same except that there will not be any motor inside the office and the heat transfer to the furnishings inside must be taken into consideration.

3.4.1 Heat transfer to furnishing in a building

There will always be some internal mass in a building, and these have been loosely included in the term “furniture” for convenience of calculation. Heat transfer to furnishing $Q_f$, may be given as:

$$Q_f = \sum M_f * C_f * (dT_f/dt)$$  \hspace{1cm} (35)

where,

$M_f$ is the mass of furniture, lb

$C_f$ is the coefficient of heat transfer for the internal mass

$T_f$ is the temperature of the furniture/internal mass
The furniture is assumed to be an isothermal mass. Also high thermal conductivity and a large surface of the furnishing are assumed. Therefore it can be assumed that \( T_f \approx T_i \).

Thus, the equation (35) above can be modified to:

\[
Q_f = \sum M_f * C_f * (dT_i/dt) \quad (36)
\]

### 3.5 Derivation of Internal Temperature Change with Respect to Time for the for an Office Model

The indoor temperature in the building exposed to natural ventilation will depend on outdoor temperature, different sources of heat available inside and heat transfer characteristics of the outer covering of the building. The heat balance equation for inside air can be written as given below:

\[
M_a C_a (dT_i/dt) = Q_w + Q_g + Q_p + Q_{ei} + Q_v + Q_m + Q_f \quad (37)
\]

Substituting the values for different heat gains from equations (1), (6), (7), (8), (12), (14), and (36) in the equation (37):

\[
M_a C_a (dT_i/dt) = \Sigma (A_w * U_w)* [T_{sa}(t) – T_i(t)] + \Sigma \{ SHGC_{\theta} * A_g * E_{D} + SHGC_{D} * A_g * (E_r + E_d) + U_g * A_g [T_o(t) – T_i(t)]\} + Q_p + 3.41*W*F_{ul}*F_{sa} + M_a * C_a * n_a (T_o(t) – T_i(t)) + 0.68*Air \text{ flow}*(M_o-M_i) - \sum M_f * C_f * (dT_i/dt) \quad (38)
\]

To reduce the complexity of the equation, constants will be assigned to values which will remain fixed at an instance of time, t. (All the constants are same as previous except X which has been replaced by \( X_{of} \)).

\[
M_a C_a + \sum M_f * C_f = X_{of} \quad (39)
\]

Equations (17) to (22), (24), and (39) can be used to simplify equation (38) to
\[
X_{of} \cdot \frac{dT_i}{dt} = A[T_{sa}(t) - T_i(t)] + B + C[T_o(t) - T_i(t)] + D(T_o(t) - T_i(t)) + E + F + J
\]
\[
= A \cdot T_{sa}(t) - A \cdot T_i(t) + B + C \cdot T_o(t) - C \cdot T_i(t) - D(T_i(t) + D(T_o(t) + E + F + J)
\]
\[
= \{A \cdot T_{sa}(t) + B + C \cdot T_o(t) + D \cdot T_o(t) + E + F + J\} - \{(A + C + D) \cdot T_i(t)\}
\]

(40)

Again, assigning single terms to multiple fixed values in equation (40):

\[
X_{of} \cdot \frac{dT_i}{dt} = (Y - Z \cdot T_i)
\]
\[
= - Z \cdot T_i \cdot (Y/Z))
\]

(41)

where,

\[
Y = \{A \cdot T_{sa}(t) + B + C \cdot T_o(t) + D \cdot T_o(t) + E + F + J\}
\]

(42)

\[
Z = (A + C + D)
\]

(43)

The equation (18) can now be written as:

\[
dT_i/(T_i \cdot (Y/Z)) = (-Z/X_{of}) \cdot dt
\]

(44)

Integrating equation (41) between the limits of internal temperature \(T_1\) at time \(t_1\) and \(T_2\) at time \(t_2\),

\[
\int_{T_1}^{T_2} \frac{dT_i}{T_i - (Y/Z)} = \int_{t_1}^{t_2} - \frac{Zdt}{X_{of}}
\]

\[
\log(T_2 - (Y/Z)) - \log(T_1 - (Y/Z)) = (-Z/X_{of}) \cdot (t_2 - t_1)
\]

(45)

Simplifying equation (45),

\[
\log((T_2 - (Y/Z))/ (T_1 - (Y/Z))) = (-Z/X_{of}) \cdot (A \cdot t)
\]
\[
((T_2 - (Y/Z))/ (T_1 - (Y/Z))) = e^{(-Z/X) \Delta t} \tag{46}
\]

Multiplying both sides of equation (32) by \((T_1 - (Y/Z))\) we get,

\[
T_2 - (Y/Z) = (T_1 - (Y/Z)) * e^{(-Z/X) \Delta t} \tag{47}
\]

Hence, the final equation for indoor air temperature in the office at time \(t_2\) when the night cooling is stopped will read as:

\[
T_2 = (Y/Z) + (T_1 - (Y/Z)) * e^{(-Z/X) \Delta t} \tag{48}
\]

Refer to previous equations for values of the variables.

### 3.6 Limitations of the Office Model

The model for indoor temperature as shown in equation (48) has the following limitations:

1. It is highly dependent on the data and equations in the ASHRAE Handbook (2001) and Mark’s Standard Handbook for Mechanical Engineers (1996). This would necessitate the availability of both books for design.

2. The current model assumes that the relative humidity is stagnant over the period of cooling time.

3. The current model assumes the entire office as a single block. Internal partitions and resulting internal temperature flows are not considered in the model. It is assumed that the temperature varies uniformly in the office, which indicates no internal temperature differences and consequently no heat transfer across internal partitions.

4. Internal mass/furniture is assumed to have ideal properties.
CHAPTER 4
SPREADSHEET TOOL TO CALCULATE RESULTANT INDOOR TEMPERATURE

4.1 SPREADSHEET TOOL FOR A MANUFACTURING PLANT MODEL

In the calculation of a resultant indoor temperature, numerous tedious equations are involved. Solving these equations manually is a very time consuming process. But when these equations are automated, results can be produced in a short period of time. Automation helps the user run the model for various combinations of thermal loads in comparatively short time frame. The entire tool is in a single workbook divided into five worksheets, viz. Input sheet, Walls sheet, Lighting sheet, Intermediate sheet and the Final sheet.

4.1.1 Input Sheet

The Input Sheet requires the following values:

1. Start Time (in solar hours)
   (Solar hour: Time is measured from midnight to midnight (0 to 24). This system does not use a.m. or p.m. notations. (Think Quest Library, 2002))

2. Duration of cooling (in hours)

3. End time (in solar hours)
4. Volume of the plant (in ft$^3$)

5. Air changes per hour

6. Design temperature (ASHRAE Handbook of Fundamentals, 2001)

7. Daily Range (ASHRAE Handbook of Fundamentals, 2001)

(Daily range is the mean difference between the daily maximum and minimum temperatures)

8. Percentage of Daily Range (ASHRAE Handbook of Fundamentals, 2001)

(Percentage of daily range is used to factor in the time of day into the calculation of the outdoor temperature)

9. Indoor Temperature before advent of night cooling

10. Outside moisture content at designed wet bulb temperature (in gr/lb)

   (Wet-bulb temperature is measured using a standard mercury-in-glass thermometer, with the thermometer bulb wrapped in muslin, which is kept wet)

11. Inside moisture content at designed relative humidity (in gr/lb)

12. Motor specifications:

   - Total horsepower of all the motors of type A (both motor and driven equipment inside)
   - Total horsepower of all the motors of type B (motor outside and driven equipment outside)
   - Total horsepower of all the motors of type C (motor inside and driven equipment outside)

13. Number of people performing various activities inside the plant:

   - Light bench work
- Walking or light machine work
- Heavy work
- Heavy machine work (lifting)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
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<td>1</td>
<td>Inputs</td>
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<td></td>
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<td>2</td>
<td>Start time (solar hour)</td>
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<td>1</td>
<td></td>
</tr>
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<td>3</td>
<td>Duration of cooling (hours)</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>End time (solar hour)</td>
<td></td>
<td>6</td>
<td></td>
</tr>
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<td>5</td>
<td>Room/House Volume (cu. ft)</td>
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</tr>
<tr>
<td>6</td>
<td>Air Changes per hour</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Design Temperature (deg. F.)</td>
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<td>Daily Range</td>
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</tr>
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<td>Percentage/100</td>
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</tr>
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<td>10</td>
<td>Initial Temperature T (deg. F.)</td>
<td></td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Outside Moisture Content at Design Temperature (in gr/ft⁵)</td>
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<td>66.75</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Inside Moisture Content at Designed Relative Humidity (in gr/ft⁵)</td>
<td></td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Total Horse Power of all motors of type A</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>(Motor in and driven equipment in)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Total Horse Power of all motors of type B</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>(Motor out and driven equipment in)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Total Horse Power of all motors of type C</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>(Motor in and driven equipment out)</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>No. of people performing following activities:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Light Bench Work</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Walking or Light Machine Work</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Heavy Work</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Heavy Machine Work (Lifting)</td>
<td></td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1: Input sheet for a Manufacturing Plant
The above preliminary inputs are used to compute values of heat gain/loss components in a plant which are carried over to other sheets. Some values such as ‘Start Temperature’ are used directly in the final sheet.

The room volume is used to obtain the value $M_a * C_a * n$. It is multiplied with the density of air 0.075 lbs/ft$^3$ to obtain mass of air $M_a$. The air mass of a room is then multiplied with the specific heat of air, $C_a = 0.24$ and the air change rate per hour, $n$, to obtain the value $M_a * C_a * n$.

The equivalent outdoor temperature $T_o$ at end time $t$ is computed by the following formula (ASHRAE Handbook of Fundamentals, 2001):

$$T_o = \text{Design temperature} - (\text{Daily Range} \times \text{Percentage})$$

The design temperature for a particular month and location is drawn from Table 4A, Chapter 27; the daily range for a particular location from Table 1B, Chapter 27; and the percentage value from Table 17, Chapter 29 of the ASHRAE Handbook of Fundamentals, 2001.

4.1.2 Walls Sheet

This sheet is used to calculate values pertaining to walls and windows of the plant unit. The values (ASHRAE Handbook of Fundamentals, 2001, Ogulata, 2000, and Thomas, 2002) that are required in this sheet are:

1. Latitude and Longitude of the location under consideration
2. Local standard time meridian
3. Month (use combo box to select a month)
4. The orientation of the walls in question (from a combo box)
5. Exposed area of each wall
6. Thermal Conductivity of each wall

7. Area of each window

8. Thermal conductivity of the window

9. Direct solar heat gain coefficient (SHGC₀)

10. Diffuse solar heat gain coefficient (SHGC_D)

Figure 4.2a: Walls sheet for a Manufacturing Plant

The latitude (L) and longitude (LON) can be obtained from Table 1A, Chapter 27 (ASHRAE Handbook of Fundamentals, 2001). The local standard time meridian (LSM) depends on the time zone in which the city or area under consideration falls. Values can be obtained from Table 14, Chapter 29. Selecting the month from the combo box causes the constants for the solar equations to be selected and used to calculate sol-air temperatures. The constants are the equation of time in minutes (ET), declination in degrees (δ), apparent solar irradiation in Btu/h.ft², dimensionless constants A, B, and C. These constants for the respective months are taken from Table 7, Chapter 30 (ASHRAE Handbook of Fundamentals, 2001).
The first step is to calculate the apparent solar time (AST) in decimal hours. The earth’s orbital velocity varies throughout the year. Hence, the AST, which is determined by a solar time sundial varies from mean time as measured by a normal clock. This variation is the equation in time (ET). The conversion between local standard time and solar time involves two steps. First the equation of time is calculated, and then the longitude correction is added. The longitude correction is 4 minutes of time per degree difference between site longitude and longitude of LSM for that time zone. AST is given by the equation,

\[
AST = LST + \left(\frac{ET}{60}\right) + \left(\frac{LSM - LON}{15}\right)
\]

where,

AST = apparent solar time (decimal hours)
LST = local solar time
ET = equation of time
LON = local longitude (decimal ° of arc)
LSM = local standard time meridian (decimal ° of arc)

(Atlantic Standard Time = 60°
Eastern Standard Time = 75°
Central Standard Time = 90°
Mountain Standard Time = 105°
Pacific Standard Time = 120°)

The position of the sun in the sky is expressed in terms of the solar altitude \(\beta\) above the horizontal and the solar azimuth \(\Phi\) measured from the south. These angles, in turn, depend on the local latitude \(L\), solar declination \(\delta\) and the apparent solar time expressed as the hour angle (H), where
The solar declination $\delta$ is the angle between the earth-sun line and the equatorial plane, and it varies throughout the year.

Solar altitude $\beta$ is the angle between the line that leads to the sun and the horizontal plane. It is obtained by:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta$$  \hspace{1cm} (52)

Direct normal irradiance $E_{DN}$ is the direct normal irradiation at the earth’s surface and is computed using the formula:

$$E_{DN} = \left[ \frac{A}{\exp(B / \sin \beta)} \right] CN,$$  \hspace{1cm} (53)

where CN is the clearness number multiplier. However, the above equation is used only if $\beta > 0$.

