Fundamentals of Refrigeration and Air Conditioning

المرحلة الثانية

محاضرة رقم (5)

الراحة الحرارية وظروف التصميم الداخلي والخارجي

Thermal Comfort and Inside and Outside Design Conditions

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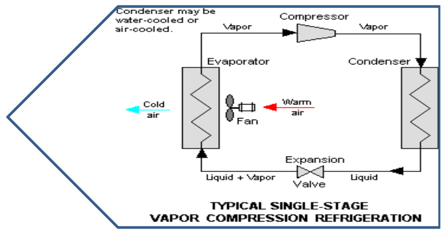
Hassan Rijabo



Lecture 6
Thermal Comfort and Inside and Outside Design Conditions

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6.1 Introduction

Design and analysis of air conditioning systems involves selection of suitable inside and outside design conditions, estimation of the required capacity of cooling or heating equipment, selection of suitable cooling/heating system, selecting supply conditions, design of air transmission and distribution systems etc. Generally, the inputs are the building specifications and its usage pattern and any other special requirements. Figure 6.1 shows the schematic of a basic summer air conditioning system. As shown in the figure, under a typical summer condition, the building gains sensible and latent heats from the surroundings and also due to internal heat sources (RSH and RLH).

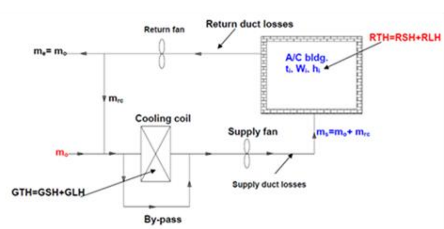

Fig.6.1 Schematic of a basic summer air conditioning system

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The supply air to the building extracts the building heat gains from the conditioned space. These heat gains along with other heat gains due to ventilation, return ducts etc. have to be extracted from the air stream by the cooling coil, so that air at required cold and dry condition can be supplied to the building to complete the cycle. In general, the sensible and latent heat transfer rates (GSH and GLH) on the cooling coil are larger than the building heat gains due to the need for ventilation and return duct losses. To estimate the required cooling capacity of the cooling coil (GTH), it is essential to estimate the building and other heat gains. The building heat gains depend on the type of the building, outside conditions and the required inside conditions. Hence selection of suitable inside and outside design conditions is an important step in the design and analysis of air conditioning systems.

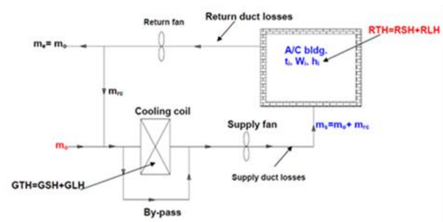

Fig.6.1 Schematic of a basic summer air conditioning system

6.2. Selection of inside design conditions:

- The required inside design conditions depend on the intended use of the building.
- Air conditioning is required either for providing suitable comfort conditions for the occupants (e.g. comfort air conditioning), or for providing suitable conditions for storage of perishable products (e.g. in cold storages) or conditions for a process to take place or for products to be manufactured (e.g. industrial air conditioning).
- The required inside conditions for cold storage and industrial air conditioning applications vary widely depending on the specific requirement. However, the required inside conditions for comfort air conditioning systems remain practically same irrespective of the size, type, location, use of the air conditioning building etc., as this is related to the thermal comfort of the human beings.

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6.3. Thermal comfort:

- Thermal comfort is defined as "**that condition of mind which expresses satisfaction with the thermal environment**". This condition is also some times called as "**neutral condition**", though in a strict sense, they are not necessarily same.
- A living human body may be likened to a heat engine in which the chemical energy contained in the food it consumes is continuously converted into work and heat.
- The process of conversion of chemical energy contained in food into heat and work is called as "**metabolism**". The rate at which the chemical energy is converted into heat and work is called as "**metabolic rate**".
- Knowledge of metabolic rate of the occupants is required as this forms a part of the cooling load of the air conditioned building. Similar to a heat engine, one can define thermal efficiency of a human being as the ratio of useful work output to the energy input.
- The thermal efficiency of a human being can vary from 0% to as high as 15-20% for a short duration.

A human body is very sensitive to temperature. The body temperature must be maintained within a narrow range to avoid discomfort, and within a somewhat wider range, to avoid danger from heat or cold stress. Studies show that at neutral condition, the temperatures should be:

Skin temperature, tskin ≈ 33.7^{o}C

Core temperature, tcore ≈ 36.8^{o}C

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- At other temperatures, the body will feel discomfort or it may even become lethal.
- It is observed that when the core temperature is between 35 to 39°C, the body experiences only a mild discomfort.
- When the temperature is lower than 35°C or higher than 39°C, then people suffer major loss in efficiency. It becomes lethal when the temperature falls below 31°C or rises above 43°C. This is shown in Fig. 6.2.

