Chapter 3

Thermal Comfort

Contents of Chapter 3

Instructions

Review Sections 1.6.1 and 1.6.2 for a discussion of the factors that affect human comfort.

Read the chapter. Re-read the parts of the chapter that are emphasized in the summary.

Objectives of Chapter 3

Having studied this chapter you should be able to:

List seven factors influencing thermal comfort.
Explain why thermal comfort depends on the individual as well as the thermal conditions.
Choose acceptable thermal design conditions.

3.1 Introduction: What is Thermal Comfort?

In Chapter 1, Sections 1.6.1 and 1.6.2, we introduced the Personal Environmental Model that illustrated the main factors that affect human comfort in an environment. In this chapter, we will focus only on those specific factors that affect thermal comfort.

Thermal comfort is primarily controlled by a building's heating, ventilating and air-conditioning systems, though the architectural design of the building may also have significant influences on thermal comfort.

This chapter is largely based on *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*.[1] In this text, we will abbreviate the title to "*Standard 55*." For a much more in-depth discussion of thermal comfort and the way experimental results are presented, see Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*.[2]

Standard 55 defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation." There is no way "state of mind" can be measured. As a result, all comfort data are based on researchers asking questions about particular situations, to build a numerical model of comfort conditions. The model is based on answers to questions by many people under many different experimental conditions.

In the next section, we will consider seven factors influencing comfort and then define acceptable thermal comfort conditions.

3.2 Seven Factors Influencing Thermal Comfort

You are a person, so you already know a lot about thermal comfort. You have a lifetime of experience. You know that physical exertion makes you "hot and sweaty." You know you can be more comfortable in a cooler space if you wear more clothes, or warmer clothes. You know that the air temperature matters and that the radiant heat from a fire can help keep you warm and comfortable. You have likely experienced feeling hot in a very humid space and been aware of a cold draft. You have anticipated that a space will be warm and comfortable or cool and comfortable when you get inside.

As a result, you have personal experience of the *seven* factors that affect thermal comfort.

Personal

1. *Activity level*
2. *Clothing*

Individual Characteristics

3. *Expectation*

Environmental Conditions and Architectural Effects

4. *Air temperature*
5. *Radiant temperature*
6. *Humidity*
7. *Air speed*.

1. Activity Level

The human body continuously produces heat through a process call "metabolism." This heat must be emitted from the body to maintain a fairly constant core temperature, and ideally, a comfortable skin temperature. We produce heat at a minimum rate when asleep. As activity increases, from sitting to walking to running, so the metabolic heat produced increases.

The standard measure of activity level is the "met." One met is the metabolic rate (heat output per unit area of skin) for an individual who is seated and at rest. Typical activity levels and the corresponding met values are shown in *Figure 3-1*.

2. Clothing

In occupied spaces, clothing acts as an insulator, slowing the heat loss from the body. As you know from experience, if you are wearing clothing that is an effective insulator, you can withstand, and feel comfortable in lower temperatures. To predict thermal comfort we must have an idea of the clothing that will be worn by the occupants.

Due to the large variety of materials, weights, and weave of fabrics, clothing estimates are just rough estimates. Each article has an insulating value, unit "clo."

For example: a long-sleeved sweat shirt is 0.34 clo, straight trousers (thin) are 0.15 clo, light underwear is 0.04 clo, ankle-length athletic socks are 0.02 clo, and sandals are 0.02 clo. These clo values can be added to give an overall clothing insulation value. In this case, the preceding set of clothes has an overall clothing insulation value of 0.57 clo.

Typical values for clothing ensembles are shown in *Figure 3-2*. All include shoes, socks, and light underwear.

Later in this chapter we will introduce a chart, *Figure 3-4*, that illustrates comfortable conditions with 0.5 clo and 1.0 clo. As you can see from *Figure 3-2*, 0.5 clo is very light clothing, and 1.0 clo is heavy indoor clothing.

3. Occupants' Expectations

People's expectations affect their perception of comfort in a building. Consider the following three scenarios that all occur on a very hot day:

- A person walks into an air-conditioned office building. The person expects the building to be thermally comfortable.