In case $\beta = 0$, then $E_{DN} = 0$.  \hspace{1cm} (54)

Seasonal changes of dust, atmosphere, and variation in earth-sun distance cause changes in A and B.

The solar azimuth angle is the angle made by the horizontal plane and the north-south line and is calculated by:

$$\cos \Phi = (\sin \beta \sin L - \sin \delta)/(\cos \beta \cos L)$$  \hspace{1cm} (55)

The solar azimuth angle is positive for afternoon hours and negative for morning hours.

After this stage, all calculations will be performed for each wall separately. The solar azimuth angle is used to compute the surface solar azimuth $\gamma$,

$$\gamma = \Phi - \psi$$  \hspace{1cm} (56)
ψ is the surface azimuth, which depends on the orientation of the wall. The values for ψ for various orientations are available in Table 9, Chapter 30 (ASHRAE Handbook of Fundamentals, 2001). If surface solar azimuth angle is greater than 90° or less than –90°, the surface in question is in the shade.

The angle of incidence for any surface is the angle between the incoming rays and a line normal to that surface.

Incident angle θ,

\[ \cos \theta = ( \cos \beta \cdot \cos \gamma \cdot \sin \Sigma ) + ( \sin \beta \cdot \cos \Sigma ) \]  

(57)

Σ is the surface tilt from horizontal, 0 degrees for horizontal surfaces and 90 degrees for vertical surfaces.

Thus for vertical surfaces, equation (57) becomes

\[ \cos \theta = \cos \beta \cdot \cos \gamma \]  

(57b)

And for horizontal surfaces,

\[ \cos \theta = \sin \beta \]  

(58)

The total short- wavelength irradiance \( E_t \) reaching a surface is the sum of the direct solar irradiance \( E_D \), diffuse sky irradiance \( E_d \) and solar radiation reflected from surrounding surfaces \( E_r \).

The direct surface irradiance \( E_D \) is computed using the formula,

\[ E_D = E_{DN} \cdot \cos \theta \text{, when } \cos \theta > 0 \]  

(59)

Otherwise, \( E_D = 0. \)  

(60)
The calculation of \( E_d \) and \( E_r \) is a two-step process. First, the \( Y \) factor, which is the ratio of sky diffuse radiation on a vertical surface to sky diffuse radiation on a horizontal surface is calculated.

Sky diffuse factor (\( Y \)) is calculated as follows,

For \( \cos \theta > -0.2 \)

Sky diffuse factor, \( Y = 0.55 + (0.437 \times \cos \theta) + (0.313 \times \cos^2 \theta) \) \hspace{1cm} (61)

For \( \cos \theta < -0.2 \)

\( Y = 0.45 \) \hspace{1cm} (62)

The second step is the computation of the radiation values

The diffuse radiation \( E_d \) is given by,

For vertical surfaces, \( E_d = C \times Y \times E_{DN} \) \hspace{1cm} (63)

For surfaces other than vertical, \( E_d = C \times E_{DN} *(1 + \cos \Sigma)/2 \) \hspace{1cm} (64)

Finally, the ground reflected irradiance is given by,

\( E_r = E_{DN} * (C + \sin \beta) * \rho_g * (1 – \cos \Sigma)/2 \) \hspace{1cm} (65)

Finally, total surface irradiance,

\( E_t = E_D + E_d + E_r \) \hspace{1cm} (66)

The total irradiance is used to compute the sol-air temperature \( T_{sa} \) using the formula,

\[
T_{sa} = T_o + \frac{\alpha}{h_o} \times E_t + \frac{\varepsilon \Delta R}{h_o}
\] \hspace{1cm} (67)

where,

\( \alpha \) is the surface absorptance for solar radiation,

\( h_o \) is the coefficient of heat transfer at the outer surface,

\( \varepsilon \) is the hemispherical emittance of surface and
\( \Delta R \) is the difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature.

The factor \( \alpha / h_o \) is the ratio of absorptance of surface for solar radiation to the coefficient of heat transfer. It is taken as 0.15 for light colored surfaces and 0.30 for dark colored surfaces.

The factor \( \epsilon \Delta R / h_o \) is assumed 0 for vertical surfaces and 7° F for horizontal surfaces.

Figure 4.2b: Walls sheet for a Manufacturing Plant

After the computation of sol-air temperature for each wall is done, the next step is to input the exposed wall area, the conductivity for the wall, area of fenestration (window), conductivity for the same and finally, SHGC values of both direct and diffuse types of radiation.

The following computations are outputted to the intermediate spreadsheet:

1. Sum of the product of wall area and conductivity of the walls
2. Sum of product of above product and sol-air temperature
3. Sum of product of window area and conductivity
4. Sum of product of above and outdoor temperature
5. Sum of all irradiation incident on the window. This is composed of two sections. They are discussed in detail in Chapter 3.

### 4.1.3 Lighting Sheet

This worksheet contains all the information about lights, fixtures, and their properties. Using combo box, user needs to provide the information about the type of lighting used and number of bulbs of the same type used in the plant. The output consists of the heat produced in Btu/hr.

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
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<td>Wavelength</td>
<td>Special Allowance Factor</td>
<td>Fixture Watts</td>
<td>No. of Bulbs</td>
<td>Heat Gain</td>
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<td>30</td>
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</tr>
</tbody>
</table>

Figure 4.3: Lighting sheet for a Manufacturing Plant

### 4.1.4 Intermediate Sheet

This worksheet is only a transitional sheet between the input, walls, and lighting sheets and the final sheet.

In this sheet, the user does not input any value. This sheet uses the information from input, walls and lighting sheets to calculate the constants used to develop the model equation. It calculates A, B, C, D, E, F, and G which are then used to calculate X, Y, and Z.
As shown the various values for the final equation are calculated and tabulated and outputted to the final sheet.

The outputs to the final sheet are:

1. The \((Y/Z)\) value

2. The exponential value, \(e^{(Z/X)\Delta t}\)
4.1.5 Final Sheet

This sheet calculates the final indoor temperature after the night cooling. The initial indoor temperature and duration are obtained from the input sheet while the intermediate sheet gives the first part of the final equation.

\[
\text{Second Part} = (T_1 - \frac{Y}{Z}) \cdot e^{-\frac{Z}{X} \Delta t} \tag{68}
\]

The indoor temperature after night cooling is computed using the formula,

\[
T_2 = \frac{Y}{Z} + \text{Second Part} \tag{69}
\]

![Figure 4.5: Final Sheet for a manufacturing plant](image)

4.2 SPREADSHEET TOOL FOR AN OFFICE BUILDING MODEL
The entire tool is in a single workbook divided into five worksheets, viz. Input sheet, Walls sheet, Lighting sheet, Intermediate sheet and the Final sheet. Walls sheet, Lighting sheet, Intermediate sheet, and Final sheet have exactly the same interface and characteristics as those for the manufacturing plant tool described in earlier section. Input sheet is slightly different which is discussed below.

4.2.1 Input Sheet

The Input Sheet requires the following values:

1. Start Time (in solar hours)
2. Duration of cooling (in hours)
3. End time (in solar hours)
4. Volume of the office building
5. Air changes per hour
6. Design temperature (ASHRAE Handbook of Fundamentals, 2001)
7. Daily Range (ASHRAE Handbook of Fundamentals, 2001)
8. Percentage of Daily Range (ASHRAE Handbook of Fundamentals, 2001)
9. Indoor Temperature before the advent of night cooling
10. Outside moisture content at designed wet bulb (in gr/lb)
11. Inside moisture content at designed relative humidity (in gr/lb)
12. Internal mass inside the office building (in lb)
13. Number of people working inside the office

The internal mass (furniture) $M_f$ is used to compute the value $M_f \times C_f$, where $C_f$, the specific heat for internal mass, is assumed to have a value of 0.6.
Figure 4.6: Input sheet for an Office Building
CHAPTER 5

CASE STUDIES, RESULTS, AND DISCUSSION

The models developed in Chapter 3 calculate the indoor temperature at the end of nighttime cooling. One can judge the practical applicability of those models by running them under various conditions. The calculated final temperature can then be compared with the comfort conditions to check whether it lies in the comfort zone. The study is carried out for five cities from each zone as divided by the U.S. Department of Energy.

5.1 Selection of a Particular City for Night Cooling

The US Department of Energy has classified the mainland United States into five main climatic zones (refer to Appendix A). The classification is on the basis of heating and cooling degree-days.

Table 5.1: Climatic Zone Classification in the U.S.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Average Annual Cooling Degree-Days</th>
<th>Average Annual Heating Degree-Days</th>
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<tbody>
<tr>
<td>1</td>
<td>Under 2,000</td>
<td>Over 7,000</td>
</tr>
<tr>
<td>2</td>
<td>Under 2,000</td>
<td>5,500 to 7,000</td>
</tr>
<tr>
<td>3</td>
<td>Under 2,000</td>
<td>4,000 to 5,499</td>
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<tr>
<td>4</td>
<td>Under 2,000</td>
<td>Under 4,000</td>
</tr>
<tr>
<td>5</td>
<td>2,000 or More</td>
<td>Under 4,000</td>
</tr>
</tbody>
</table>
The studies were made for one city in each zone. Accordingly, the following five cities were selected:

1. Zone 1: Minneapolis, MN
2. Zone 2: Toledo, OH
3. Zone 3: Louisville, KY
4. Zone 4: Raleigh, NC
5. Zone 5: Brownsville, TX

The cases were studied for a manufacturing plant as well as for an office building assuming suitable data for each of them.

5.2 Data for a Manufacturing Plant Model

Properties of plant unit
- Area of plant unit: 300 ft * 200 ft
- Height of plant unit: 20 ft
- Initial indoor temperature: 85°F (before starting night time cooling)

Properties of walls
- Thermal conductivity (U-value): 0.068
- Clearness number (CN): 1
- Ground reflectivity ($\rho_g$): 0.2

Properties of windows
- Thermal conductivity (U-value): 0.56
- Diffuse solar heat gain coefficient (SHGC$_D$): 0.38
Incident solar heat gain coefficient (SHGC): depending on value of incident angle $\theta$ and corresponding value of SHGC from Table 13, Chapter 30, ASHRAE Fundamentals 2001.

**Properties of Motors**

The horsepower of all the motors of the same type (i.e., A, B or C) are added to represent an effective motor of that capacity. The assumed powers for one full shift are as follows:

- Type A: 200 hp
- Type B: 150 hp
- Type C: 50 hp
- $F_{um}$ (Motor use factor) = 1
- $F_{lm}$ (Motor load factor) = 1

**Properties of lights**

- $F_{ul}$ (lighting use factor) = 1
- Special allowance factor depends upon the specific type of light, ballast, fixture etc. (refer ‘2001 ASHRAE Fundamentals Handbook’, Chapter 29, Table 2)

- No. of ‘96 in T12 ES Lamp’ = 75
- No. of ‘Circlite 32 W Lamp’ = 160
- No. of ‘200 W Lamp’ = 86
- No. of ‘32 W Lamp’ = 75
- No. of ‘40 W Lamp’ = 75

**No. of workers performing various tasks**

- Light bench work: 30
Walking or light machine work: 100
Heavy work: 100
Heavy machine work: 70

Other assumptions

Each wall is assumed to have a single effective window.

It is assumed that HVAC system vents are used for providing natural ventilation.

Roof area is assumed to be same as the floor area. (considering only flat ceiling area)

Relative humidity is assumed at 50%.

The effects of change in relative humidity over the night cooling time are not taken into account.

All the walls are made up of the same material.

Same type of glass is used for all the windows.

The entire plant is assumed to be a single unit.

Air Changes per Hour (ACH) value is 6. (For a factory or a manufacturing plant, ACH values vary from 6 to 12, ASHRAE Handbook of Fundamentals (2001).

5.3 Case Studies Using the Manufacturing Plant Model

The plant model is studied for six different cases for finding the suitable hours for night cooling. These cases are given as follows:
Case 1

The variation of indoor air temperature with a fixed starting time at 12 midnight with varying durations i.e., 3, 5, and 8 hours was studied. The calculations for sol-air temperature, surface irradiance, equivalent outdoor temperature, solar intensity and such other factors were performed on a monthly basis.

Figure 5.1: Indoor temperature variation in Minneapolis, MN
Figure 5.2: Indoor temperature variation in Toledo, OH

Figure 5.3: Indoor temperature variation in Louisville, KY
Figure 5.4: Indoor temperature variation in Raleigh, NC

Figure 5.5: Indoor temperature variation in Brownsville, TX
It can be seen from the chart that the change in temperature varies for different zones for different months. Hence, the number of months selected for analysis for a particular zone is different. The temperature increases from the month of March to reach its peak value in July and then it starts decreasing.

**Case 2**

The variations of indoor temperature were studied by keeping the duration same with changing start and end times. The duration is fixed for five hours. Different starting times are 1 pm, 2 pm, 11 pm, and 12 midnight.

![Fixed Duration](image)

**Figure 5.6:** Temperature variations with fixed duration in Minneapolis, MN
Figure 5.7: Temperature variations with fixed duration in Toledo, OH

Figure 5.8: Temperature variations with fixed duration in Louisville, KY
Figure 5.9: Temperature variations with fixed duration in Raleigh, NC

Figure 5.10: Temperature variations with fixed duration in Brownsville, TX
It can be seen from the figures 5.6 to 5.10 that 12 midnight to 5 pm has always resulted in the lowest temperature among the four series.