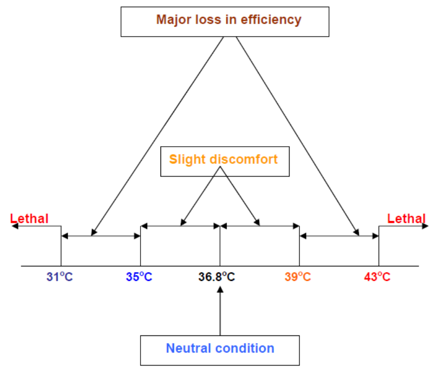

Fig. 6.2 Affect of the variation of core temperature on a human being

Lecture6. Thermal comfort and Inside and outside design conditions

6.4: Heat balance equation for a human being:

- The temperature of human body depends upon the energy balance between itself and the surrounding thermal environment.
- Taking the human body as the control volume, one can write the thermal energy (heat) balance equation for the human body as:

$$Q_{gen} = Q_{sk} + Q_{res} + Q_{st}$$

Where

Qgen = Rate at which heat is generated inside the body

Qsk = Total heat transfer rate from the skin

Qres = Heat transfer rate due to respiration, and

Qst = Rate at which heat is stored inside the body

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- The heat generation rate Q_{gen} is given by:

$$Q_{gen} = M(1-\eta) \approx M$$

Where
M = Metabolic rate, and
η = Thermal efficiency ≈ 0 for most of the activities

- The metabolic rate depends on the activity. It is normally measured in the unit "**met**".
- A **met** is defined as the metabolic rate per unit area of a sedentary person and is found to be equal to about **58.2 W/m²**. This is also known as "basal metabolic rate". Table 5.1 shows typical metabolic rates for different activities:

Typical metabolic rates

Activity	Specifications	Metabolic rate
Resting	Sleeping	0.7 met
	Reclining	0.8 met
	Seated, quite	1.0 met
	Standing, relaxed	1.2 met
Walking	0.89 m/s	2.0 met
	1.79 m/s	3.8 met
Office activity	Typing	1.1 met
Driving	Car	1.0 to 2.0 met
	Heavy vehicles	3.2 met
Domestic activities	Cooking	1.6 to 2.0 met
	Washing dishes	1.6 met
	House cleaning	2.0 to 3.4 met
Dancing	-	2.4 to 4.4 met
Teaching	-	1.6 met
Games and sports	Tennis, singles	3.6 to 4.0 met
	Gymnastics	4.0 met
	Basket ball	5.0 to 7.6 met
	Wrestling	7.0 to 8.7 met

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- Studies show that the metabolic rate can be correlated to the rate of respiratory oxygen consumption and carbon dioxide production. Based on this empirical equations have been developed which relate metabolic rate to O2 consumption and CO2 production.
- Since the metabolic rate is specified per unit area of the human body (naked body), it is essential to estimate this area to calculate the total metabolic rate. Even though the metabolic rate and heat dissipation are not uniform throughout the body, for calculation purposes they are assumed to be uniform.
- The human body is considered to be a cylinder with uniform heat generation and dissipation. The surface area over which the heat dissipation takes place is given by an empirical equation, called as Du Bois Equation. This equation expresses the surface area as a function of the mass and height of the human being. It is given by:

$$A_{Du} = 0.202\, m^{0.425} h^{0.725}$$

Where

ADu = Surface area of the naked body, m2

m = Mass of the human being, kg

h = Height of the human being, m

- Since the area given by Du Bois equation refers to a naked body, a correction factor must be applied to take the clothing into account. This correction factor, defined as the "ratio of surface area with clothes to surface area without clothes" has been determined for different types of clothing. These values are available in ASHRAE handbooks. Thus from the metabolic rate and the surface area, one can calculate the amount of heat generation, Q_{gen}.
- The total heat transfer rate from the skin Qsk is given by:

$$Q_{sk} = \pm Q_{conv} \pm Q_{rad} + Q_{evp}$$

Where

Qconv = Heat transfer rate due to convection (sensible heat)

Qrad = Heat transfer rate due to radiation (sensible heat), and

Qevp = Heat transfer rate due to evaporation (latent heat)

The convective and radiative heat transfers can be positive or negative, i.e., a body may lose or gain heat by convection and radiation, while the evaporation heat transfer is always positive, i.e., a body always looses heat by evaporation.