Activity	met*
Sleeping	0.7
Reading or writing, seated in office	1.0
Filing, standing in office	1.4
Walking about in office	1.7
Walking 2 mph	2.0
Housecleaning	2.0 to 3.4
Dancing, social	2.4 to 4.4
Heavy machine work	4.0

Figure 3-1 Typical Metabolic Heat Generation for Various Activities (*Standard 55*, Normative Appendix A, Extracted data) [* $1\,\text{met} = 50\,\text{kcal}/(\text{h} \cdot \text{m}^2)$]

Ensemble Description	clo*
Trouser, short sleeve shirt	0.57
Knee-length skirt, short-sleeve shirt (sandals)	0.54
Trousers, long-sleeved shirt, suit jacket	0.96
Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater	1.10
Long-sleeved coveralls, T-shirt	0.72

Figure 3-2 Typical Insulation Values for Clothing Ensembles (*Standard 55*, Appendix B, Table B-1, extracted data) [*1 clo = $0.155\,m^2 \cdot K/W$]

- A person walks into a prestigious hotel. The person expects it to be cool, regardless of the outside temperature.
- A person walks into an economical apartment building with obvious natural ventilation and open windows. The person has lower expectations for a cool environment. The person anticipates, even hopes, that it will be cooler inside, but not to the same extent as the air-conditioned office building or the hotel.

Standard 55 recognizes that the expectations for thermal comfort are significantly different in buildings where the occupants control opening windows, as compared to a mechanically cooled building. To address this difference, *Standard 55* provides different criteria for naturally ventilated buildings, as compared to the criteria for mechanically cooled, air-conditioned buildings.

This difference in expectations also shows up in buildings where occupants have a thermostat to control their zone. In general, if occupants have a thermostat in their space, they are more satisfied with their space, even when the performance of the thermostat is very restricted or non-existent (dummy thermostat). This is discussed in Section 3.3, "Conditions for Comfort."

4. Air Temperature

When we are referring to air temperature in the context of thermal comfort, we are talking about the temperature in the space where the person is located. This temperature can vary from head to toe and can vary with time.

5. Radiant Temperature

Radiant heat is heat that is transmitted from a hotter body to a cooler body with no effect on the intervening space. An example of radiant heat transfer occurs when the sun is shining on you. The **radiant temperature** is the temperature at which a black sphere would emit as much radiant heat as it received from its surroundings.

In an occupied space, the floor, walls, and ceiling may be at a temperature that is very close to the air temperature. For internal spaces, where the temperature of the walls, floor, and ceiling are almost the same as the air temperature, the radiant temperature will be constant in all directions and virtually the same as the air temperature.

When a person is sitting close to a large window on a cold, cloudy, winter day, the average radiant temperature may be significantly lower than the air temperature. Similarly, in spaces with radiant floors or other forms of radiant heating, the average radiant temperature will be above the air temperature during the heating season.

6. Humidity

Low humidity: We know that, for some people, low humidity can cause specific problems, like dry skin, dry eyes, and static electricity. However, low humidity does not generally cause thermal discomfort. *Standard 55* does not define minimum humidity as an issue of thermal discomfort, nor does it address those individuals who have severe responses to low humidity.

High humidity: *Standard 55* does define the maximum humidity ratio for comfort at 0.012 kg/kg which is also 12 g/kg. This level of moisture in the air can also cause serious mold problems in the building and to its contents, since it is equivalent to 100% relative humidity at 17 °C.

7. Air Speed

The higher the air speed over a person's body, the greater the cooling effect. Air velocity that exceeds 0.2 meters per second (m/s), or cool temperatures combined with any air movement, may cause discomfort—a draft. Drafts are most noticeable when they blow across the feet and/or the head level, because individuals tend to have less protection from clothing in these areas of their body.

3.3 Conditions for Comfort

Standard 55 deals with indoor thermal comfort in normal living environments and office-type environments. It does not deal with occupancy periods of less than 15 minutes.

The Standard recognizes that individual perceptions of comfort can be significantly modified by prior exposure. For example, consider people coming into a building that is air-conditioned to 28 °C on a very hot day, when it is 40 °C outside. The building is obviously cooler as they enter it, a pleasant experience. After they have been in the building for half an hour, they will have adjusted and will probably consider the building excessively warm.

When considering issues of comfort, the Standard addresses two situations:

1. **Buildings with occupant-operable windows**
2. **Buildings with mechanically conditioned spaces**.