Case 3

This case considered the variation of indoor temperature with respect to the natural ventilation rate. In modern HVAC systems, the natural ventilation rate can be controlled. The air changes per hour were 6, 8, 10, 11, and 12.

Figure 5.11: Variation of temperature with respect to ventilation rate in Minneapolis, MN
Figure 5.12: Variation of temperature with respect to ventilation rate in Toledo, OH

Figure 5.13: Variation of temperature with respect to ventilation rate in Louisville, KY
Figure 5.14: Variation of temperature with respect to ventilation rate in Raleigh, NC

Figure 5.15: Variation of temperature with respect to ventilation rate in Brownsville, TX
It can be seen from the graphs that the increase in air changes per hour drops the indoor temperature.

**Case 4**

In this case, the variation is studied with respect to varying coefficient of heat transfer for walls ($U_w$). The study was done with $U_w$ values 0.068, 0.092, 0.101. Three months representing relatively higher temperatures (Jun, July, August) are chosen for this study. Assumed cooling duration is 12 midnight to 8 a.m.

**Table 5.2: Description of Walls**

<table>
<thead>
<tr>
<th>Description of walls</th>
<th>$U_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light colored 4 in. brick, 2 in. of R-10 insulation, and 8 in. light weight concrete block</td>
<td>0.068</td>
</tr>
<tr>
<td>EIFS finish, R-5 insulation board, sheathing, gyp board</td>
<td>0.092</td>
</tr>
<tr>
<td>Brick, R-5 insulation board, sheathing, gyp board</td>
<td>0.101</td>
</tr>
</tbody>
</table>
Figure 5.16: Indoor temperature variations with respect to varying $U_w$ values in Minneapolis, MN

Figure 5.17: Indoor temperature variations with respect to varying $U_w$ values in Toledo, OH
Figure 5.18: Indoor temperature variations with respect to varying $U_w$ values in Louisville, KY.

Figure 5.19: Indoor temperature variations with respect to varying $U_w$ values in Raleigh, NC.
It can be seen from the graphs that increasing the coefficient of heat transfer of wall results in slight increase in temperature.

**Case 5**

Temperature variation due to varying relative humidity is studied. Initially the relative humidity was assumed as 50%. The study has been conducted with relative humidity values of 10%, 30%, 50%, 70%, and 90%. Assumed cooling duration is 12 midnight to 8 a.m.
Figure 5.21: Indoor temperature variations with respect to varying relative humidity in Minneapolis, MN

Figure 5.22: Indoor temperature variations with respect to varying relative humidity in Toledo, OH
Figure 5.23: Indoor temperature variations with respect to varying relative humidity in Louisville, KY

Figure 5.24: Indoor temperature variations with respect to varying relative humidity in Raleigh, NC
Figure 5.25: Indoor temperature variations with respect to varying relative humidity in Brownsville, TX

From the graphs above, documenting the calculated temperatures for case 5, variation of indoor temperature shows a fixed pattern for all the cities. There is a decrease in temperature with increase in relative humidity.

Case 6

The manufacturing plant may run for half shifts (i.e., for 4 hours) instead of full shifts. This case evaluates the variation in indoor temperature due to full shifts with half load as well as the variation in indoor temperature due to half shift with full load. Duration of half shift is four hours. In the case of half load, number of people, number of lights, and motor horse power are reduced to half.
Figure 5.26: Indoor temperature variation with respect to varying shifts and loads in Minneapolis, MN

Figure 5.27: Indoor temperature variation with respect to varying shifts and loads in Toledo, OH
Figure 5.28: Indoor temperature variation with respect to varying shifts and loads in Louisville, KY

Figure 5.29: Indoor temperature variation with respect to varying shifts and loads in Raleigh, NC
In the case of every city, the indoor temperature considerably decreases with the decrease in loads or shifts. From Figures 5.26 to 5.30, it can be observed that resultant indoor temperature decreases with the decrease in loads or duration of shift.

5.4 Data for an Office Model

Properties of plant unit:

- Area of plant unit: 50 ft * 40 ft
- Height of plant unit: 12 ft
- Initial indoor temperature: 80°F (before starting night time cooling)

Properties of walls:
Thermal conductivity (U-value): 0.068

Clearness number (CN): 1

Ground reflectivity ($\rho_g$): 0.2

**Properties of windows:**

- Thermal conductivity (U-value): 0.56
- Diffuse solar heat gain coefficient (SHGC_D): 0.38
- Incident solar heat gain coefficient (SHGC_θ): depending on value of incident angle $\theta$ and corresponding value of SHGC from Table 13, Chapter 30, ASHRAE Fundamentals 2001.

**Properties of lights:**

- $F_{ui}$ (lighting use factor) = 1
- Special allowance factor depends upon the specific type of light, ballast, fixture etc. (refer ‘2001 ASHRAE Fundamentals Handbook’, Chapter 29, Table 2)

- No. of ‘96 in T12 ES Lamp’ = 10
- No. of ‘Circlite 32 W Lamp’ = 40
- No. of ‘200 W Lamp’ = 0
- No. of ‘32 W Lamp’ = 0
- No. of ‘40 W Lamp’ = 0

**No. of workers performing various tasks:**

- Light bench work: 15

**Other assumptions:**

- Each wall is assumed to have a single effective window.
It is assumed that HVAC system vents are used for providing natural ventilation.

Roof area is assumed to be same as the floor area. (considering only flat ceiling area)

Relative humidity is assumed at 50%.

The effects of change in relative humidity over the night cooling time are not taken into account.

It is assumed that all the walls are made up of same material.

Same type of glass is used for all the windows.

The entire plant is assumed to be a single unit.

The furniture is assumed to be an isothermal mass.

Also assumed is high thermal conductivity and ideal surface of the furnishing.

Air Changes per Hour (ACH) value is 6. (For a factory or a manufacturing plant, ACH values vary from 6 to 12, ASHRAE Handbook of Fundamentals (2001).

5.5 Case Studies for an Office Model

Case 1

The variation of indoor air temperature with a fixed starting time at 12 midnight with varying durations (i.e. 3, 5, and 8) hours was studied. The calculations for sol-air temperature, surface irradiance, equivalent outdoor temperature, solar intensity and such other factors were performed on a monthly basis.
Figure 5.31: Indoor temperature variation in Minneapolis, MN

Figure 5.32: Indoor temperature variation in Toledo, OH
Figure 5.33: Indoor temperature variation in Louisville, KY

Figure 5.34: Indoor temperature variation in Raleigh, NC
Case 2

The variations of indoor temperature were studied by keeping the duration the same with changing start and end times. The duration is fixed for five hours. Different starting times are 1 pm, 2 pm, 11 pm, and 12 midnight.
Figure 5.36: Temperature variations with fixed duration in Minneapolis, MN

Figure 5.37: Temperature variations with fixed duration in Toledo, OH
Figure 5.38: Temperature variations with fixed duration in Louisville, KY

Figure 5.39: Temperature variations with fixed duration in Raleigh, NC
Case 3

This case considered the variation of indoor temperature with respect to the natural ventilation rate. In modern HVAC systems, the natural ventilation rate can be controlled. The air changes per hour are 5, 6, 7, and 8.
Figure 5.41: Indoor temperature variations with respect to varying relative humidity in Minneapolis, MN

Figure 5.42: Indoor temperature variations with respect to varying relative humidity in Toledo, OH
Figure 5.43: Indoor temperature variations with respect to varying relative humidity in Louisville, KY

Figure 5.44: Indoor temperature variations with respect to varying relative humidity in Raleigh, NC
Case 4

In this case, the variation is studied with respect to varying the coefficient of heat transfer for walls ($U_w$). The study was done with $U_w$ values 0.068, 0.092, 0.101. Three months representing relatively higher temperatures (Jun, July, and August) are chosen for this study.

<table>
<thead>
<tr>
<th>Description of a wall</th>
<th>$U_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light colored 4 in. brick, 2 in. of R-10 insulation, and 8 in. light weight concrete block</td>
<td>0.068</td>
</tr>
<tr>
<td>EIFS finish, R-5 insulation board, sheathing, gyp board</td>
<td>0.092</td>
</tr>
<tr>
<td>Brick, R-5 insulation board, sheathing, gyp board</td>
<td>0.101</td>
</tr>
</tbody>
</table>
Figure 5.46: Indoor temperature variations with respect to varying $U_w$ values in Minneapolis, MN

Figure 5.47: Indoor temperature variations with respect to varying $U_w$ values in Toledo, OH
Figure 5.48: Indoor temperature variations with respect to varying $U_w$ values in Louisville, KY

Figure 5.49: Indoor temperature variations with respect to varying $U_w$ values in Raleigh, NC
Temperature variation due to varying relative humidity is studied. Initially the relative humidity was assumed at 50%. The study has been conducted with relative humidity values of 10%, 30%, 50%, 70%, and 90%.

Figure 5.50: Indoor temperature variations with respect to varying $U_w$ values in Brownsville, TX

Case 5
Figure 5.51: Indoor temperature variations with respect to varying relative humidity in Minneapolis, MN

Figure 5.52: Indoor temperature variations with respect to varying relative humidity in Toledo, OH
Figure 5.53: Indoor temperature variations with respect to varying relative humidity in Louisville, KY
Figure 5.54: Indoor temperature variations with respect to varying relative humidity in Raleigh, NC

![Graph showing indoor temperature variations with respect to relative humidity in Raleigh, NC.](image)

Figure 5.55: Indoor temperature variations with respect to varying relative humidity in Brownsville, TX

**Case 6**

In this case, the mass inside the office has changed to check the variation in the indoor temperature. Initially the mass was assumed to be 6000 lb. This case studies the change in indoor air temperature when the masses are 4000 lb, 6000 lb, and 8000 lb respectively.
Figure 5.56: Indoor temperature variations with respect to varying mass in Minneapolis, MN

Figure 5.57: Indoor temperature variations with respect to varying mass in Toledo, OH
Figure 5.58: Indoor temperature variations with respect to varying mass in Louisville, KY

Figure 5.59: Indoor temperature variations with respect to varying mass in Raleigh, NC
Varying Mass

![Graph](image)

**Figure 5.60:** Indoor temperature variations with respect to varying mass in Brownsville, TX

### 5.6 General Observations and Discussion

From the above case studies, some general facts can be drawn, such as:

- Whereas natural cooling for longer duration can be carried out, the truth remains that internal temperature must always be within the comfort range for occupants at the time of normal use. Hence, natural cooling cannot be carried out for months in which the temperature indoors falls below the comfort ranges recommended by Brager et al. (2000) (refer to Appendix J).

- By varying the cooling times and ventilation rates, internal temperature variation can be controlled to suit thermal comfort requirements. The variation of duration
must be accompanied by optimal end time adjustments to ensure optimum derivation of the desired decrease or increase in indoor air temperature.

➢ The difference in the moisture contents of indoor and outdoor air impacts resultant temperature. As the designed relative humidity increases, a decrease in the value of resultant temperature is observed.

➢ To design an effective mixed mode system, detailed study of all the input parameters must be made. Each case will have its own peculiarities, and consequently, its own specific natural ventilation opportunities. A designer must endeavor to carry out various permutations to arrive at a desirable plan for a hybrid system.
CHAPTER 6

RECOMMENDATIONS

Based on the case studies in the previous chapter, this section recommends specific cooling times based on acceptable temperature ranges as suggested in the comfort chart given by Brager and Dear, 2000 (refer to Appendix H).

6.1 Methodology

The following procedure is followed to find the suitable duration of cooling.

- Using NOAA website, mean monthly outdoor temperatures for specific months and for specific cities are obtained. (Source: www.nws.noaa.gov/climatex.html)

- Using these outdoor temperatures, comfort zone for indoor temperatures is obtained with the help of the comfort chart by Brager and Dear, 2000 (refer to Appendix H). Using the different case studies mentioned in Chapter 5, suitable cooling time is found out for the above mentioned comfort zone.

- Recommendations are given based on two different settings. In one of them, the objective is to maximize comfort by choosing the temperature values at the middle portion of a chart, hence called ‘Conservative Setting’. In the second setting, the objective is to maximize the duration of cooling by choosing the temperature values at the border of a chart, hence called ‘Non Conservative Setting’. 
6.2 Regional Recommendations for a Manufacturing Plant

The U.S. is divided in five climatic zones as discussed in the previous chapter. The recommendations are made for one city in each zone.

Zone 1: Minneapolis, MN.

Using monthly average temperatures, comfort ranges are derived (refer to Table 6.1) for Minneapolis from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

➢ It is observed that for the months from November to March, the temperature resulting due to exposure to natural ventilation is lower than the lowest value of the comfort chart for those months. Hence, nighttime cooling is not recommended in those months for Zone 1.

➢ However, in the summer and spring months, short duration night cooling at low air change rates could be useful to reduce the air-conditioning loads.