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- According to Belding and Hatch, the convective, radiative and evaporative heat transfer rates from the naked body of an average adult , Qc, Qr and Qe, respectively, are given by:

$$Q_c = 14.8\,V^{0.5}(t_b - t)$$
$$Q_r = 11.603\,(t_b - t_s)$$
$$Q_e = 181.76\,V^{0.4}(p_{s,b} - p_v)$$

- In the above equation all the heat transfer rates are in watts, temperatures are in °C and velocity is in m/s; $p_{s,b}$ and p_v are the saturated pressure of water vapour at surface temperature of the body and partial pressure of water vapour in air, respectively, in kPa.
- From the above equations it is clear that the convective heat transfer from the skin can be increased either by increasing the surrounding air velocity (V) and/or by reducing the surrounding air DBT (t). The radiative heat transfer rate can be increased by reducing the temperature of the surrounding surfaces with which the body exchanges radiation. The evaporative heat transfer rate can be increased by increasing the surrounding air velocity and/or by reducing the moisture content of surrounding air.

- The heat transfer rate due to respiration Qres is given by:

$$Q_{res} = C_{res} + E_{res}$$

Where

C_{res} = Dry heat loss from respiration (sensible, positive or negative)

E_{res} = Evaporative heat loss from respiration (latent, always positive)

- For comfort, the rate of heat stored in the body Qst should be zero, i.e.,

$$Q_{st} = 0 \text{ at neutral condition}$$

- A sedentary person at neutral condition loses about 40 % of heat by evaporation, about 30 % by convection and 30 % by radiation. However, this proportion may change with other factors. For example, the heat loss by evaporation increases when the DBT of the environment increases and/or the activity level increases

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6.5. Factors affecting thermal comfort:

- Thermal comfort is affected by several factors. These are:
- 1. Physiological factors such as age, activity, sex and health. These factors influence the metabolic rate. It is observed that of these factors, the most important is activity. Other factors are found to have negligible effect on thermal comfort.
- 2. Insulating factor due to clothing. The type of clothing has strong influence on the rate of heat transfer from the human body. The unit for measuring the resistance offered by clothes is called as "**clo**". 1 clo is equal to a resistance of about 0.155 m^2.K/W. Typical clo values for different types of clothing have been estimated and are available in the form of tables. For example, a typical business suit has a clo value of 1.0, while a pair of shorts has a clo value of about 0.05.
- 3. Environmental factors. Important factors are the dry bulb temperature, relative humidity, air motion and surrounding surface temperature. Of these the dry bulb temperature affects heat transfer by convection and evaporation, the relative humidity affects heat loss by evaporation, air velocity influences both convective and evaporative heat transfer and the surrounding surface temperature affects the radiative heat transfer.

6.6. Indices for thermal comfort:

- It is seen that important factors which affect thermal comfort are the activity, clothing, air DBT, RH, air velocity and surrounding temperature.
- It should be noted that since so many factors are involved, many combinations of the above conditions provide comfort.
- ASHRAE has defined a comfort chart based on the effective and operative temperatures. Figure 6.3 shows the ASHRAE comfort chart with comfort zones for summer and winter conditions. It can be seen from the chart that the comfort zones are bounded by effective temperature lines, a constant RH line of 60% and dew point temperature of 2°C.
- The upper and lower limits of humidity (i.e. 60 % RH and 2°C DPT, respectively) are based on the moisture content related considerations of dry skin, eye irritation, respiratory health and microbial growth. The comfort chart is based on statistical sampling of a large number of occupants with activity levels less than 1.2 met. On the chart, the region where summer and winter comfort zones overlap, people in winter clothing feel slightly warm and people in summer clothing feel slightly cool. Based on the chart ASHARE makes the following recommendations:

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Inside design conditions for Winter:

T_{op} between 20.0 to 23.5°C at a RH of 60%

T_{op} between 20.5 to 24.5°C at a DPT of 2°C

Inside design conditions for Summer:

T_{op} between 22.5 to 26.0°C at a RH of 60%

T_{op} between 23.5 to 27.0°C at a DPT of 2°C

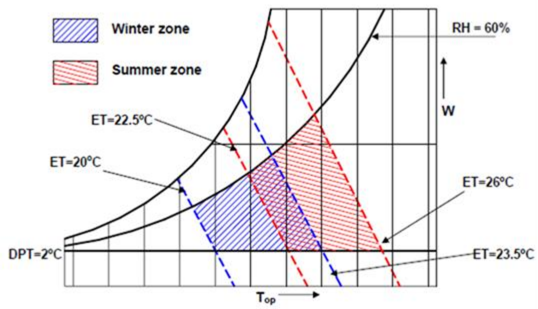

Fig.6.3 ASHRAE comfort chart for a sedentary person (activity ≈ 1.2 met

Table **6.2** shows the recommended comfort conditions for different seasons and clothing suitable at 50 % RH, air velocity of 0.15 m/s and an activity level of ≤ 1.2 met.

