

HVAC ME472

Taibah University - Yanbu Branch
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Mechanical Engineering Department

Heating, Ventilating, and Air Conditioning

HVAC ME472
Part 5

Cooling And Heating Load Calculations - Introduction

- ❑ The heating and cooling load calculations are carried out to estimate the required capacity of heating and cooling systems.
- ❑ Information regarding the design indoor and outdoor conditions, specifications of the building, specifications of the conditioned space (such as the occupancy, activity level, various appliances and equipment used etc.) and any special requirements of the particular application should be accounted.
- ❑ For comfort applications, the required indoor conditions are fixed by the criterion of thermal comfort.
- ❑ For industrial or commercial applications the required indoor conditions are fixed by the particular processes being performed or the products being stored.

Cooling And Heating Load Calculations – Heating Load

- ❑ Heating load calculations are carried out to estimate the heat loss from the building in winter so as to arrive at required heating capacities.
- ❑ Internal heat sources such as occupants or appliances are beneficial as they compensate some of the heat losses.
- ❑ The heat load calculations are carried out assuming steady state conditions and neglecting internal heat sources.
- ❑ For more accurate estimation of heating loads, one has to take into account the thermal capacity of the walls and internal heat sources, which makes the problem more complicated.

Cooling And Heating Load Calculations – Cooling Load

- ❑ For estimating **cooling loads**, one has to consider the **unsteady state processes**, as the **peak cooling load** occurs during the **day time** and the outside conditions also vary **significantly** throughout the day due to **solar radiation**.
- ❑ In addition, all **internal sources** add on to the **cooling loads** and **neglecting** them would lead to **underestimation** of the required cooling capacity and the possibility of not being able to **maintain** the required **indoor conditions**.
- ❑ Thus cooling load calculations are inherently more **complicated** as it involves solving **unsteady** equations with **unsteady** boundary conditions and internal heat sources.

Cooling And Heating Load Calculations – Balance Point

- The **balance point** is that at which the **solar radiation** (Q_{solar}) and **internal heat generation rate** (Q_{int}) exactly **balance the heat losses** from the building.

$$(Q_{solar} + Q_{int})_{sensible} = UA (T_{in} - T_{out}) \quad (16-1)$$

Where U is the overall heat transfer coefficient

A is the surface area of the building

T_{in} is the required indoor temperature

T_{out} is the outdoor air temperature

- **T_{out} is called the outdoor balanced temperature at the balance point.**
- **If T_{out} is greater than the balance point, then there is a need for cooling the building**
- **If T_{out} is less than the balance point, then there is a need for heating the building**

A building has a U-value of 0.5 W/m².K and a total exposed surface area of 384m². The building is subjected to an external load (only sensible) of 2 kW and an internal load of 1.2 kW (sensible). If the required internal temperature is 25°C, state whether a cooling system is required or a heating system is required when the **external temperature is 3°C**. How the results will change, if the U-value of the building is reduced to 0.36 W/m.K?

$$T_{\text{out,bal}} = T_{\text{in}} - \frac{(Q_{\text{solar}} + Q_{\text{int}})_{\text{sensible}}}{UA} = 25 - \frac{(2 + 1.2) \times 1000}{0.5 \times 384} = 8.33^{\circ}\text{C}$$

Since the outdoor temperature at balance point is greater than the external temperature ($T_{\text{ext}} < T_{\text{out,bal}}$);

the building requires heating (Ans.)

When the U-value of the building is reduced to 0.36 W/m.K, the new balanced outdoor temperature is given by:

$$T_{\text{out,bal}} = T_{\text{in}} - \frac{(Q_{\text{solar}} + Q_{\text{int}})_{\text{sensible}}}{UA} = 25 - \frac{(2 + 1.2) \times 1000}{0.36 \times 384} = 1.85^{\circ}\text{C}$$

Since now the outdoor temperature at balance point is smaller than the external temperature ($T_{\text{ext}} > T_{\text{out,bal}}$);

the building now requires cooling (Ans.)

The above example shows that adding more insulation to a building extends the cooling season and reduces the heating season.

Methods of estimating cooling and heating loads

- ❑ Generally, **heating** and **cooling** load calculations involve a systematic, stepwise procedure.
- ❑ All the building **energy flows** should be **taken** into account.
- ❑ In practice, a **variety of methods** ranging from simple **rules-of-thumb** to complex **Transfer Function Methods** are used to arrive at the building **loads**.
- ❑ For example, **Table 1** shows **typical data** on required cooling capacities based on the **floor area** or **application**.
- ❑ Such **rules-of-thumb** are useful in **preliminary** estimation of the equipment **size** and **cost**.
- ❑ The main **conceptual drawback** of **rules-of-thumb** methods is the **presumption** that the building design will not make any **difference**. Thus the rules for a **badly designed building** are typically **the same** as for a good one.