Situation 1: Buildings with Occupant-Operable Windows

People behave differently when they have windows they can control. They have different, less demanding, expectations due to their knowledge of the

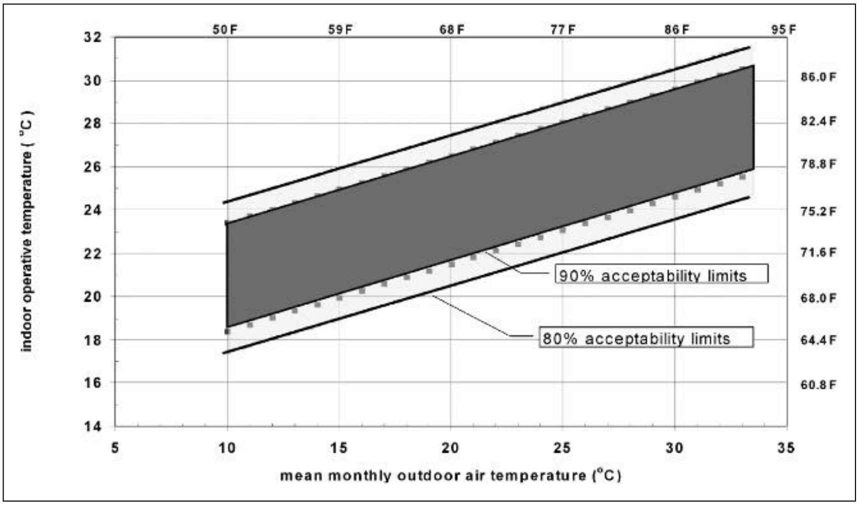

Figure 3-3 Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces (*Standard 55*, Figure 5.3)

external environment and their control over the windows. They will also choose how they dress, knowing that the building temperatures will be significantly influenced by external temperatures.

Figure 3-3, shows the **acceptable range** of "indoor operative temperatures" plotted against "mean monthly air temperature" for

Activity levels of 1.0 to 1.3 met
Person not in direct sunlight
Air velocity below 0.2 m/s
No specific clothing ensemble values

This acceptable range is called the **comfort envelope**.

The **indoor operative temperature** is the average of the air temperature and radiant temperature.

The **mean monthly outdoor temperature** is the average of the hourly temperatures; data is normally available from government environmental-monitoring departments.

The chart only goes down to a mean monthly temperature of 10 °C, indicating that operant-controlled windows (opening windows) do not provide acceptable thermal comfort conditions in cooler climates during the winter.

The plot shows the range of comfortable operative temperatures for 80% acceptability, the normal situation, and a narrower comfort band that will provide a higher standard of comfort, 90% acceptability. For example, for a location with a maximum summer mean-monthly temperature of 20 °C, the range for 80% acceptability is between 20.5 °C and 27.5 °C.

Note that the normal situation suggests that 20% of the occupants, or 1 in 5, will not find the thermal conditions acceptable!

Situation 2: Buildings with Mechanically Conditioned Spaces

Mechanically conditioned spaces are arranged into three classes:

Class A – high comfort
Class B – normal comfort
Class C – relaxed standard of comfort

Standard 55 includes comfort charts for Class B spaces only. To calculate comfort conditions for Classes A and C, the designer uses a BASIC computer program. The BASIC program listing is included in *Standard 55*, Appendix D.

The Class B thermal limits are based on 80% acceptability, leaving about 10% of the occupants not comfortable due to the overall thermal conditions and 10% not comfortable due to local thermal discomfort.

Class B Comfort Criteria

The Standard provides a psychrometric chart, *Figure 3-4*, showing acceptable conditions for a Class B space for:

Activity between 1.0 and 1.3 met
Clothing 0.5 to 1.0 clo
The air speed is to be below 0.2 m/s
The person must not be in direct sunlight

For spaces where it is reasonable to assume that clothing will be around 0.5 clo in the summer, and a design humidity of between 40% and 50%, the acceptable conditions, the comfort envelope, will be within the heavy lines on the chart.