Season	Clothing	I_{cl}	$T_{op,opt}$	T_{op} range for 90% acceptance
Winter	Heavy slacks, long sleeve shirt and sweater	0.9 clo	22°C	20 to 23.5 °C
Summer	Light slacks and short sleeve shirt	0.5 clo	24.5°C	23 to 26°C
	Minimal (shorts)	0.05 clo	27°C	26 to 29 °C

The above values may be considered as recommended inside design conditions for comfort air conditioning. It will be shown later that the **cost of air conditioning (initial plus running) increases as the required inside temperature increases in case of winter and as the required inside condition decreases in case of summer**. Hence, air conditioning systems should be operated at as low a temperature as acceptable in winter and as high a temperature as acceptable in summer.

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6.7. Selection of outside design conditions:

- The ambient temperature and moisture content vary from hour-to-hour and from day-to-day and from place-to-place. For example, in summer the ambient temperature increases from sunrise, reaches a maximum in the afternoon and again decreases towards the evening. On a given day, the relative humidity also varies with temperature and generally reaches a minimum value when the ambient temperature is maximum.

- For most of the major locations of the world, meteorological data is available in the form of mean daily or monthly maximum and minimum temperatures and corresponding relative humidity or wet bulb temperature. As mentioned before, to estimate the required cooling capacity of an air conditioning plant, it is essential to fix the outside design conditions in addition to the inside conditions.

- It is obvious that the selected design conditions may prevail only for a short a duration, and most of the time the actual outside conditions will be different from the design values. As a result, for most of the time the plant will be running at off-design conditions.

The design outside conditions also depend on the following factors:

a) Type of the structure, i.e., whether it is of heavy construction, medium or light
b) Insulation characteristics of the building
c) Area of glass or other transparent surfaces
d) Type of usage
e) Nature of occupancy
f) Daily range (difference between maximum and minimum temperatures in a given day)

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6.7.1. Outdoor design conditions for summer:

- Selection of maximum dry and wet bulb temperatures at a particular location leads to excessively large cooling capacities as the maximum temperature generally persists for only a few hours in a year. Hence it is recommended that the outdoor design conditions for summer be chosen based on the values of dry bulb and mean coincident wet bulb temperature that is equaled or exceeded 0.4, 1.0 or 2.0 % of total hours in an year. These values for major locations in the world are available in data books, such as AHRAE handbooks. Whether to choose the 0.4 % value or 1.0 % value or 2.0 % value depends on specific requirements.
- In the absence of any special requirements, the 1.0% or 2% value may be considered for summer outdoor design conditions.

Lecture6. Thermal comfort and Inside and outside design conditions

6.7.1. Outdoor design conditions for summer:

2021 ASHRAE Handbook - Foundamentals (SI)

BAGHDAD INTL, IRAQ (WMO: 406500)

Lat:**33.267N** Long:**44.233E** Elev:**35** StdP: **100.91** Time zone:**3.00 (E03)** Period:**03-19** WBAN:**99999**

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	**15.4**	**47.1**	**21.9**	**46.0**	**21.6**	**44.8**	**21.1**	**23.4**	**42.6**	**22.7**	**42.1**	**22.1**	**41.6**	**4.9**	**320**

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6.7.2. Outdoor design conditions for winter:

- Similar to summer, it is not economical to design a winter air conditioning for the worst condition on record as this would give rise to very high heating capacities. Hence it is recommended that the outdoor design conditions for winter be chosen based on the values of dry bulb temperature that is equaled or exceeded 99.6 or 99.0 % of total hours in an year. Similar to summer design conditions, these values for major locations in the world are available in data books, such as AHRAE handbooks. Generally the 99.0% value is adequate, but if the building is made of light-weight materials, poorly insulated or has considerable glass or space temperature is critical, then the 99.6% value is recommended.

6.7.2. Outdoor design conditions for winter:

2021 ASHRAE Handbook - Foundamentals (SI)

BAGHDAD INTL, IRAQ (WMO: 406500)

Lat:**33.267N** Long:**44.233E** Elev:**35** StdP: **100.91** Time zone:**3.00 (E03)** Period:**03-19** WBAN:**99999**

Annual Heating, Humidification, and Ventilation Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB		WSF
			99.6%			99%			0.4%		1%				
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
1	**1.8**	**3.1**	**-8.5**	**1.8**	**10.6**	**-6.7**	**2.1**	**11.8**	**10.6**	**15.2**	**9.5**	**15.0**	**1.8**	**300**	**0.468**

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