Methods of estimating cooling and heating loads

Table 16-1

Sl.no	Application	Required cooling capacity (TR) for 1000 ft ² of floor area
1.	Office buildings: External zones	<u>25% glass:</u> 3.5 TR <u>50% glass:</u> 4.5 TR <u>75% glass:</u> 5.0 TR
	Internal zones	2.8 TR
2.	Computer rooms	6.0 – 12.0 TR
3.	Hotels Bedrooms	<u>Single room:</u> 0.6 TR per room <u>Double room:</u> 1.0 TR per room
	Restaurants	5.0 - 9.0 TR
4.	Department stores Basement & ground floors	4.5 – 5.0 TR
	Upper floors	3.5 – 4.5 TR
5.	Shops	5.0 TR
6.	Banks	4.5 – 5.5 TR
7.	Theatres & Auditoriums	0.07 TR per seat

Required cooling capacities for various applications based on rules-of-thumb (Croome and Roberts, 1981)

Methods of estimating cooling and heating loads

- ❑ More **accurate** load estimation methods involve a **combination** of **analytical** methods and **empirical** results obtained from actual data,
- ❑ For example the use of **Cooling Load Temperature Difference (CLTD)** for estimating **fabric heat gain** and the use of **Solar Heat Gain Factor (SHGF)** for estimating **heat transfer through fenestration**.
- ❑ These methods are very **widely used** by air conditioning engineers as they yield **reasonably accurate results** and estimations can be carried out **manually** in a relatively short time.
- ❑ ASHRAE suggests **different methods** for estimating **cooling** and **heating** loads based on **applications**, such as for **residences**, for **commercial buildings** etc.

Cooling Load Calculations

- ❑ The **cooling load** experienced by a building **varies** in magnitude from **zero** (no cooling required) to a **maximum value**.
- ❑ The **design cooling load** is a load near the **maximum magnitude**, but is **not normally the maximum**.
- ❑ **Design cooling load** takes into account **all** the loads experienced by a building under a specific set of **assumed conditions**. These are:
 1. **Design data for outside conditions**. These have been collected for **various** locations of the world and are available in tabular form in various handbooks.
 2. The load on the building due to **solar radiation** is estimated for clear sky.
 3. The building **occupancy** is assumed to be at **full design capacity**.
 4. All building **equipment** and **appliances** are considered to be **operating** at a reasonably representative **capacity**.

Cooling Load Calculations

□ The total building cooling load consists of:

1. External Loads:

✓ heat transferred through the **building envelope** (walls, roof, floor, windows, doors etc.)

2. Internal Loads:

✓ heat generated by **occupants**, **equipment**, and **lights**.

□ The percentage of **external** versus **internal** load **varies** with building type, site climate, and building design.

□ The **total cooling load** on any building consists of both **sensible** as well as **latent** load components.

