THERMAL COMFORT IN HOUSING AND THERMAL ENVIORMENTS

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Summary

The main function of a building is to provide a healthy and comfortable thermal environment for occupants while maintaining minimum energy consumption. The fundamental of humans' thermal comfort is descried and the parameters influencing the thermal comfort have been introduced. The thermal comfort requirement is the basic parameter in the design of a building. This chapter also describes the thermal comfort requirements for elderly and disabled persons.

1. Introduction

People spend more than 90% of their time in an artificial environment (a dwelling, a workplace, or a transport vehicle). When energy costs soared during the energy crisis of the early 1970s, the building envelope was tightened to reduce uncontrolled air leakage, and outdoor air supply was sharply reduced in many mechanically ventilated buildings and commercial aircraft (Haghighat et al. 1999). Since then there has been growing concern and uncertainty with the quality of the indoor environment due to commonly attributed adverse effects on comfort, health and productivity (Haghighat and Donnini 1999). The purpose of heating or cooling systems is to provide an acceptable microclimate and maintain suitable conditions for its intended use. The thermal environment must be considered in the design of a ventilation system, whether it is for a room or for a building, as it is fundamental to the comfort and well being of the human occupants.
The environmental quality of a space is determined by the occupant's response to various environmental stimuli and his integration of these inputs into a comfort response. If one assumes that sufficient heating or cooling capacity is available to maintain the desired average temperature within a space, then a comfortable thermal environment will be completely dependent upon the distribution of conditioned air in the space. From a thermal standpoint, it is possible to have an average temperature (existing at some point in the space), which satisfies overall criteria for thermal balance. At the same time, there may be conditions, which cause the local temperatures throughout the space to vary from this average or mean value. The objective of a good air distribution system is to produce, within the occupied space, the proper combination of temperature, air motion, and relative humidity to keep the occupants comfortable.

Designers and operators of ventilation systems should be familiar with the comfort requirements necessary to achieve an acceptable indoor climate. This requires knowledge of the heat balance between the human body and the internal environment, the factors that influence thermal comfort and discomfort.

A summary of the qualitative information on calculating the heat exchange between people and the environment from the works of Fanger (1967,1970), Hardy (1949), Rapp and Gagge (1967), Gagge and Hardy (1967), ASHRAE Handbook of Fundamentals (1993) follows.

2. Thermo-regulatory system

The primary function of thermoregulation is to maintain the body core within the range of temperature, which is essential for proper functioning. The hypothalamus is the temperature control center. It is the part of the brain that is linked to the thermoreceptors, the skin, and the muscles. The hypothalamus receives nerves pulses from temperature sensors and then sends information to different body organs to maintain a constant body core temperature. Controlling metabolic heat production rate, sweat, control of blood flow, muscle contraction and shivering are how temperature is regulated. The body core temperature is approximately 37°C under normal conditions. It must be maintained within a narrow range (to avoid discomfort), and within a wide range (to avoid danger from heat or cold stress). However, the skin temperature is usually different for different parts of the body. The variation in skin temperature over body is reduced when the body is in a state of thermal equilibrium. Usually, for operative temperature between 23 and 27°C, for normally clothes, secondary people, no action from the physiological control system is required to maintain normal body temperature.

Under colder conditions, the rate of heat loss from the skin to the environment increases. The body then decreases the blood flow to the skin, which cools the skin and subjacent tissues and maintains the temperatures of the superficial and the deep tissues fall. At this point, the body will generate heat through muscular tension, shivering, or spontaneous activity. If these reactions do not work, the core body temperature can fall below 35°C, where major losses in efficiency are noted (such as manual dexterity): temperature lower than 31°C can be lethal. While body is undergoing this outdoor temperature change, it adjusts by providing life-sustaining conditions for the crucial internal regions at the expense of the further peripheral tissues. Since the hands and feet are furthest from the central body mass, their temperature will fall faster. A similar phenomenon occurs to the ears since they are a smaller surface area per unit of thermal mass as opposed to the torso.