(Unless mentioned otherwise, ACH = 6 as per the assumption made in Chapter 5)
Table 6.1: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Minneapolis, MN

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>46.4</td>
<td>62-75</td>
<td>63-73</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>May</td>
<td>59.2</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>June</td>
<td>68.3</td>
<td>69-81</td>
<td>71-80</td>
<td>12 to 8</td>
<td>12 to 5</td>
</tr>
<tr>
<td>July</td>
<td>73.1</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>August</td>
<td>70.5</td>
<td>70-82</td>
<td>72-81</td>
<td>12 to 8 with ACH=12</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>September</td>
<td>60.9</td>
<td>67-80</td>
<td>69-78</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>October</td>
<td>48.6</td>
<td>63-75</td>
<td>64-73</td>
<td>12 to 3</td>
<td>-</td>
</tr>
</tbody>
</table>

Zone 2: Toledo, Ohio. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.2) for Toledo from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- Night cooling can be a viable option for the months of April, May, June, July, August and September in Toledo, where indoor temperatures are well within comfort ranges.
- It is observed that for the months from November to March, the temperature resulting due to exposure to natural ventilation is lower than the lowest value of
the comfort chart for those months. Hence, nighttime cooling is not recommended in those months for Zone 2.

Table 6.2: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Toledo, OH

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>46.4</td>
<td>63-75</td>
<td>64-74</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>May</td>
<td>59.6</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>June</td>
<td>70</td>
<td>70-82</td>
<td>72-80</td>
<td>12 to 8</td>
<td>12 to 3</td>
</tr>
<tr>
<td>July</td>
<td>74</td>
<td>71-83</td>
<td>73-81</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>August</td>
<td>72.2</td>
<td>71-83</td>
<td>72.5-81</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>September</td>
<td>64</td>
<td>65.5-79</td>
<td>67-77</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>October</td>
<td>53.2</td>
<td>64-77</td>
<td>66-75</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 3: Louisville, KY. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.3) for Louisville from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- The comfort ranges are compared with the indoor temperatures. Night cooling can be used between the months of April to October.
- For the remaining months, night ventilation will not be conducive to Zone 3.
<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>47</td>
<td>62-75</td>
<td>63-73</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>April</td>
<td>56.4</td>
<td>65-78.5</td>
<td>66-77</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>May</td>
<td>65.9</td>
<td>69.5-81</td>
<td>71-79.5</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>June</td>
<td>74.4</td>
<td>71-83</td>
<td>72-81</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=12</td>
</tr>
<tr>
<td>July</td>
<td>78.5</td>
<td>72.5-84</td>
<td>74-82.5</td>
<td>1 to 6</td>
<td>12 to 5 with ACH=12</td>
</tr>
<tr>
<td>August</td>
<td>77.1</td>
<td>72-84</td>
<td>73.5-82</td>
<td>11 to 4 or 12 to 8 with ACH=12</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>September</td>
<td>70</td>
<td>70-82</td>
<td>72-81</td>
<td>12 to 8</td>
<td>12 to 5</td>
</tr>
<tr>
<td>October</td>
<td>58.3</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 10</td>
<td>12 to 8</td>
</tr>
</tbody>
</table>

Zone 4: Raleigh, NC. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.4) for Raleigh from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- Night ventilation will be unsuitable between the months of November and March.
- In this region, sharp changes are seen when the durations and end times are varied as compared to other regions. This can be exploited for maximizing the comfort of the occupants.
Table 6.4: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Raleigh, NC

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>50.7</td>
<td>64-76</td>
<td>65-74</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>April</td>
<td>59.1</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>May</td>
<td>67</td>
<td>68.5-81</td>
<td>70.5-79.5</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>June</td>
<td>74.7</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=12</td>
</tr>
<tr>
<td>July</td>
<td>78.8</td>
<td>72.5-84</td>
<td>74-82.5</td>
<td>1 to 6</td>
<td>12 to 5 with ACH=12</td>
</tr>
<tr>
<td>August</td>
<td>77.1</td>
<td>72-84</td>
<td>73.5-82</td>
<td>12 to 8 with ACH=12</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>September</td>
<td>71.1</td>
<td>69-82</td>
<td>71-80.5</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=11</td>
</tr>
<tr>
<td>October</td>
<td>60</td>
<td>67.5-79.5</td>
<td>69-77.5</td>
<td>12 to 8</td>
<td>N/A</td>
</tr>
<tr>
<td>November</td>
<td>50.9</td>
<td>64.5-76.5</td>
<td>63.5-74.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 5: Brownsville, TX. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.5) for Brownsville from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- Night cooling will be very beneficial for almost all the months.
For certain months, a two pronged strategy of increasing durations and delaying end times will allow night cooling for these months also. This can also be done with the changes in ventilation rate.

**Table 6.5: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Brownsville, TX**

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>60.5</td>
<td>67-80</td>
<td>69-78</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>February</td>
<td>62.9</td>
<td>68-80.5</td>
<td>70-79</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>March</td>
<td>69.5</td>
<td>69-82</td>
<td>71-81</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>April</td>
<td>74.5</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=11</td>
</tr>
<tr>
<td>May</td>
<td>80</td>
<td>73-85</td>
<td>74-83</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>June</td>
<td>83.4</td>
<td>74-86</td>
<td>75-84</td>
<td>12 to 8 with ACH=8</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>July</td>
<td>84.6</td>
<td>75-87</td>
<td>76-85</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=12</td>
</tr>
<tr>
<td>August</td>
<td>84.6</td>
<td>75-87</td>
<td>76-85</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=10</td>
</tr>
<tr>
<td>September</td>
<td>81.6</td>
<td>73-86</td>
<td>75-84</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=10</td>
</tr>
<tr>
<td>October</td>
<td>75.7</td>
<td>72-83</td>
<td>74-82</td>
<td>2 to 7</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>November</td>
<td>68.5</td>
<td>69-82</td>
<td>71-81</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>December</td>
<td>62</td>
<td>68-80</td>
<td>70-79</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
</tbody>
</table>
6.3 Regional Recommendations for an Office Building

Zone 1: Minneapolis, MN.

Using monthly average temperatures, comfort ranges are derived (refer to Table 6.6) for Minneapolis from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

➢ It is observed that for the months from October to March, the temperature resulting due to exposure to natural ventilation is lower than the lowest value of the comfort chart for those months. Hence, nighttime cooling is not recommended in those months for Zone 1.

➢ However, in the summer and spring months, night cooling with some variations in air changes rates could be useful to reduce the air-conditioning loads during the day.

(Unless mentioned otherwise, ACH = 4 as per the assumption made in Chapter 5)
Table 6.6: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Minneapolis, MN

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>46.4</td>
<td>62-75</td>
<td>63-73</td>
<td>12 to 3</td>
<td>N/A</td>
</tr>
<tr>
<td>May</td>
<td>59.2</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>June</td>
<td>68.3</td>
<td>69-81</td>
<td>71-80</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>July</td>
<td>73.1</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>1 to 6 or 2 to 7</td>
</tr>
<tr>
<td>August</td>
<td>70.5</td>
<td>70-82</td>
<td>72-81</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>September</td>
<td>60.9</td>
<td>67-80</td>
<td>69-78</td>
<td>12 to 8</td>
<td>12 to 3</td>
</tr>
<tr>
<td>October</td>
<td>48.6</td>
<td>63-75</td>
<td>64-73</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 2: Toledo, Ohio. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.7) for Toledo from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- Night cooling can be a very viable option for the months of April, May, June, July, August and September in Toledo, where indoor temperatures are well within comfort ranges.
- It is observed that for the months from October to March, the temperature resulting due to exposure to natural ventilation is lower than the lowest value of the comfort chart for those months. Hence, nighttime cooling is not recommended in those months for Zone 2.
### Table 6.7: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Toledo, OH

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>46.4</td>
<td>63-75</td>
<td>64-74</td>
<td>12 to 3</td>
<td>N/A</td>
</tr>
<tr>
<td>May</td>
<td>59.6</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 3</td>
<td>12 to 3</td>
</tr>
<tr>
<td>June</td>
<td>70</td>
<td>70-82</td>
<td>72-80</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>July</td>
<td>74</td>
<td>71-83</td>
<td>73-81</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>August</td>
<td>72.2</td>
<td>71-83</td>
<td>72.5-81</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>September</td>
<td>64</td>
<td>65.5-79</td>
<td>67-77</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>October</td>
<td>53.2</td>
<td>64-77</td>
<td>66-75</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 3: Louisville, KY. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.8) for Louisville from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- The comfort ranges are compared with the indoor temperatures. Night cooling can be used between the months of April to October.
- Indoor temperatures can be adjusted by varying the relevant factors.
- For the remaining months, night ventilation will not be conducive to Zone 3.
Table 6.8: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Louisville, KY

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>47</td>
<td>62-75</td>
<td>63-73</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>April</td>
<td>56.4</td>
<td>65-78.5</td>
<td>66-77</td>
<td>12 to 5</td>
<td>N/A</td>
</tr>
<tr>
<td>May</td>
<td>65.9</td>
<td>69.5-81</td>
<td>71-79.5</td>
<td>12 to 8</td>
<td>12 to 8 or 12 to 8 with ACH=6</td>
</tr>
<tr>
<td>June</td>
<td>74.4</td>
<td>71-83</td>
<td>72-81</td>
<td>12 to 8</td>
<td>2 to 7 or 12 to 8 with ACH=8</td>
</tr>
<tr>
<td>July</td>
<td>78.5</td>
<td>72.5-84</td>
<td>74-82.5</td>
<td>12 to 8 with ACH=5</td>
<td>12 to 5</td>
</tr>
<tr>
<td>August</td>
<td>77.1</td>
<td>72-84</td>
<td>73.5-82</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>September</td>
<td>70</td>
<td>70-82</td>
<td>72-81</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>October</td>
<td>58.3</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 4: Raleigh, NC. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.9) for Raleigh from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- Night ventilation will be unsuitable between the months of November and February.
In this region, sharp changes are seen when the durations and end times are varied as compared to other regions. This can be exploited for maximizing the comfort of the occupants.

### Table 6.9: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Raleigh, NC

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>50.7</td>
<td>64-76</td>
<td>65-74</td>
<td>12 to 2</td>
<td>N/A</td>
</tr>
<tr>
<td>April</td>
<td>59.1</td>
<td>66-79</td>
<td>68-77</td>
<td>12 to 8</td>
<td>N/A</td>
</tr>
<tr>
<td>May</td>
<td>67</td>
<td>68.5-81</td>
<td>70.5-79.5</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>June</td>
<td>74.7</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>11 to 4 or 12 to 8 with ACH=7</td>
</tr>
<tr>
<td>July</td>
<td>78.8</td>
<td>72.5-84</td>
<td>74-82.5</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>August</td>
<td>77.1</td>
<td>72-84</td>
<td>73.5-82</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>September</td>
<td>71.1</td>
<td>69-82</td>
<td>71-80.5</td>
<td>12 to 6 with ACH=5 or 6</td>
<td>2 to 7</td>
</tr>
<tr>
<td>October</td>
<td>60</td>
<td>67.5-79.5</td>
<td>69-77.5</td>
<td>12 to 2</td>
<td>N/A</td>
</tr>
<tr>
<td>November</td>
<td>50.9</td>
<td>64.5-76.5</td>
<td>63.5-74.5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Zone 5: Brownsville, TX. Using monthly average temperatures, comfort ranges are derived (refer to Table 6.10) for Brownsville from the chart provided in Appendix H. The results of case studies are then compared with the comfort ranges for arriving at cooling time recommendations.

- **Night cooling will be very beneficial for almost all the months.**
For certain months, a two-pronged strategy of increasing durations and delaying end times will allow night cooling for these months also. This can also be done with the changes in ventilation rate.