Cooling Load Calculations

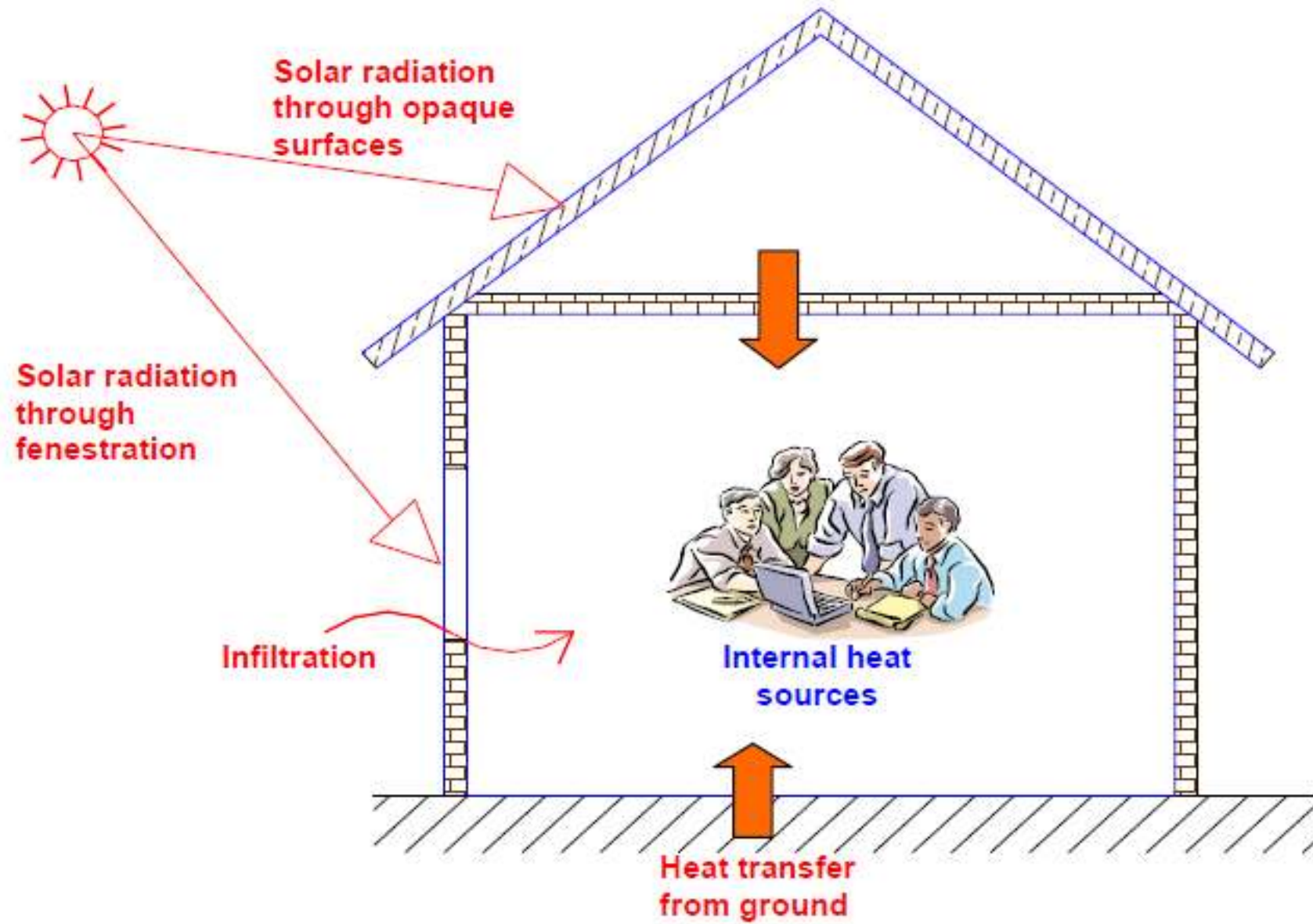


Figure 16-1, Various cooling loads components

Estimation of external loads

a) Heat transfer through opaque surfaces:

This is a **sensible** heat transfer process. The **heat transfer rate** through **opaque** surfaces such as walls, roof, floor, doors etc. is given by:

$$Q_{opaque} = U.A.CLTD \quad (16-2)$$

- ✓ CLTD is the **Cooling Load Temperature Difference**. This could be obtained from tables for **sunlit surfaces** with possibility of adjustment based on the conditions of the design.
- ✓ For surfaces which are **not sunlit** or which have **negligible** thermal mass (such as doors), the **CLTD** value is simply equal to the **temperature difference** across the wall or roof ($T_{out} - T_{in}$)

Estimation of external loads

Roof type	Mass per unit area, kg/m ²	Heat capacity, kJ/m ² .K	Solar Time, h													
			07	08	09	10	11	12	13	14	15	16	17	18	19	20
3	90	90	-2	1	5	11	18	25	31	36	39	40	40	37	32	25
4	150	120	1	0	2	4	8	13	18	24	29	33	35	36	35	32
5	250	230	4	4	6	8	11	15	18	22	25	28	29	30	29	27
6	365	330	9	8	7	8	8	10	12	15	18	20	22	24	25	26

Description of Roof types:

Type 3: 100 mm thick, lightweight concrete

Type 4: 150 mm thick, lightweight concrete

Type 5: 100 mm thick, heavyweight concrete

Type 6: Roof terrace systems

Table 16-2, A typical CLTD table for a roof without suspended ceiling prepared & presented by ASHRAE