Under hotter conditions, the rate of heat loss from the skin to the environment decreases. The body then increases the blood flow to the skin, which causes the skin surface temperature to come closer to the temperature of the deep tissues. Under even hotter conditions, when the body core temperature rises above 37°C, the body starts to release water from sweat glands for evaporative cooling. If this reaction does not work, as in high humidities, reduced air movement, and added clothing, and the body core temperature rises above 39°C, major losses in efficiency are noted (such as sluggishness); temperatures above 43 ^{o}C can be lethal.

3. Heat balance

The heat balance equation for the human body is the equation of the rate of heat production to the rate of heat loss. The human body continuously generates heat. Therefore, heat must be dissipated for body to stay within the comfort range. The total metabolic energy produced within the body is the metabolic energy required for the person's activity plus that required for shivering. Some of the body's energy production may be expanded as external work done by muscles. The remaining difference is either stored (which will cause the body temperature to rise) or dissipated to the environment through the skin surface and respiratory tract. This heat dissipation from the body occurs by several modes of heat exchange: sensible heat flow from the skin and during respiration, latent heat flow from the evaporation of sweat and moisture diffused through the skin, and latent heat due to the evaporation of moisture during respiration. Sensible heat flow from the skin is a mixture of conduction, convection and radiation for a clothed person.

Fanger (1970,1982) developed the steady-state model, which assumes that the body is in a state of thermal equilibrium with negligible heat storage. At steady state, the rate of heat production in the body, by metabolism and by performance of external work, equals the heat loss from the body to the environment, by the process of evaporation, respiration, radiation, convection, and conduction:

$$M - W = (C + R + E_{sk}) + (C_{res} + E_{res}) \tag{1}$$

where M = rate of metabolic heat production, W/m^2
W = rate of mechanical work accomplished, W/m^2
C+R = sensible heat loss from skin, W/m^2
E_{sk} = rate of total evaporative heat loss from the skin, W/m^2
C_{res} = rate of convective heat loss from respiration, W/m^2
E_{res} = rate of evaporative heat loss from respiration, W/m^2

The unit m^2 refers to the surface area of the nude body.

3.1 Sensible heat loss

Heat transfer from the skin surface to the surrounding air is treated in two sections; from the skin through the clothing and from the clothing to the environment. The convective heat loss can be expressed in terms of a heat transfer coefficient and the difference between the mean temperature of the outer surface of the clothed body and the environmental temperature:

$$C = f_{cl} h_c (t_{cl} - t_a) \tag{2}$$

where C = convective heat loss, W/m^2
f_{cl} = clothing area factor=A_{cl}/A_D
h_C = convective heat transfer coefficient at clothing surface, W/m^2K
t_{cl} = mean temperature of the outer surface of the clothed body, °C,
t_a = air temperature, °C
A_{cl} = surface area of clothed body, m^2, and
A_D = DuBois surface area of nude body, m^2

Values of f_{cl} can be found in Table 1 for various clothing ensembles (McCullogh and Jones 1984; McCullogh et al. 1989).

DuBois (1916) originally proposed the most useful measure of the nude body surface area:

$$A_D = 0.202 m^{0.425} L^{0.725}$$

where m = mass, kg, and
L = height, m.

In mechanically ventilated environment, forced convection, h_c depends on the relative air speed and can be estimated from

$h_c = 12.1\ v^{0.5}\ \ W/m^2\ K$

and in non-ventilated environment, natural convection, h_c depends on the temperature difference between clothing and air

$h_c = 2.38\ (t_{cl} - t_a)^{0.25}\quad W/m^2\ K$

The surface temperature of clothing, t_{cl}, can be estimated by:

$$t_{cl} = 35.7 - 0.028(M - W) - 0.155\ l_{cl}\ [3.96\text{x}10^{-8}\ f_{cl}\ \{(t_{cl} + 273)^4 - (t_r + 273)^4\} + f_{cl}\ h_{cl}\ (t_{cl} - t_a)] \qquad (3)$$