Table 6.10: Monthly Outdoor Temperature and Indoor Comfort Ranges with Recommendations for Brownsville, TX

<table>
<thead>
<tr>
<th>Months</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
<th>Non-Conservative Recommendations</th>
<th>Conservative Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>60.5</td>
<td>67-80</td>
<td>69-78</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>February</td>
<td>62.9</td>
<td>68-80.5</td>
<td>70-79</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
<tr>
<td>March</td>
<td>69.5</td>
<td>69-82</td>
<td>71-81</td>
<td>12 to 8</td>
<td>1 to 6</td>
</tr>
<tr>
<td>April</td>
<td>74.5</td>
<td>71-83</td>
<td>73-82</td>
<td>12 to 8</td>
<td>12 to 5</td>
</tr>
<tr>
<td>May</td>
<td>80</td>
<td>73-85</td>
<td>74-83</td>
<td>12 to 8</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>June</td>
<td>83.4</td>
<td>74-86</td>
<td>75-84</td>
<td>2 to 7</td>
<td>12 to 8 with ACH=12</td>
</tr>
<tr>
<td>July</td>
<td>84.6</td>
<td>75-87</td>
<td>76-85</td>
<td>12 to 8</td>
<td>12 to 5</td>
</tr>
<tr>
<td>August</td>
<td>84.6</td>
<td>75-87</td>
<td>76-85</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=11</td>
</tr>
<tr>
<td>September</td>
<td>81.6</td>
<td>73-86</td>
<td>75-84</td>
<td>12 to 8</td>
<td>12 to 5 or 12 to 8 with ACH=11</td>
</tr>
<tr>
<td>October</td>
<td>75.7</td>
<td>72-83</td>
<td>74-82</td>
<td>2 to 7 or 12 to 8 with ACH=8</td>
<td>12 to 5 with ACH=8</td>
</tr>
<tr>
<td>November</td>
<td>68.5</td>
<td>69-82</td>
<td>71-81</td>
<td>12 to 8</td>
<td>2 to 7</td>
</tr>
<tr>
<td>December</td>
<td>62</td>
<td>68-80</td>
<td>70-79</td>
<td>12 to 8</td>
<td>12 to 8</td>
</tr>
</tbody>
</table>
6.4 Comparison with Ogulata’s Model

Ogulata (2001) developed an analytical model which is based on the assumptions of the periodic heat flow in one direction through the various components of the model building at Adana-Turkey. The model is shown below:

\[ T_i(t) = a_{i0} + \sum_{n=1}^{\infty} (a_n \cos \omega_n t + b_n \sin \omega_n t) \]

Where,

- \( t \) is the solar hour measured from midnight solar hour
- \( a_{i0}, a_{in}, b_{in} \) are Fourier coefficients
- \( \omega_n \) is the frequency given by, \( n \cdot \omega_1 \) where, \( \omega_1 = \pi/12 \)

The models differ mainly in the computation of sol-air temperature. The sol-air temperature for the model developed in this chapter uses the equations and factors in the ASHRAE Handbook (2001) whereas Ogulata (2000) developed an equation for calculating sol-air temperature as a periodic function of time shown below:

\[ T_{sa}(t) = a_{so} + \sum_{n=1}^{\infty} a_{sn} \cos(\omega_n t - \psi_n) \]

Where,

- \( a_{so} \) and \( a_{sn} \) are Fourier coefficients
- \( \psi_n \) is given by the relation, \( \tan \psi_n = (b_{in}/a_{in}) \)

Ogulata’s model does not take into account the latent and sensible heat gains due to people, and/or lighting, and/or motors if any. Also, the effect of difference in moisture contents between indoor and outdoor air on indoor temperature is also not taken into consideration while deriving the equation.
6.5 Comparison with Thomas’s Model

Thomas and Kumar (2002) developed a model which is mainly based on the guidelines provided in ASHRAE Handbook of Fundamentals (2001). This model targets residential buildings. Equation for the model is given below:

\[ T_2 = \frac{Y}{Z} + (T_1 - \frac{Y}{Z}) \times e^{-\frac{Z}{X} \times (\Delta t)} \]

Where,

- \( T_2 \) is the resultant indoor temperature after night cooling.
- \( X, Y, \) and \( Z \) are variables used to reduce the complexity of the equation.
- \( \Delta t \) is the duration for which night cooling being carried out.

This equation is exactly same as obtained in this study, but the the components forming variables \( X, Y, \) and \( Z \) are different. Since this study is targeted at residential buildings, it assumes no motors inside the house. This model does not take into account the latent and sensible heat gains due to people, and/or lighting, and/or motors if any. Also, the effect of difference in moisture contents between indoor and outdoor air on indoor temperature is also not taken into consideration while deriving the equation.

6.6 Future Research

1. Individual climatic zones can be studied in detail for a more accurate result to account for variations within a zone.

2. Internal partitions could also be looked into for incorporation into the model.

The current model assumes that all the parts of the building experience temperature change uniformly.
3. This model assumes stagnant relative humidity. Effect of variation of relative humidity can be studied in more detail over shorter durations.

4. Daytime cooling should also be studied for the months falling in summer and spring.
REFERENCES


27. Website, http://www.tpub.com/content/construction/14279/img/14279-241_1.jpg


30. Xiaoshu Lu, and M. Viljanen, On Controlling Indoor Thermal and Moisture Content for An Occupied Building, Air Distribution in Rooms; Ventilation for
Appendix A

Map Showing Climatic Regions in USA

Appendix B

Map Showing the Relationship Among Dry Bulb Temperature, Wet Bulb Temperature, and Relative Humidity

Source: [http://www.tpub.com/content/construction/14279/img/14279_241_1.jpg](http://www.tpub.com/content/construction/14279/img/14279_241_1.jpg)
Appendix C

Constants Required to Calculate Total Radiance at a Surface

<table>
<thead>
<tr>
<th>Month</th>
<th>Equation of Time</th>
<th>Declination $\delta$</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>minutes</td>
<td>degrees</td>
<td>Btu/h*ft$^2$</td>
<td>Dimensionless Ratios</td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>-11.2</td>
<td>-20</td>
<td>390</td>
<td>0.142</td>
<td>0.058</td>
</tr>
<tr>
<td>February</td>
<td>-13.9</td>
<td>-10.8</td>
<td>385</td>
<td>0.144</td>
<td>0.060</td>
</tr>
<tr>
<td>March</td>
<td>-7.5</td>
<td>0</td>
<td>376</td>
<td>0.156</td>
<td>0.071</td>
</tr>
<tr>
<td>April</td>
<td>1.1</td>
<td>11.6</td>
<td>360</td>
<td>0.180</td>
<td>0.097</td>
</tr>
<tr>
<td>May</td>
<td>3.3</td>
<td>20</td>
<td>350</td>
<td>0.196</td>
<td>0.121</td>
</tr>
<tr>
<td>June</td>
<td>-1.4</td>
<td>23.45</td>
<td>345</td>
<td>0.205</td>
<td>0.134</td>
</tr>
<tr>
<td>July</td>
<td>-6.2</td>
<td>20.6</td>
<td>344</td>
<td>0.207</td>
<td>0.136</td>
</tr>
<tr>
<td>August</td>
<td>-2.4</td>
<td>12.3</td>
<td>351</td>
<td>0.201</td>
<td>0.122</td>
</tr>
<tr>
<td>September</td>
<td>7.5</td>
<td>0</td>
<td>365</td>
<td>0.177</td>
<td>0.092</td>
</tr>
<tr>
<td>October</td>
<td>15.4</td>
<td>-10.5</td>
<td>378</td>
<td>0.160</td>
<td>0.073</td>
</tr>
<tr>
<td>November</td>
<td>13.8</td>
<td>-19.8</td>
<td>387</td>
<td>0.149</td>
<td>0.063</td>
</tr>
<tr>
<td>December</td>
<td>1.6</td>
<td>-23.45</td>
<td>391</td>
<td>0.142</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Source: ASHRAE Handbook of Fundamentals, 2001 (Chapter 29, Table 16).
Appendix D

Table of Percentage of Daily Temperature Range

<table>
<thead>
<tr>
<th>Time, h</th>
<th>Percentage</th>
<th>Time, h</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>92</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>96</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>99</td>
<td>16</td>
<td>3</td>
</tr>
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<td>5</td>
<td>100</td>
<td>17</td>
<td>10</td>
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<td>6</td>
<td>98</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>93</td>
<td>19</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>84</td>
<td>20</td>
<td>47</td>
</tr>
<tr>
<td>9</td>
<td>71</td>
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</tbody>
</table>

Source: ASHRAE Handbook of Fundamentals, 2001 (Chapter 29, Table 17).
Appendix E

User’s manual for the Spreadsheet Tool for a Manufacturing Plant

This manual helps users in understanding about using the workbook.

The first step is to enable the visual basic macros embedded in the spreadsheet tool. These macros might not get activated if the macros security level is set as high. It is preferable to set the security level low for this particular application.

To do so, on opening the spreadsheet, click the “Enable Macros” button on the prompt that appears, shown below.

![Figure E.1: “Enable Macros” button](image)

The Workbook opens with the first worksheet, the “Input” sheet.
In this sheet, all rose colored fields require input values. The user has to be concerned only with the rose fields. The value to be entered in the field is written on the left of the field on the same row, illustrated in figure D.2. Combo boxes are provided to input the horsepower rating of the particular type of motors.

![Figure E.2: The Input sheet](image-url)
“Walls” is the next sheet in this section. As in the previous sheet, the ‘rose’ fields indicate values to be entered by the user. The month for which calculation is being carried out is to be selected from the combo box provided.

At three places, compute buttons are provided for the values of $E_{DN}$, $Y$ and $E_D$. These buttons are provided for added convenience and to make allowances to conditional statements.

For each wall, computation, combo boxes are provided to input the orientation of the walls.

The cell marked with ‘light orange’ indicates $E_{DN}$ value. The cells marked with peacock blue show some important values required for calculation.

Figure E.3A: The “Walls” sheet
Figure E.3B: The “Walls” sheet

In the “Lighting” sheet, combo buttons are provided to select the type of lighting. The user also needs to input the number of such lighting provided in the cells which are marked with ‘rose’.
Figure E.4: The “Lighting” sheet

In the “Final” sheet, the final values of indoor temperature, as well as various components of the equation, are displayed. Also available are navigation labels to display the other two sheets.
## Final Calculations for Indoor Temperature

<p>| | | | | | | | | | | | | |</p>
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</table>

Figure E.5: “Final” sheet
Appendix F

User’s manual for the Spreadsheet Tool for an Office Building

This manual helps the user in understanding about using the workbook.

The first step is to enable the visual basic macros embedded in the spreadsheet tool. As mentioned previously, these macros might not get activated if the macros security level is set on high. It is preferable to set the security level low for this particular application.

To do so, on opening the spreadsheet, click the “Enable Macros” button on the prompt that appears, shown below.

![Figure F.1: “Enable Macros” button](image)

The Workbook opens with the first worksheet, the “Input” sheet.
In this sheet, all rose colored fields require input values. The user has to be concerned only with the rose fields. The value to be entered in the field is written on the left of the field on the same row, illustrated in figure E.2.

Figure F.2: The Input sheet

“Walls” is the next sheet in this section. As in the previous sheet, the ‘rose’ fields indicate values to be entered by the user. The month for which calculation is being carried out is to be selected from the combo box provided.

At three places, compute buttons are provided for the values of $E_DN$, $Y$ and $E_D$. These buttons are provided for added convenience and to make allowances to conditional statements.
For each wall computation, combo boxes are provided to input the orientation of the walls.

The cell marked with ‘light orange’ indicates $E_{DN}$ value. The cells marked with peacock blue show some important values required for calculation.

Figure F.3A: The “Walls” sheet
Figure F.3B: The “Walls” sheet

In the “Lighting” sheet, combo buttons are provided to select the type of lighting. The user also needs to input the number of such lighting provided which is marked with ‘rose’.
Figure F.4: The “Lighting” sheet

In the “Final” sheet, the final values of indoor temperature, as well as various components of the equation, are displayed.
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
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</table>

Figure F.5: The “Final” sheet
Appendix G

This chapter includes various temperatures used for drawing the results and recommendations. Design temperature is used as an input in the model while mean monthly outdoor temperature is used to find comfort zones.

Toledo, OH

<table>
<thead>
<tr>
<th>Months</th>
<th>Design Temperature (°F)</th>
<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
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<tbody>
<tr>
<td>April</td>
<td>75.6</td>
<td>46.4</td>
<td>63-75</td>
<td>64-74</td>
</tr>
<tr>
<td>May</td>
<td>81.4</td>
<td>59.6</td>
<td>66-79</td>
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<td>June</td>
<td>86.6</td>
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<td>70-82</td>
<td>72-80</td>
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<tr>
<td>July</td>
<td>88.1</td>
<td>74</td>
<td>71-83</td>
<td>73-81</td>
</tr>
<tr>
<td>August</td>
<td>87.7</td>
<td>72.2</td>
<td>71-83</td>
<td>72.5-81</td>
</tr>
<tr>
<td>September</td>
<td>82.9</td>
<td>64</td>
<td>65.5-79</td>
<td>67-77</td>
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<tr>
<td>October</td>
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<td>53.2</td>
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Minneapolis, MN

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<th>Mean Monthly Outdoor Temperature (°F)</th>
<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
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<td>April</td>
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<td>July</td>
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<td>73-82</td>
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<tr>
<td>August</td>
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</tr>
<tr>
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Louisville, KY

<table>
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<th>Comfort Range (90% comfort) (°F)</th>
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<td>69.5-81</td>
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<td>June</td>
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<td>74.4</td>
<td>71-83</td>
<td>72-81</td>
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<td>74-82.5</td>
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<tr>
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<td>73.5-82</td>
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<td>70</td>
<td>70-82</td>
<td>72-81</td>
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<tr>
<td>October</td>
<td>76.8</td>
<td>58.3</td>
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<td>68-77</td>
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</table>

Raleigh, NC

<table>
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<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
</tr>
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<tbody>
<tr>
<td>March</td>
<td>73.9</td>
<td>50.7</td>
<td>64-76</td>
<td>65-74</td>
</tr>
<tr>
<td>April</td>
<td>78.5</td>
<td>59.1</td>
<td>66-79</td>
<td>68-77</td>
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<td>70.5-79.5</td>
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### Brownsville, TX

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<th>Comfort Range (80% comfort) (°F)</th>
<th>Comfort Range (90% comfort) (°F)</th>
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</thead>
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<td>69-78</td>
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<td>62.9</td>
<td>68-80.5</td>
<td>70-79</td>
</tr>
<tr>
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<td>69.5</td>
<td>69-82</td>
<td>71-81</td>
</tr>
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<tr>
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<td>75.7</td>
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<td>74-82</td>
</tr>
<tr>
<td>November</td>
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<td>68.5</td>
<td>69-82</td>
<td>71-81</td>
</tr>
<tr>
<td>December</td>
<td>78.7</td>
<td>62</td>
<td>68-80</td>
<td>70-79</td>
</tr>
</tbody>
</table>

### References

- Web link: [http://www.nws.noaa.gov/climatex.html](http://www.nws.noaa.gov/climatex.html)
Appendix H

Data derived from Example 4, Chapter 29, ASHRAE Handbook of Fundamentals, 2001

This data is used to describe the walls of the building in consideration.