Estimation of external loads

Solar Time, h	Orientation							
	N	NE	E	SE	S	SW	W	NW
7	3	4	5	5	4	6	7	6
8	3	4	5	5	4	5	6	5
9	3	6	7	5	3	5	5	4
10	3	8	10	7	3	4	5	4
11	4	10	13	10	4	4	5	4
12	4	11	15	12	5	5	5	4
13	5	12	17	14	7	6	6	5
14	6	13	18	16	9	7	6	6
15	6	13	18	17	11	9	8	7
16	7	13	18	18	13	12	10	8
17	8	14	18	18	15	15	13	10
18	9	14	18	18	16	18	17	12
19	10	14	17	17	16	20	20	15
20	11	13	17	17	16	21	22	17
CLTD_{max}	11	14	18	18	16	21	23	18

Table 16-3, The CLTD values for a D-Type (100-mm face brick with 200-mm concrete block and interior finish or 100-mm face brick and 100-mm concrete brick with interior finish) wall with solar time for different orientations ceiling prepared and presented by ASHRAE

The value of CLTD extracted from Table needs to be corrected so that the actual value is found for different cases, and hence it will be called corrected CLTD and can be calculated from the following equation:

$$(\text{CLTD})_{\text{corr.}} = (\text{CLTD} + \text{LM})k + (25.5 - T_i) + (T_{o,m} - 29.4)f$$

where **LM is latitude correction factor**, which can be obtained from **Table 9–2** for horizontal and vertical surfaces. **The factor k is colour adjustment factor such that k = 1.0 for dark colored roof, and k = 0.5 for permanently light colored roofs.** If the roof construction details are not specified or the construction is different from that specified in Table 9–1, approximate cooling load temperature differences can be obtained from Table 9–3. This simplified table gives the CLTD for sunlit roofs of light, medium and heavy constructions. The temperature difference $(25.5 - T_i)$ of Eq. (9 – 2) is a correction value for indoor design temperature where T_i is the room or inside design temperature, °C. On the other hand, the temperature difference $(T_{o,m} - 29.4)$ is a correction factor for outdoor **mean temperature $T_{o,m}$** . It is related to the outdoor design temperature T_o , according to the relation:

$$T_{o,m} = T_o - \frac{\text{DR}}{2}$$

Where **DR is the daily range** temperature which equals to the difference between the average maximum and average minimum daily temperatures for the warmest month of the summer season. The outdoor mean temperature $T_{o,m}$ is also expressed as:

$$T_{o,m} = (T_{\text{max.}} + T_{\text{min.}})/2$$

The data of Table 9-1 through Table 9-12 are calculated based on the following conditions and assumptions:

- (1) Dark colour surface for solar radiation absorption ($k = 1.0$).
- (2) Inside design temperature T_i , is 25.5 oC.
- (3) Outside ambient temperature T_o , is 35 oC.
- (4) Temperature daily range D.R, is 12 oC.
- (5) Outside mean temperature $T_{o,m}$, is 29.4 oC.
- (6) Latitude angle of the location is 40o N.
- (7) Day and month of the year is July 21st .
- (8) No exterior shading for glass windows and doors.
- (9) Inside heat transfer coefficients is 8.3 W/m².oC.
- (10) Outside heat transfer coefficients is 17 W/m².oC.

The factor f of Eq. (9 -1) is attic or roof fan factor such that $f = 1.0$, if there is no attic or roof fan. The value of the attic or roof fan factor f , is 0.75 if there is an attic or roof fan. For sunlit walls, Table 9–4 is used to obtain the CLTD values according to the wall orientation and wall construction group, which is described in Table 9–5. The (CLTD)corr. for walls is calculated using Eq. (9-2) and Table 9–2 for LM correction in the same way explained for the sunlit roofs.

The only difference occurred is in the colour adjustment factor k , where the k values are taken as follows:

(a) $k = 1.00$ for dark colour walls.

(b) $k = 0.83$ for permanent medium colour walls.

(c) $k = 0.65$ for permanent light colour walls.

The heat transfer rate through sunlit walls or sunlit roofs is calculated from the following equation:

$$Q = UA(CLTD) \text{ corr. (9-4)}$$

If the wall construction for a given application is different from that listed in Table 9–5, then Table 9–6 may be used instead of Table 9–4 to obtain an approximate value of,CLTD. The wall construction for this case may be classified as light, medium or heavy weight construction, irrespective of the exact details of the wall material.

TABLE 9-2 Latitude-Month correction factor LM, as applied to walls and horizontal roofs, north latitudes.