Ensemble description[1]	f_{cl}
Walking shorts, shorts-sleeve shirt	1.10
Trousers, short-sleeve shirt	1.15
Trousers, long-sleeve short	1.20
Same as above, plus suit jacket	1.23
Trousers, long-sleeve shirt, long sleeve sweater, t-shirt	1.28
Sweat pants, sweat shirt	1.19
Long-sleeve, pajama top, long pajama trousers, short ¾ sleeve robe, slippers	1.32
Knee-length skirt, short-sleeve shirt, panty hose, sandals	1.26
Knee-length shirt, short-sleeve shirt, half slip, panty hose, long-sleeve sweater	1.46
Same as above, replace sweater with suit jacket	1.30
Ankle-length skirt, long-sleeve shirt, suit jacket, panty hose	1.46

[1]all ensembles include shoes (unless otherwise noted), brief/panties, and socks (unless panty hose noted)

Table 1: Typical values of clothing area factor

Heat exchange by radiation occurs between the body surface (clothing and skin) and the surrounding surfaces (internal room surfaces, heat sources, and heat sinks). The radiative heat loss from the outer surface of a clothed body can be expressed in a similar fashion:

$$R = f_{cl} h_r (t_{cl} - t_r) \qquad (4)$$

where R = radiative heat loss, W/m^2
h_r = linear radiant heat transfer coefficient at clothing surface, $W/(m^2K)$, and
t_r = mean radiant temperature, °C

The linear radiant heat transfer coefficient, h_r, can be calculated by:

$$h_r = 4\varepsilon\sigma(A_r/A_D)[273.2 + (t_{cl} + t_r)/2]^3 \tag{5}$$

where ε = emissivity of clothed body, usually 0.95,
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^{2}K), and
A_r = effective radiation area of body. m^2.

The ration A_r / A_D is 0.70 for a seated person and 0.73 for a person that is standing (Fanger, 1967). For typical indoor temperatures, h_r =4.7 W/(m^{2}K). The mean radiant temperature can be calculated from areas, view factors, and temperatures of room surfaces (Kreith and Bohn 1999), or can be measured directly. It is defined as the uniform temperature of the surrounding surfaces, which will result in the same heat exchange by radiation from a person as in the actual environment. The clothing temperature depends on the metabolic rate, the thermal resistance of the clothing, and the air temperature (see Equation 3).

Using equation 2 and 4, the radiation and convection heat transfer may be combined into a single equation to give the sensible transfer from the body to the surroundings:

$$C + R = f_{cl}\left[h_c(t_{cl} - t_a) + h_r(t_{cl} - t_r)\right] \tag{6}$$

which leads to

$$C + R = f_{cl}h(t_{cl} - t_0) \tag{7}$$

where h is the combined radiation and convection heat transfer coefficient ($h = h_r + h_c$). The operative temperature is determined by the combination of the heat transfer by radiation, and the air speed. It is the average of the mean radiant and air temperature weighted by their respective heat transfer coefficients, and is given by:

$$t_o = (h_r t_r + h_c t_a)/(h_r+h_c) \tag{8}$$

The transport of sensible heat through clothing involves conduction, convection, and radiation:

$$C + R = (t_{sk} - t_{cl})/I_{cl} \tag{9}$$

where t_{sk} = skin temperature, °C and
I_{cl} = thermal resistance of clothing, W/(m^{2}K) or clo (1 clo=0.155 m^{2}K/ W)

Typical values of I_{cl} for different clothing ensembles are given in Table 2 (McCullough and Jones 1984 and McCullough et al 1989). If it is not possible to find an already measured clothing ensemble as in the above table, a value can be estimated from the summation of individual garments. Table 3 gives a list of individual items of clothing (McCullough and Jones 1984).