1. Description of wall: Light colored, 4 in. brick, 2 in. insulation and 8 in. lightweight concrete block. An air space is included between the brick and insulation.

2. Overall thermal conductivity (U-factor) = 0.068 Btu/h ft²·°F.

3. Clearness number (CN) = 1

4. Ground reflectivity ($\rho_g$): 0.2

5. $\alpha/h_o = 0.15$ for light colored wall
Appendix I
Data Derived from Example 6, Chapter 29 and Table 13, Chapter 30, ASHRAE Handbook of Fundamentals, 2001

This data is used to describe the windows for the building unit described in Chapter 5.

2. Window U-factor: 0.56 Btu/h ft²°F
3. Window area: 20 ft²
4. $\text{SHGC}_D = 0.38$
5. $\text{SHGC}_\theta$ values for different values of incidence angle $\theta$

<table>
<thead>
<tr>
<th>Incidence angle $\theta$ (degrees)</th>
<th>$\text{SHGC}_\theta$</th>
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</thead>
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</tr>
<tr>
<td>60</td>
<td>0.35</td>
</tr>
<tr>
<td>70</td>
<td>0.27</td>
</tr>
<tr>
<td>80</td>
<td>0.14</td>
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</table>
Appendix J

Chart Showing Comfort Ranges for Natural Ventilation

Appendix K

Table Showing the Relationship between Grains of Moisture Per Pound of Dry Air Vs. Dew Point Temperature

Table 12.4.15  Grains of Moisture per Pound of Dry Air (Grams of Moisture per kg of Dry Air) vs. Dew-Point Temperature, °F

<table>
<thead>
<tr>
<th>DP (°F)</th>
<th>gr (g)</th>
<th>DP (°F)</th>
<th>gr (g)</th>
<th>DP (°F)</th>
<th>gr (g)</th>
<th>DP (°F)</th>
<th>gr (g)</th>
<th>DP (°F)</th>
<th>gr (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(−17.8)</td>
<td>5.50 (0.787)</td>
<td>16 (−8.9)</td>
<td>12.36 (1.767)</td>
<td>32 (0)</td>
<td>26.40 (3.775)</td>
<td>48 (8.9)</td>
<td>49.30 (0.708)</td>
<td>64 (17.8)</td>
<td>89.18 (12.733)</td>
</tr>
<tr>
<td>(−17.2)</td>
<td>5.79 (0.828)</td>
<td>17 (−8.3)</td>
<td>12.99 (1.857)</td>
<td>33 (0.6)</td>
<td>27.32 (3.935)</td>
<td>49 (9.4)</td>
<td>51.42 (0.735)</td>
<td>65 (18.3)</td>
<td>92.40 (13.213)</td>
</tr>
<tr>
<td>(−16.7)</td>
<td>6.10 (0.872)</td>
<td>18 (−7.8)</td>
<td>13.63 (1.949)</td>
<td>34 (1.1)</td>
<td>28.66 (4.098)</td>
<td>50 (10.0)</td>
<td>53.38 (0.763)</td>
<td>66 (18.9)</td>
<td>95.76 (13.694)</td>
</tr>
<tr>
<td>(−16.1)</td>
<td>6.43 (0.919)</td>
<td>19 (−7.2)</td>
<td>14.30 (2.045)</td>
<td>35 (1.7)</td>
<td>29.83 (4.265)</td>
<td>51 (10.6)</td>
<td>55.45 (0.792)</td>
<td>67 (19.4)</td>
<td>99.19 (14.184)</td>
</tr>
<tr>
<td>(−15.6)</td>
<td>6.77 (0.968)</td>
<td>20 (−6.7)</td>
<td>15.01 (2.146)</td>
<td>36 (2.2)</td>
<td>31.07 (4.443)</td>
<td>52 (11.1)</td>
<td>57.58 (0.824)</td>
<td>68 (20.0)</td>
<td>102.8 (14.700)</td>
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<tr>
<td>(−15.0)</td>
<td>7.12 (1.018)</td>
<td>21 (−6.1)</td>
<td>15.75 (2.252)</td>
<td>37 (2.8)</td>
<td>32.33 (4.623)</td>
<td>53 (11.7)</td>
<td>59.74 (0.854)</td>
<td>69 (20.6)</td>
<td>106.4 (15.215)</td>
</tr>
<tr>
<td>(−14.4)</td>
<td>7.50 (1.073)</td>
<td>22 (−5.5)</td>
<td>16.53 (2.364)</td>
<td>38 (3.3)</td>
<td>33.62 (4.807)</td>
<td>54 (12.2)</td>
<td>61.99 (0.885)</td>
<td>70 (21.1)</td>
<td>110.2 (15.759)</td>
</tr>
<tr>
<td>(−13.9)</td>
<td>7.89 (1.128)</td>
<td>23 (−5.0)</td>
<td>17.33 (2.478)</td>
<td>39 (3.9)</td>
<td>34.97 (5.000)</td>
<td>55 (12.8)</td>
<td>64.34 (0.920)</td>
<td>71 (21.7)</td>
<td>114.2 (16.330)</td>
</tr>
<tr>
<td>(−13.3)</td>
<td>8.30 (1.187)</td>
<td>24 (−4.4)</td>
<td>18.17 (2.598)</td>
<td>40 (4.4)</td>
<td>36.36 (5.199)</td>
<td>56 (13.3)</td>
<td>66.75 (0.945)</td>
<td>72 (22.2)</td>
<td>118.2 (16.903)</td>
</tr>
<tr>
<td>(−12.8)</td>
<td>8.73 (1.248)</td>
<td>25 (−3.9)</td>
<td>19.05 (2.724)</td>
<td>41 (5.0)</td>
<td>37.80 (5.405)</td>
<td>57 (13.9)</td>
<td>69.23 (0.990)</td>
<td>73 (22.8)</td>
<td>122.4 (17.503)</td>
</tr>
<tr>
<td>(−12.2)</td>
<td>9.18 (1.313)</td>
<td>26 (−3.3)</td>
<td>19.97 (2.856)</td>
<td>42 (5.5)</td>
<td>39.31 (5.621)</td>
<td>58 (14.4)</td>
<td>71.82 (1.027)</td>
<td>74 (23.3)</td>
<td>126.6 (18.104)</td>
</tr>
<tr>
<td>(−11.7)</td>
<td>9.65 (1.380)</td>
<td>27 (−2.8)</td>
<td>20.94 (2.994)</td>
<td>43 (6.1)</td>
<td>40.88 (5.846)</td>
<td>59 (15.0)</td>
<td>74.48 (1.065)</td>
<td>75 (23.9)</td>
<td>131.1 (18.747)</td>
</tr>
<tr>
<td>(−11.1)</td>
<td>10.15 (1.451)</td>
<td>28 (−2.2)</td>
<td>21.93 (3.136)</td>
<td>44 (6.7)</td>
<td>42.48 (6.073)</td>
<td>60 (15.6)</td>
<td>77.21 (1.104)</td>
<td>76 (24.4)</td>
<td>135.7 (19.405)</td>
</tr>
<tr>
<td>(−10.6)</td>
<td>10.66 (1.524)</td>
<td>29 (−1.7)</td>
<td>22.99 (3.287)</td>
<td>45 (7.2)</td>
<td>44.14 (6.312)</td>
<td>61 (16.1)</td>
<td>80.08 (1.141)</td>
<td>77 (25.0)</td>
<td>140.4 (20.077)</td>
</tr>
<tr>
<td>(−10.0)</td>
<td>11.20 (1.602)</td>
<td>30 (−1.1)</td>
<td>24.07 (3.442)</td>
<td>46 (7.8)</td>
<td>45.87 (6.559)</td>
<td>62 (16.7)</td>
<td>83.02 (1.187)</td>
<td>78 (25.6)</td>
<td>145.3 (20.778)</td>
</tr>
<tr>
<td>(−9.4)</td>
<td>11.77 (1.685)</td>
<td>31 (−0.6)</td>
<td>25.21 (3.605)</td>
<td>47 (8.3)</td>
<td>47.66 (6.815)</td>
<td>63 (17.2)</td>
<td>86.03 (1.230)</td>
<td>79 (26.1)</td>
<td>150.3 (21.493)</td>
</tr>
</tbody>
</table>

APPENDIX L

Program Listing for Spreadsheet Tool
Private Sub ComboBox1_Change()

If ComboBox1.Text = " " Then
    Cells(27, 10).Value = 0
ElseIf ComboBox1.Text = "0.05" Then
    Cells(27, 10).Value = 360
ElseIf ComboBox1.Text = "0.08" Then
    Cells(27, 10).Value = 580
ElseIf ComboBox1.Text = "0.125" Then
    Cells(27, 10).Value = 900
ElseIf ComboBox1.Text = "0.16" Then
    Cells(27, 10).Value = 1160
ElseIf ComboBox1.Text = "0.25" Then
    Cells(27, 10).Value = 1180
ElseIf ComboBox1.Text = "0.33" Then
    Cells(27, 10).Value = 1500
ElseIf ComboBox1.Text = "0.75" Then
    Cells(27, 10).Value = 2650
ElseIf ComboBox1.Text = "1" Then
    Cells(27, 10).Value = 3390
ElseIf ComboBox1.Text = "1.5" Then
    Cells(27, 10).Value = 4960
ElseIf ComboBox1.Text = "2" Then
    Cells(27, 10).Value = 6440
ElseIf ComboBox1.Text = "3" Then
    Cells(27, 10).Value = 9430
ElseIf ComboBox1.Text = "5" Then
    Cells(27, 10).Value = 15500
ElseIf ComboBox1.Text = "7.5" Then
    Cells(27, 10).Value = 22700
ElseIf ComboBox1.Text = "10" Then
    Cells(27, 10).Value = 29900
ElseIf ComboBox1.Text = "15" Then
    Cells(27, 10).Value = 44400
ElseIf ComboBox1.Text = "20" Then
    Cells(27, 10).Value = 58500
ElseIf ComboBox1.Text = "25" Then
    Cells(27, 10).Value = 72300
ElseIf ComboBox1.Text = "30" Then
    Cells(27, 10).Value = 85700
ElseIf ComboBox1.Text = "40" Then
    Cells(27, 10).Value = 114000
ElseIf ComboBox1.Text = "50" Then
    Cells(27, 10).Value = 143000
ElseIf ComboBox1.Text = "60" Then
    Cells(27, 10).Value = 172000
ElseIf ComboBox1.Text = "75" Then
    Cells(27, 10).Value = 212000
ElseIf ComboBox1.Text = "100" Then
    Cells(27, 10).Value = 283000
ElseIf ComboBox1.Text = "125" Then
    Cells(27, 10).Value = 353000
ElseIf ComboBox1.Text = "150" Then
    Cells(27, 10).Value = 420000
ElseIf ComboBox1.Text = "200" Then
    Cells(27, 10).Value = 569000
ElseIf ComboBox1.Text = "300" Then


Private Sub ComboBox2_Change()

    If ComboBox2.Text = " " Then
        Cells(30, 10).Value = 0
    ElseIf ComboBox2.Text = "0.05" Then
        Cells(30, 10).Value = 130
    ElseIf ComboBox2.Text = "0.08" Then
        Cells(30, 10).Value = 200
    ElseIf ComboBox2.Text = "0.125" Then
        Cells(30, 10).Value = 320
    ElseIf ComboBox2.Text = "0.16" Then
        Cells(30, 10).Value = 400
    ElseIf ComboBox2.Text = "0.25" Then
        Cells(30, 10).Value = 640
    ElseIf ComboBox2.Text = "0.33" Then
        Cells(30, 10).Value = 840
    ElseIf ComboBox2.Text = "0.75" Then
        Cells(30, 10).Value = 1900
    ElseIf ComboBox2.Text = "1" Then
        Cells(30, 10).Value = 2550
    ElseIf ComboBox2.Text = "1.5" Then
        Cells(30, 10).Value = 3820
    ElseIf ComboBox2.Text = "2" Then
        Cells(30, 10).Value = 5090
    ElseIf ComboBox2.Text = "3" Then
        Cells(30, 10).Value = 7640
    ElseIf ComboBox2.Text = "5" Then
        Cells(30, 10).Value = 12700
    ElseIf ComboBox2.Text = "7.5" Then
        Cells(30, 10).Value = 19100
    ElseIf ComboBox2.Text = "10" Then
        Cells(30, 10).Value = 24500
    ElseIf ComboBox2.Text = "15" Then
        Cells(30, 10).Value = 38200
    ElseIf ComboBox2.Text = "20" Then
        Cells(30, 10).Value = 50900
    ElseIf ComboBox2.Text = "25" Then
        Cells(30, 10).Value = 63600
    ElseIf ComboBox2.Text = "30" Then
        Cells(30, 10).Value = 76300
    ElseIf ComboBox2.Text = "40" Then
        Cells(30, 10).Value = 102000
    ElseIf ComboBox2.Text = "50" Then
        Cells(30, 10).Value = 127000
    ElseIf ComboBox2.Text = "60" Then
        Cells(30, 10).Value = 153000
    ElseIf ComboBox2.Text = "75" Then
        Cells(30, 10).Value = 191000
    ElseIf ComboBox2.Text = "100" Then
        Cells(30, 10).Value = 255000
    ElseIf ComboBox2.Text = "125" Then
        Cells(30, 10).Value = 318000