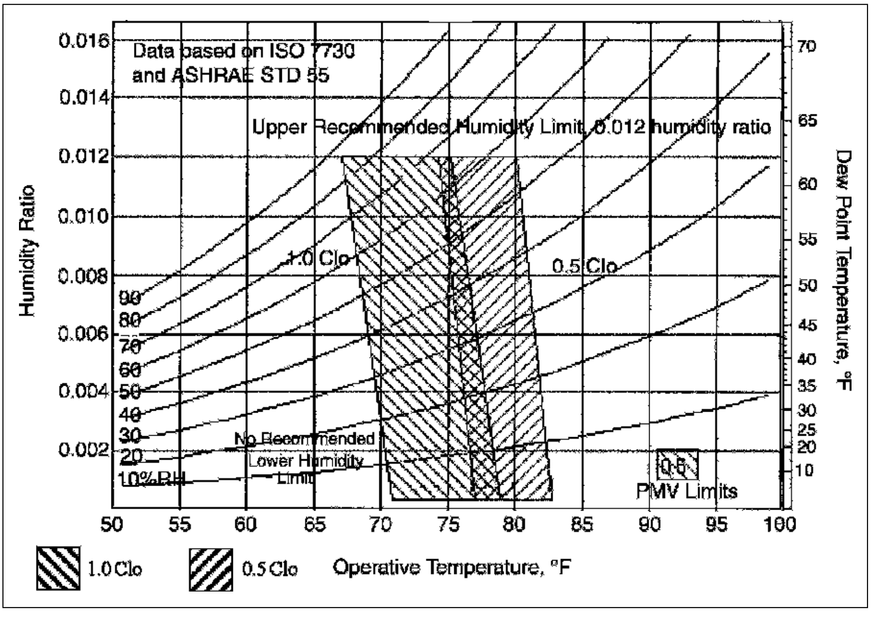

Figure 3-4 Acceptable Range of Operative Temperature and Humidity for Spaces that Meet the Criteria Specified Above (*Standard 55*, Figure 5.2.1.1)

Remember that the chart is for 80% acceptability, although ideally 100% of the occupants would find the conditions thermally acceptable. The occupants do have some limited flexibility with clothing in most situations. The ideal situation, but prohibitively expensive in most cases, is to provide all the occupants with their own temperature control.

Example 1: Let us suppose we wish to minimize the size of the air-conditioning plant; then we could choose design conditions of 27 °C at 50% relative humidity (**rh**), and 28 °C at 40% rh. It must be recognized that when the designer designs on the limit, it means that more people are likely to be uncomfortable than if the designer chooses to design for the center of the comfort temperature band.

Example 2: Let us consider a different situation, a prestige office building with, at the design stage, unknown tenants. Here we should allow for both light dress and full suits, the full range 0.5 to 1.0 clo. If the design relative-humidity is to be 50%, then we should select the area of overlap and choose 24.5 °C as our design temperature.

Example 3: As a third example let us consider a desert town with an outside design-condition of 35 °C and 20% relative humidity. If we pass the incoming air over a suitably sized evaporative cooler, the air will be cooled and humidified to 25 °C and 40% which is nicely within the comfort zone for people with 0.5 clo. In this case, we can achieve acceptable thermal comfort for supply ventilation using an evaporative cooler.

3.4 Managing Under Less Than Ideal Conditions

The above charts are based on relatively ideal conditions—conditions that do not always exist. The Standard goes into considerable detail about the limits for non-ideal conditions and we will briefly introduce them here.

Elevated Air Speed

Increasing the air speed over the body causes increased cooling. Elevated air speed can be used to advantage to offset excessive space temperatures. The temperature limits specified are increased by up to 3 °C, as long as the air speed is within the occupant's control and limited to below 0.8 m/s.

The personal desk fan provides a simple example of placing air speed under individual control. For example, in the case of a naturally ventilated space where the acceptable temperature range was 21 °C to 26.5 °C, the acceptable temperature range would be increased to a higher range of 21 °C to 29.5 °C with the addition of a fan that was controlled by the occupant.

Draft

Draft discomfort depends on air temperature, velocity and turbulence. In general the steadier the draft the less the discomfort—it does not draw attention to itself so much! People are much more sensitive to cold drafts than they are to warm drafts. As a result the same velocity of air may produce complaints of cold drafts while cooling in the summer but no complaints when heating in the winter.

Vertical Temperature Difference

Vertical temperature difference between feet and head typically occurs in heated buildings. Warm air is less dense and tends to rise. Therefore, a warm air supply tends to rise, leaving the lower portion of the space cooler.

Also, many buildings in cool climates have a poorly insulated floor slab-on-grade, which makes for a cold floor and cool air just above the floor.

The variation in air temperature from feet to head is generally acceptable as long as it does not exceed 3 °C.