Ensemble description[1]	I_{cl}

Walking shorts, shorts-sleeve shirt	0.36
Trousers, short-sleeve shirt	0.57
Trousers, long-sleeve short	0.61
Same as above, plus suit jacket	0.96
Trousers, long-sleeve shirt, long sleeve sweater, t-shirt	1.01
Sweat pants, sweat shirt	0.74
Long-sleeve, pajama top, long pajama trousers, short ¾ sleeve robe, slippers	0.96
Knee-length skirt, short-sleeve shirt, panty hose, sandals	0.54
Knee-length shirt, short-sleeve shirt, half slip, panty hose, long-sleeve sweater	1.10
Same as above, replace sweater with suit jacket	1.04
Ankle-length skirt, long-sleeve shirt, suit jacket, panty hose	1.10

[1]all ensembles include shoes (unless otherwise noted), briefs/panties, and socks (unless panty hose noted)

Table 2: Thermal resistance of clothing ensembles

In more recent work (de Dear and Fountain, 1994, Donnini et al, 1996), the notion of chair insulation was incorporated in the total clothing insulation value. The different chairs found were categorized as to the amount of contact the person had with the chair. The recent work of McCullough et al (1994) was used to determine the additional clo values of the chairs. These chair clo values were added to the garment clo values of the occupants.

Garment		I_{ch}
Underwear	Brief	0.04
	Panties	0.03
	Bra	0.01
Footwear	Ankle-length athletic socks	0.02
	Calf-length socks	0.03
	Panty hose	0.02
	Sandals	0.02
Shirts/blouses	Sleeveless, scoop-neck blouses	0.12
	Short-sleeve, dress shirt	0.19
	Long-sleeve, dress shirt	0.25
	Short-sleeve, knit sport shirt	0.17
Trousers	Walking shorts	0.08
	Straight trousers, thin	0.15
	Straight trousers, thick[1]	0.24
Dresses and skirts, knee length	Skirt, thin	0.14
	Shirt, thick	0.23
	Short-sleeve shirtdress, thin[1]	0.29
	Sleeveless, scoop neck, thin	0.23
Sweaters	Sleeves vest, thin	0.13
	Sleeves vest, thick	0.22
	Long-sleeve, thin	0.25
	Long-sleeve, thick	0.36
Suit jackets and vests,	Single-breasted, thin	0.36

lined		
	Single-breasted, thick	0.44
	Sleeveless vest, thin	0.10

[1]a thin garment is made of a light fabric, usually worn in summer, and a thick garment is made of a heavy fabric, usually worn in winter

Table 3: Thermal resistance of individual clothing items

McCullough et al (1994) reported that clothing insulation values increased 0.1 to 0.3 clo when a mankind sat in real chairs. The amount of the increase was related to the amount of chair surface area in contact with the body. The authors stated that to determine the intrinsic insulation around a person, the I_{cl} clo values for chair insulation should be added to the I_{cl} clo for garment. In their study, six different types of chairs were evaluated (a wooden stool, a metal folding chair, a computer chair, a carrel chair, a desk chair, and an executive chair). They used four different types of clothing ensembles:

-a heavy business suit <briefs, t-shirt, long-sleeve dress shirt (shirt collar), necktie, belt, suit jacket (single-breasted), long dress trousers, calf-length dress socks, hard-soled street shoes>

-a shirt and trousers <briefs, short-sleeved shirt (shirt collar), long trousers(thin), calf-length dress socks, hard-soled street shoes>

-a blouse and straight skirt< panties, long-sleeved shirt (shirt collar), straight skirt (knee length), pantyhose, hard-soled street shoes>

-a blouse and a pleated skirt< panties, long-sleeved blouse (shirt collar), pleated skirt (knee length), pantyhose, hard-soled street shoes>.

Table 4 summarizes their results.

Ensemble	Clothing area factor, f_{cl}	Added insulation of chair relative to no chair, clo					
		Stool	Folding	Computer	Carrel	Desk	Executive
Suit	1.32	0.13	0.10	0.22	0.32	0.26	0.33
Trousers	1.15	0.11	0.10	0.18	0.19	0.17	0.22
Straight skirt	1.29	-	-	-	-	-	0.17
Pleated skirt	1.33	-	-	-	-	-	0.17

Table 4: Added insulation of chairs

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