End Sub
ElseIf ComboBox2.Text = "150" Then
    Cells(30, 10).Value = 382000
ElseIf ComboBox2.Text = "200" Then
    Cells(30, 10).Value = 509000
ElseIf ComboBox2.Text = "250" Then
    Cells(30, 10).Value = 636000
End If

End Sub

Private Sub ComboBox3_Change()
    If ComboBox3.Text = "" Then
        Cells(33, 10).Value = 0
    ElseIf ComboBox3.Text = "0.05" Then
        Cells(33, 10).Value = 240
    ElseIf ComboBox3.Text = "0.08" Then
        Cells(33, 10).Value = 380
    ElseIf ComboBox3.Text = "0.125" Then
        Cells(33, 10).Value = 590
    ElseIf ComboBox3.Text = "0.16" Then
        Cells(33, 10).Value = 760
    ElseIf ComboBox3.Text = "0.25" Then
        Cells(33, 10).Value = 540
    ElseIf ComboBox3.Text = "0.33" Then
        Cells(33, 10).Value = 660
    ElseIf ComboBox3.Text = "0.75" Then
        Cells(33, 10).Value = 740
    ElseIf ComboBox3.Text = "1" Then
        Cells(33, 10).Value = 850
    ElseIf ComboBox3.Text = "1.5" Then
        Cells(33, 10).Value = 1140
    ElseIf ComboBox3.Text = "2" Then
        Cells(33, 10).Value = 1350
    ElseIf ComboBox3.Text = "3" Then
        Cells(33, 10).Value = 1790
    ElseIf ComboBox3.Text = "5" Then
        Cells(33, 10).Value = 2790
    ElseIf ComboBox3.Text = "7.5" Then
        Cells(33, 10).Value = 3640
    ElseIf ComboBox3.Text = "10" Then
        Cells(33, 10).Value = 4490
    ElseIf ComboBox3.Text = "15" Then
        Cells(33, 10).Value = 6210
    ElseIf ComboBox3.Text = "20" Then
        Cells(33, 10).Value = 7610
    ElseIf ComboBox3.Text = "25" Then
        Cells(33, 10).Value = 8680
    ElseIf ComboBox3.Text = "50" Then
        Cells(33, 10).Value = 15700
    ElseIf ComboBox3.Text = "60" Then
        Cells(33, 10).Value = 18900
    ElseIf ComboBox3.Text = "75" Then
        Cells(33, 10).Value = 21200
    ElseIf ComboBox3.Text = "100" Then
        Cells(33, 10).Value = 28300
    ElseIf ComboBox3.Text = "125" Then
        Cells(33, 10).Value = 35300
End If
ElseIf ComboBox3.Text = "150" Then
    Cells(33, 10).Value = 37800
ElseIf ComboBox3.Text = "200" Then
    Cells(33, 10).Value = 50300
ElseIf ComboBox3.Text = "250" Then
    Cells(33, 10).Value = 62900
End If
End Sub

Private Sub Worksheet_Activate()
    ComboBox1.Clear
    ComboBox1.AddItem " "
    ComboBox1.AddItem "0.05"
    ComboBox1.AddItem "0.08"
    ComboBox1.AddItem "0.125"
    ComboBox1.AddItem "0.16"
    ComboBox1.AddItem "0.25"
    ComboBox1.AddItem "0.33"
    ComboBox1.AddItem "0.75"
    ComboBox1.AddItem "1"
    ComboBox1.AddItem "1.5"
    ComboBox1.AddItem "2"
    ComboBox1.AddItem "3"
    ComboBox1.AddItem "5"
    ComboBox1.AddItem "7.5"
    ComboBox1.AddItem "10"
    ComboBox1.AddItem "15"
    ComboBox1.AddItem "20"
    ComboBox1.AddItem "25"
    ComboBox1.AddItem "30"
    ComboBox1.AddItem "40"
    ComboBox1.AddItem "50"
    ComboBox1.AddItem "60"
    ComboBox1.AddItem "75"
    ComboBox1.AddItem "100"
    ComboBox1.AddItem "125"
    ComboBox1.AddItem "150"
    ComboBox1.AddItem "200"
    ComboBox1.AddItem "300"
    ComboBox2.Clear
    ComboBox2.AddItem " "
    ComboBox2.AddItem "0.05"
    ComboBox2.AddItem "0.08"
    ComboBox2.AddItem "0.125"
    ComboBox2.AddItem "0.16"
    ComboBox2.AddItem "0.25"
    ComboBox2.AddItem "0.33"
    ComboBox2.AddItem "0.75"
    ComboBox2.AddItem "1"
    ComboBox2.AddItem "1.5"
    ComboBox2.AddItem "2"
    ComboBox2.AddItem "3"
    ComboBox2.AddItem "5"
    ComboBox2.AddItem "7.5"
    ComboBox2.AddItem "10"
ComboBox2.AddItem "15"
ComboBox2.AddItem "20"
ComboBox2.AddItem "25"
ComboBox2.AddItem "30"
ComboBox2.AddItem "40"
ComboBox2.AddItem "50"
ComboBox2.AddItem "60"
ComboBox2.AddItem "75"
ComboBox2.AddItem "100"
ComboBox2.AddItem "125"
ComboBox2.AddItem "150"
ComboBox2.AddItem "200"
ComboBox2.AddItem "300"

ComboBox3.Clear
ComboBox3.AddItem " 
ComboBox3.AddItem "0.05"
ComboBox3.AddItem "0.08"
ComboBox3.AddItem "0.125"
ComboBox3.AddItem "0.16"
ComboBox3.AddItem "0.25"
ComboBox3.AddItem "0.33"
ComboBox3.AddItem "0.75"
ComboBox3.AddItem "1"
ComboBox3.AddItem "1.5"
ComboBox3.AddItem "2"
ComboBox3.AddItem "3"
ComboBox3.AddItem "5"
ComboBox3.AddItem "7.5"
ComboBox3.AddItem "10"
ComboBox3.AddItem "15"
ComboBox3.AddItem "20"
ComboBox3.AddItem "25"
ComboBox3.AddItem "30"
ComboBox3.AddItem "40"
ComboBox3.AddItem "50"
ComboBox3.AddItem "60"
ComboBox3.AddItem "75"
ComboBox3.AddItem "100"
ComboBox3.AddItem "125"
ComboBox3.AddItem "150"
ComboBox3.AddItem "200"
ComboBox3.AddItem "300"

End Sub
Private Sub ComboBox1_Change()
If ComboBox1.Text = "January" Then
Cells(2, 11).Value = -11.2
Cells(3, 11).Value = -20
Cells(4, 11).Value = 390
Cells(5, 11).Value = 0.142
Cells(6, 11).Value = 0.058
End If
If ComboBox1.Text = "February" Then
Cells(2, 11).Value = -13.9
Cells(3, 11).Value = -10.8
Cells(4, 11).Value = 385
Cells(5, 11).Value = 0.144
Cells(6, 11).Value = 0.06
End If
If ComboBox1.Text = "March" Then
Cells(2, 11).Value = -7.5
Cells(3, 11).Value = 0
Cells(4, 11).Value = 376
Cells(5, 11).Value = 0.156
Cells(6, 11).Value = 0.071
End If
If ComboBox1.Text = "April" Then
Cells(2, 11).Value = 1.1
Cells(3, 11).Value = 11.6
Cells(4, 11).Value = 360
Cells(5, 11).Value = 0.18
Cells(6, 11).Value = 0.097
End If
If ComboBox1.Text = "May" Then
Cells(2, 11).Value = 3.3
Cells(3, 11).Value = 20
Cells(4, 11).Value = 350
Cells(5, 11).Value = 0.196
Cells(6, 11).Value = 0.121
End If
If ComboBox1.Text = "June" Then
Cells(2, 11).Value = -1.4
Cells(3, 11).Value = 23.45
Cells(4, 11).Value = 345
Cells(5, 11).Value = 0.205
Cells(6, 11).Value = 0.134
End If
If ComboBox1.Text = "July" Then
Cells(2, 11).Value = -6.2
Cells(3, 11).Value = 20.6
Cells(4, 11).Value = 344
Cells(5, 11).Value = 0.207
Cells(6, 11).Value = 0.136
End If
If ComboBox1.Text = "August" Then
Cells(2, 11).Value = -2.4
Cells(3, 11).Value = 12.3
Cells(4, 11).Value = 351
Cells(5, 11).Value = 0.201
Cells(6, 11).Value = 0.122
End If
If ComboBox1.Text = "September" Then
    Cells(2, 11).Value = 7.5
    Cells(3, 11).Value = 0
    Cells(4, 11).Value = 365
    Cells(5, 11).Value = 0.177
    Cells(6, 11).Value = 0.092
End If
If ComboBox1.Text = "October" Then
    Cells(2, 11).Value = 15.4
    Cells(3, 11).Value = -10.5
    Cells(4, 11).Value = 378
    Cells(5, 11).Value = 0.16
    Cells(6, 11).Value = 0.073
End If
If ComboBox1.Text = "November" Then
    Cells(2, 11).Value = 13.8
    Cells(3, 11).Value = -19.8
    Cells(4, 11).Value = 387
    Cells(5, 11).Value = 0.149
    Cells(6, 11).Value = 0.063
End If
If ComboBox1.Text = "December" Then
    Cells(2, 11).Value = 1.6
    Cells(3, 11).Value = -23.45
    Cells(4, 11).Value = 391
    Cells(5, 11).Value = 0.142
    Cells(6, 11).Value = 0.057
End If
End Sub

Private Sub ComboBox2_Change()
If ComboBox2.Text = "N" Then
    Cells(32, 3).Value = 180
ElseIf ComboBox2.Text = "NE" Then
    Cells(32, 3).Value = -135
ElseIf ComboBox2.Text = "E" Then
    Cells(32, 3).Value = -90
ElseIf ComboBox2.Text = "SE" Then
    Cells(32, 3).Value = -45
ElseIf ComboBox2.Text = "S" Then
    Cells(32, 3).Value = 0
ElseIf ComboBox2.Text = "SW" Then
    Cells(32, 3).Value = 45
ElseIf ComboBox2.Text = "W" Then
    Cells(32, 3).Value = 90
ElseIf ComboBox2.Text = "NW" Then
    Cells(32, 3).Value = 135
End If
End Sub

Private Sub ComboBox3_Change()
If ComboBox3.Text = "N" Then
    Cells(32, 5).Value = 180
ElseIf ComboBox3.Text = "NE" Then...
Cells(32, 5).Value = -135
ElseIf ComboBox3.Text = "E" Then
Cells(32, 5).Value = -90
ElseIf ComboBox3.Text = "SE" Then
Cells(32, 5).Value = -45
ElseIf ComboBox3.Text = "S" Then
Cells(32, 5).Value = 0
ElseIf ComboBox3.Text = "SW" Then
Cells(32, 5).Value = 45
ElseIf ComboBox3.Text = "W" Then
Cells(32, 5).Value = 90
ElseIf ComboBox3.Text = "NW" Then
Cells(32, 5).Value = 135
End If
End Sub

Private Sub ComboBox4_Change()
If ComboBox4.Text = "N" Then
Cells(32, 7).Value = 180
ElseIf ComboBox4.Text = "NE" Then
Cells(32, 7).Value = -135
ElseIf ComboBox4.Text = "E" Then
Cells(32, 7).Value = -90
ElseIf ComboBox4.Text = "SE" Then
Cells(32, 7).Value = -45
ElseIf ComboBox4.Text = "S" Then
Cells(32, 7).Value = 0
ElseIf ComboBox4.Text = "SW" Then
Cells(32, 7).Value = 45
ElseIf ComboBox4.Text = "W" Then
Cells(32, 7).Value = 90
ElseIf ComboBox4.Text = "NW" Then
Cells(32, 7).Value = 135
End If
End Sub

Private Sub ComboBox5_Change()
If ComboBox5.Text = "N" Then
Cells(32, 9).Value = 180
ElseIf ComboBox5.Text = "NE" Then
Cells(32, 9).Value = -135
ElseIf ComboBox5.Text = "E" Then
Cells(32, 9).Value = -90
ElseIf ComboBox5.Text = "SE" Then
Cells(32, 9).Value = -45
ElseIf ComboBox5.Text = "S" Then
Cells(32, 9).Value = 0
ElseIf ComboBox5.Text = "SW" Then
Cells(32, 9).Value = 45
ElseIf ComboBox5.Text = "W" Then
Cells(32, 9).Value = 90
ElseIf ComboBox5.Text = "NW" Then
Cells(32, 9).Value = 135
End If
End Sub