Lat.	Month	Direction									Horizontal Roofs
		N	NNW	NW	ENE	E	ESE	SE	SSE	S	
16	December	-2.2	-3.3	-4.4	-4.4	-2.2	-0.5	2.2	5.0	7.2	-5.0
	Jan./Nov.	-2.2	-3.3	-3.8	-3.8	-2.2	-0.5	2.2	4.4	6.6	-3.8
	Feb./Oct.	-1.6	-2.7	-2.7	-2.2	-1.1	0.0	1.1	2.7	3.8	-2.2
	Mar/Sept.	-1.6	-1.6	-1.1	-1.1	-0.5	-0.5	0.0	0.0	0.0	-0.5
	Apr./Aug.	-0.5	0.0	-0.5	-0.5	-0.5	-1.6	-1.6	-2.7	-3.3	0.0
	May/July	2.2	1.6	1.6	0.0	-0.5	-2.2	-2.7	-3.8	-3.8	0.0
	June	3.3	2.2	2.2	0.5	-0.5	-2.2	-3.3	-4.4	-3.8	0.0
24	December	-2.7	-3.8	-5.5	-6.1	-4.4	-2.7	1.1	5.0	6.6	-9.4
	Jan./Nov.	-2.2	-3.3	-4.4	-5.0	-3.3	-1.6	-1.6	5.0	7.2	-6.1
	Feb./Oct.	-2.2	-2.7	-3.3	-3.3	-1.6	-0.5	1.6	3.8	5.5	-3.8
	Mar/Sept.	-1.6	-2.2	-1.6	-1.6	-0.5	-0.5	0.5	1.1	2.2	-1.6
	Apr./Aug.	-1.1	-0.5	0.0	-0.5	-0.5	-1.1	-0.5	-1.1	-1.6	0.0
	May/July	0.5	1.1	1.1	0.0	0.0	-1.6	-1.6	-2.7	-3.3	0.5
	June	1.6	1.6	1.6	0.5	0.0	-1.6	-2.2	-3.3	-3.3	0.5

32	December	-2.7	-3.8	-5.5	-6.1	-4.4	-2.7	1.1	5.0	6.6	-9.4
	Jan./Nov.	-2.7	-3.8	-5.0	-6.1	-4.4	-2.2	1.1	5.0	6.6	-8.3
	Feb./Oct.	-2.2	-3.3	-3.8	-4.4	-2.2	-1.1	2.2	4.4	6.1	-5.5
	Mar/Sept.	-1.6	-2.2	-2.2	-2.2	-1.1	-0.5	1.6	2.7	3.8	-2.7
	Apr./Aug.	-1.1	-1.1	-0.5	-1.1	0.0	-0.5	0.0	5.0	0.5	-0.5
	May/July	0.5	0.5	0.5	0.0	0.0	-0.5	-0.5	-1.6	-1.6	0.5
	June	0.5	1.1	1.1	0.5	0.0	-1.1	-1.1	-2.2	-2.2	1.1
40	December	-3.3	-4.4	-5.5	-7.2	-5.5	-3.8	0.0	3.8	5.5	-11.6
	Jan./Nov.	-2.7	-3.8	-5.5	-6.6	-5.0	-3.3	0.5	4.4	6.1	-10.5
	Feb./Oct.	-2.7	-3.8	-4.4	-5.0	-3.3	-1.6	1.6	4.4	6.6	-7.7
	Mar/Sept.	-2.2	-2.7	-2.7	-3.3	-1.6	0.5	2.2	3.8	5.5	-4.4
	Apr./Aug.	-1.1	-1.6	-1.6	-1.1	0.0	0.0	1.1	1.6	2.2	1.6
	May/July	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
	June	0.5	0.5	0.5	0.5	0.0	0.5	0.0	0.0	-0.5	1.1
48	December	-3.3	-4.4	-6.1	-7.7	-7.2	-5.5	-1.6	1.1	3.3	-13.8
	Jan./Nov.	-3.3	-4.4	-6.1	-7.2	-6.1	-4.4	-0.5	2.7	4.4	-13.3
	Feb./Oct.	-2.7	-3.8	-5.5	-6.1	-4.4	-2.7	0.5	4.4	6.1	-10.0
	Mar/Sept.	-2.2	-3.3	-3.3	-3.8	-2.2	-0.5	2.2	4.4	6.1	-6.1
	Apr./Aug.	-1.6	-1.6	-1.6	-1.6	-0.5	0.0	2.2	3.3	3.8	-2.7
	May/July	0.0	-0.5	0.0	0.0	0.5	0.5	1.6	1.6	2.2	0.0
	June	0.5	0.5	1.1	0.5	1.1	0.5	1.1	1.1	1.6	1.1

An air conditioned room that stands on a well ventilated basement measures 3 m wide, 3 m high and 6 m deep. One of the two 3 m walls faces west and contains a double glazed glass window of size 1.5m by1.5m, mounted flush with the wall with no external shading. There are no heat gains through the walls other than the one facing west. Calculate the sensible, latent and total heat gains on the room, room sensible heat factor from the following information. What is the required cooling capacity?