Floor Surface Temperatures

Floor surface temperatures should be within the range 19–29 °C for people wearing shoes and not sitting on the floor. The maximum temperature limits the amount of heat that can be provided by a heated (radiant) floor. The minimum temperature, 19 °C, is much higher than most designers realize! Note that a cold floor can make it impossible to produce thermal comfort, regardless of the temperature of the space.

Cyclic Temperature Changes

In a space that is controlled by an on/off thermostat that reacts slowly to temperature change, the space can experience a significant temperature range in a short time. The occupants can perceive this variation as discomfort.

When the temperature cycles up and down fairly regularly with time, with a cycle time of less than 15 minutes, the temperature range should be limited to a range of 1 °C.

Radiant Temperature Variation

Radiant temperature variation is acceptable, within limits. People are generally quite accepting of a warm wall, but warm ceilings are a source of discomfort if the ceiling radiant temperature is more than 5 °C above the general radiant temperature.

A poorly insulated roof in a hot sunny climate can cause very uncomfortable conditions due to the high radiant temperature of the ceiling.

3.5 Requirements of Non-Standard Groups

This has been a very brief look at the variations in thermal conditions that can influence the basic comfort charts in *Figures 3-1* and *3-2*. There has been no mention of different requirements for different age groups or sexes. Most research is done on healthy adults, and *Standard 55* admits this fact by noting that there is little data on the comfort requirements for children, the disabled or the infirm.

However, most research on differences between groups indicates that different acceptability is due to different behavior, rather than different thermal comfort requirements. For example, elderly people often like a warmer temperature than younger people do. This is reasonable, since the elderly tend to be much less active, resulting in a lower met rate. In a similar way, women are thought to prefer a warmer temperature than men, but comparative studies indicate that the reason for the difference is that women wear a lower clo value ensemble of clothes.

Lastly there is the idea that people prefer their space to be cooler in summer and warmer in winter. Consider a one-level house. In summer, it is hot and sunny outside. As a result, the walls and roof become much warmer than they are in cooler weather. For the occupant, the radiant temperature is higher, and therefore, to maintain the same thermal conditions, the air temperature needs to be lower. Conversely, in cold winter weather, the walls, windows, and ceilings become cooler and the occupant will need a higher air temperature to maintain the same level of comfort.

The Next Step

Having considered thermal comfort in this chapter, we will go on to consider indoor air comfort, termed *Ventilation and Indoor Air Quality*, in Chapter 4.

Summary

This chapter has considered the many facets of thermal comfort. It is important that you are aware that the air temperature at the thermostat is not always a good indicator of thermal comfort. The design of the space and individual clothing choices can have major influences on thermal comfort.

3.1 Introduction – What is Thermal Comfort?

Standard 55 defines comfort as "that condition of mind which expresses satisfaction with the thermal environment; it requires subjective evaluation."

3.2 Seven Factors Influencing Thermal Comfort

You have personal experience of the seven factors that affect thermal comfort: personal comfort, including activity level and clothing; individual characteristics, including expectation; environmental conditions and architectural effects, including air temperature, radiant temperature, humidity, and air speed.

3.3 Conditions for Comfort

This section focuses on the factors that influence thermal comfort in normal living environments and office-type environments with occupancy periods in excess of 15 minutes. These include occupant operable windows and naturally conditioned spaces, and mechanically conditioned spaces. Mechanically conditioned spaces are arranged into three classes: Class A – high comfort; Class B – normal comfort; Class C – relaxed standard of comfort. The Standard provides a psychrometric chart showing 80% acceptable conditions for a Class B space for activity between 1.0 and 1.3 met; clothing 0.5 to 1.0 clo; air speed below 0.2 m/s; with the added condition that the person is not in direct sunlight. To calculate comfort conditions for Classes A and C, the designer uses a BASIC computer program.

3.4 Managing Under Less Than Ideal Conditions

Non-ideal conditions include: elevated air speed, draft, vertical temperature difference, floor surface temperatures, cyclic temperature changes, and radiant temperature variation.

3.5 Requirements of Non-Standard Groups

Most of the research for *Standard 55* was based on the responses of healthy adults. When designing for non-standard groups, consider their additional needs for comfort.

Bibliography

1. ASHRAE. 2004. *ASHRAE Standard 55–2004, Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
2. ASHRAE. 2005. *2005 ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.