Private Sub CommandButton1_Click()
If Cells(38, 3).Value > 0 Then
  Cells(42, 3).Value = (Cells(38, 3).Value) * (Cells(25, 5).Value)
Else
  Cells(42, 3).Value = 0
End If

If Cells(38, 5).Value > 0 Then
  Cells(42, 5).Value = (Cells(38, 5).Value) * (Cells(25, 5).Value)
Else
  Cells(42, 5).Value = 0
End If

If Cells(38, 7).Value > 0 Then
  Cells(42, 7).Value = (Cells(38, 7).Value) * (Cells(25, 5).Value)
Else
  Cells(42, 7).Value = 0
End If

If Cells(38, 9).Value > 0 Then
  Cells(42, 9).Value = (Cells(38, 9).Value) * (Cells(25, 5).Value)
Else
  Cells(42, 9).Value = 0
End If

If Cells(38, 11).Value > 0 Then
Else
  Cells(42, 11).Value = 0
End If

End Sub

Private Sub CommandButton2_Click()
  If Cells(14, 12).Value > 0 Then
    Cells(25, 5).Value = (Cells(4, 11).Value / Cells(18, 12))
  Else
    Cells(25, 5).Value = 0
  End If
End Sub

Private Sub CommandButton3_Click()
  If Cells(38, 3).Value > -0.2 Then
    Cells(47, 3).Value = 0.55 + (0.437 * (Cells(38, 3).Value)) + (0.313 * (Cells(44, 3).Value))
  Else
    Cells(47, 3).Value = 0.45
  End If

  If Cells(38, 5).Value > -0.2 Then
    Cells(47, 5).Value = 0.55 + (0.437 * (Cells(38, 5).Value)) + (0.313 * (Cells(44, 5).Value))
  Else
    Cells(47, 5).Value = 0.45
  End If

  If Cells(38, 7).Value > -0.2 Then
    Cells(47, 7).Value = 0.55 + (0.437 * (Cells(38, 7).Value)) + (0.313 * (Cells(44, 7).Value))
  Else
    Cells(47, 7).Value = 0.45
  End If

  If Cells(38, 9).Value > -0.2 Then
    Cells(47, 9).Value = 0.55 + (0.437 * (Cells(38, 9).Value)) + (0.313 * (Cells(44, 9).Value))
  Else
    Cells(47, 9).Value = 0.45
  End If
End Sub
Cells(47, 9).Value = 0.55 + (0.437 * (Cells(38, 9).Value)) + (0.313 * (Cells(44, 9).Value))
Else
Cells(47, 9).Value = 0.45
End If
If Cells(38, 11).Value > -0.2 Then
Cells(47, 11).Value = 0.55 + (0.437 * (Cells(38, 11).Value)) + (0.313 * (Cells(44, 11).Value))
Else
Cells(47, 11).Value = 0.45
End If
End Sub

Private Sub Label1_Click()
Sheet1.Activate
End Sub

Private Sub Label2_Click()
Sheet3.Activate
End Sub

Private Sub Worksheet_Activate()
ComboBox1.Clear
ComboBox1.AddItem " "
ComboBox1.AddItem "January"
ComboBox1.AddItem "February"
ComboBox1.AddItem "March"
ComboBox1.AddItem "April"
ComboBox1.AddItem "May"
ComboBox1.AddItem "June"
ComboBox1.AddItem "July"
ComboBox1.AddItem "August"
ComboBox1.AddItem "September"
ComboBox1.AddItem "October"
ComboBox1.AddItem "November"
ComboBox1.AddItem "December"
ComboBox2.Clear
ComboBox2.AddItem "N"
ComboBox2.AddItem "NE"
ComboBox2.AddItem "E"
ComboBox2.AddItem "SE"
ComboBox2.AddItem "S"
ComboBox2.AddItem "SW"
ComboBox2.AddItem "W"
ComboBox2.AddItem "NW"
ComboBox3.Clear
ComboBox3.AddItem "N"
ComboBox3.AddItem "NE"
ComboBox3.AddItem "E"
ComboBox3.AddItem "SE"
ComboBox3.AddItem "S"
ComboBox3.AddItem "SW"
ComboBox3.AddItem "W"
ComboBox3.AddItem "NW"
ComboBox4.Clear
ComboBox4.AddItem "N"
ComboBox4.AddItem "NE"
ComboBox4.AddItem "E"
ComboBox4.AddItem "SE"
ComboBox4.AddItem "S"
ComboBox4.AddItem "SW"
ComboBox4.AddItem "W"
ComboBox4.AddItem "NW"

ComboBox5.Clear
ComboBox5.AddItem "N"
ComboBox5.AddItem "NE"
ComboBox5.AddItem "E"
ComboBox5.AddItem "SE"
ComboBox5.AddItem "S"
ComboBox5.AddItem "SW"
ComboBox5.AddItem "W"
ComboBox5.AddItem "NW"

End Sub
Private Sub ComboBox1_Change()
If ComboBox1.Text = "" Then
Cells(3, 3).Value = "0 
Cells(3, 4).Value = 0
Cells(3, 5).Value = 0
Cells(3, 6).Value = 0
ElseIf ComboBox1.Text = "96 in T12 ES Lamp" Then
Cells(3, 3).Value = "Electronic"
Cells(3, 4).Value = 60
Cells(3, 5).Value = 1.15
Cells(3, 6).Value = 69
ElseIf ComboBox1.Text = "96 in T12 ES HO Lamp" Then
Cells(3, 3).Value = "Electronic"
Cells(3, 4).Value = 95
Cells(3, 5).Value = 0.84
Cells(3, 6).Value = 80
ElseIf ComboBox1.Text = "96 in T8 Lamp" Then
Cells(3, 3).Value = "Electronic"
Cells(3, 4).Value = 59
Cells(3, 5).Value = 0.98
Cells(3, 6).Value = 58
End If
End Sub

Private Sub ComboBox2_Change()
If ComboBox2.Text = "" Then
Cells(6, 3).Value = "0 
Cells(6, 4).Value = 0
Cells(6, 5).Value = 0
Cells(6, 6).Value = 0
ElseIf ComboBox2.Text = "Circlite 20 W Lamp" Then
Cells(6, 3).Value = "Mag-PH"
Cells(6, 4).Value = 20
Cells(6, 5).Value = 1
Cells(6, 6).Value = 20
ElseIf ComboBox2.Text = "Circlite 22 W Lamp" Then
Cells(6, 3).Value = "Mag-PH"
Cells(6, 4).Value = 22
Cells(6, 5).Value = 0.91
Cells(6, 6).Value = 20
ElseIf ComboBox2.Text = "Circlite 32 W Lamp" Then
Cells(6, 3).Value = "Mag-PH"
Cells(6, 4).Value = 32
Cells(6, 5).Value = 1.25
Cells(6, 6).Value = 40
End If
End Sub

Private Sub ComboBox3_Change()
If ComboBox3.Text = "" Then
Cells(9, 3).Value = "0 
Cells(9, 4).Value = 0
Cells(9, 5).Value = 0
Cells(9, 6).Value = 0
ElseIf ComboBox3.Text = "35 W Lamp" Then
Cells(9, 3).Value = "HID"
Cells(9, 4).Value = 35
Cells(9, 5).Value = 1.31
Cells(9, 6).Value = 46
ElseIf ComboBox3.Text = "50 W Lamp" Then
  Cells(9, 3).Value = "HID"
  Cells(9, 4).Value = 50
  Cells(9, 5).Value = 1.32
  Cells(9, 6).Value = 66
ElseIf ComboBox3.Text = "70 W Lamp" Then
  Cells(9, 3).Value = "HID"
  Cells(9, 4).Value = 35
  Cells(9, 5).Value = 1.31
  Cells(9, 6).Value = 46
ElseIf ComboBox3.Text = "100 W Lamp" Then
  Cells(9, 3).Value = "HID"
  Cells(9, 4).Value = 100
  Cells(9, 5).Value = 1.38
  Cells(9, 6).Value = 138
ElseIf ComboBox3.Text = "150 W Lamp" Then
  Cells(9, 3).Value = "HID"
  Cells(9, 4).Value = 150
  Cells(9, 5).Value = 1.25
  Cells(9, 6).Value = 188
ElseIf ComboBox3.Text = "200 W Lamp" Then
  Cells(9, 3).Value = "HID"
  Cells(9, 4).Value = 200
  Cells(9, 5).Value = 1.25
  Cells(9, 6).Value = 250
End If
End Sub

Private Sub ComboBox4_Change()
  If ComboBox4.Text = " " Then
    Cells(12, 3).Value = "0"
    Cells(12, 4).Value = 0
    Cells(12, 5).Value = 0
    Cells(12, 6).Value = 0
  ElseIf ComboBox4.Text = "32 W Lamp" Then
    Cells(12, 3).Value = "HID"
    Cells(12, 4).Value = 32
    Cells(12, 5).Value = 1.34
    Cells(12, 6).Value = 43
  ElseIf ComboBox4.Text = "50 W Lamp" Then
    Cells(12, 3).Value = "HID"
    Cells(12, 4).Value = 50
    Cells(12, 5).Value = 1.44
    Cells(12, 6).Value = 72
  ElseIf ComboBox4.Text = "70 W Lamp" Then
    Cells(12, 3).Value = "HID"
    Cells(12, 4).Value = 70
    Cells(12, 5).Value = 1.36
    Cells(12, 6).Value = 95
  ElseIf ComboBox4.Text = "100 W Lamp" Then
    Cells(12, 3).Value = "HID"
    Cells(12, 4).Value = 100
Cells(12, 5).Value = 1.28
Cells(12, 6).Value = 128
ElseIf ComboBox4.Text = "150 W Lamp" Then
  Cells(12, 3).Value = "HID"
  Cells(12, 4).Value = 150
  Cells(12, 5).Value = 1.27
  Cells(12, 6).Value = 190
ElseIf ComboBox4.Text = "175 W Lamp" Then
  Cells(12, 3).Value = "HID"
  Cells(12, 4).Value = 175
  Cells(12, 5).Value = 1.23
  Cells(12, 6).Value = 215
End If
End Sub

Private Sub ComboBox5_Change()
  If ComboBox5.Text = " " Then
    Cells(15, 3).Value = "0 "
    Cells(15, 4).Value = 0
    Cells(15, 5).Value = 0
    Cells(15, 6).Value = 0
  ElseIf ComboBox5.Text = "40 W Lamp" Then
    Cells(15, 3).Value = "HID"
    Cells(15, 4).Value = 40
    Cells(15, 5).Value = 1.25
    Cells(15, 6).Value = 50
  ElseIf ComboBox5.Text = "50 W Lamp" Then
    Cells(15, 3).Value = "HID"
    Cells(15, 4).Value = 50
    Cells(15, 5).Value = 1.48
    Cells(15, 6).Value = 74
  ElseIf ComboBox5.Text = "75 W Lamp" Then
    Cells(15, 3).Value = "HID"
    Cells(15, 4).Value = 75
    Cells(15, 5).Value = 1.24
    Cells(15, 6).Value = 93
  ElseIf ComboBox5.Text = "100 W Lamp" Then
    Cells(15, 3).Value = "HID"
    Cells(15, 4).Value = 100
    Cells(15, 5).Value = 1.25
    Cells(15, 6).Value = 125
  ElseIf ComboBox5.Text = "175 W Lamp" Then
    Cells(15, 3).Value = "HID"
    Cells(15, 4).Value = 175
    Cells(15, 5).Value = 1.17
    Cells(15, 6).Value = 205
  End If
End Sub

Private Sub Worksheet_Activate()
  ComboBox1.Clear
  ComboBox1.AddItem " "
  ComboBox1.AddItem "96 in T12 ES Lamp"
  ComboBox1.AddItem "96 in T12 ES HO Lamp"
  ComboBox1.AddItem "96 in T8 Lamp"
ComboBox2.Clear
ComboBox2.AddItem " "
ComboBox2.AddItem "Circlite 20 W Lamp"
ComboBox2.AddItem "Circlite 22 W Lamp"
ComboBox2.AddItem "Circlite 32 W Lamp"

ComboBox3.Clear
ComboBox3.AddItem " "
ComboBox3.AddItem "35 W Lamp"
ComboBox3.AddItem "50 W Lamp"
ComboBox3.AddItem "70 W Lamp"
ComboBox3.AddItem "100 W Lamp"
ComboBox3.AddItem "150 W Lamp"
ComboBox3.AddItem "200 W Lamp"

ComboBox4.Clear
ComboBox4.AddItem " "
ComboBox4.AddItem "32 W Lamp"
ComboBox4.AddItem "50 W Lamp"
ComboBox4.AddItem "70 W Lamp"
ComboBox4.AddItem "100 W Lamp"
ComboBox4.AddItem "150 W Lamp"
ComboBox4.AddItem "175 W Lamp"

ComboBox5.Clear
ComboBox5.AddItem " "
ComboBox5.AddItem "40 W Lamp"
ComboBox5.AddItem "50 W Lamp"
ComboBox5.AddItem "75 W Lamp"
ComboBox5.AddItem "100 W Lamp"
ComboBox5.AddItem "175 W Lamp"

End Sub