Inside conditions	:	25°C dry bulb, 50 percent RH
Outside conditions	:	43°C dry bulb, 24°C wet bulb
U-value for wall	:	1.78 W/m ² .K
U-value for roof	:	1.316 W/m ² .K
U-value for floor	:	1.2 W/m ² .K
Effective Temp. Difference (ETD) for wall:	:	25°C
Effective Temp. Difference (ETD) for roof:	:	30°C
U-value for glass	;	3.12 W/m ² .K
Solar Heat Gain (SHG) of glass	;	300 W/m ²
Internal Shading Coefficient (SC) of glass:	:	0.86
Occupancy	:	4 (90 W sensible heat/person) (40 W latent heat/person)
Lighting load	:	33 W/m ² of floor area
Appliance load	:	600 W (Sensible) + 300 W(latent)
Infiltration	:	0.5 Air Changes per Hour
Barometric pressure	:	101 kPa

External loads:

a) Heat transfer rate through the walls: Since only west wall measuring 3m x 3m with a glass windows of 1.5m x 1.5m is exposed; the heat transfer rate through this wall is given by:

$$Q_{\text{wall}} = U_{\text{wall}} A_{\text{wall}} \text{ETD}_{\text{wall}} = 1.78 \times (9 - 2.25) \times 25 = 300.38 \text{ W (Sensible)}$$

b) Heat transfer rate through roof:

$$Q_{\text{roof}} = U_{\text{roof}} A_{\text{roof}} \text{ETD}_{\text{roof}} = 1.316 \times 18 \times 30 = 710.6 \text{ W (Sensible)}$$

c) Heat transfer rate through floor: Since the room stands on a well-ventilated basement, we can assume the conditions in the basement to be same as that of the outside (i.e., 43°C dry bulb and 24°C wet bulb), since the floor is not exposed to solar radiation, the driving temperature difference for the roof is the temperature difference between the outdoor and indoor, hence:

$$Q_{\text{floor}} = U_{\text{floor}} A_{\text{floor}} \text{ETD}_{\text{floor}} = 1.2 \times 18 \times 18 = 388.8 \text{ W (Sensible)}$$

Estimation of external loads

b) Heat transfer through fenestration:

- ✓ Heat transfer by conduction due to **temperature difference** **across** the window

$$Q_{window} = U.A.CLTD \quad (16-3)$$

- CLTD is ΔT across the window and A equal to the total area of the window

- ✓ Heat transfer due to solar radiation through the window.

$$Q_{trans} = A_{unshaded} \cdot SHGF_{max} \cdot SC \cdot CLF \quad (16-4)$$

where $A_{unshaded}$ is the area exposed to solar radiation,

$SHGF_{max}$ maximum Solar Heat Gain Factor

SC Shading Coefficient,

CLF Cooling Load Factor. ratio cooling load to maximum solar heat gain;

Estimation of external loads

Month	Orientation of the surface					
	N/shade	NE/NW	E/W	SE/SW	S	Horizontal
December	69	69	510	775	795	500
Jan, Nov	75	90	550	785	775	555
Feb, Oct	85	205	645	780	700	685
Mar, Sept	100	330	695	700	545	780
April, Aug	115	450	700	580	355	845
May, July	120	530	685	480	230	865
June	140	555	675	440	190	870

Table 16-4, The maximum SHGF values in W/m^2 for 32° N latitude for different months and orientations (direction a glass is facing), prepared and presented by ASHRAE

Estimation of external loads

Type of glass	Thickness mm	No internal shading	Shading Coefficient, SC			
			Venetian blinds		Roller shades	
			Medium	Light	Dark	Light
<u>Single glass</u> Regular	3	1.00	0.64	0.55	0.59	0.25
<u>Single glass</u> Plate	6-12	0.95	0.64	0.55	0.59	0.25
<u>Single glass</u> Heat absorbing	6	0.70	0.57	0.53	0.40	0.30
<u>Double glass</u> Regular	3	0.90	0.57	0.51	0.60	0.25
<u>Double glass</u> Plate	6	0.83	0.57	0.51	0.60	0.25
<u>Double glass</u> Reflective	6	0.2-0.4	0.2-0.33	-	-	-

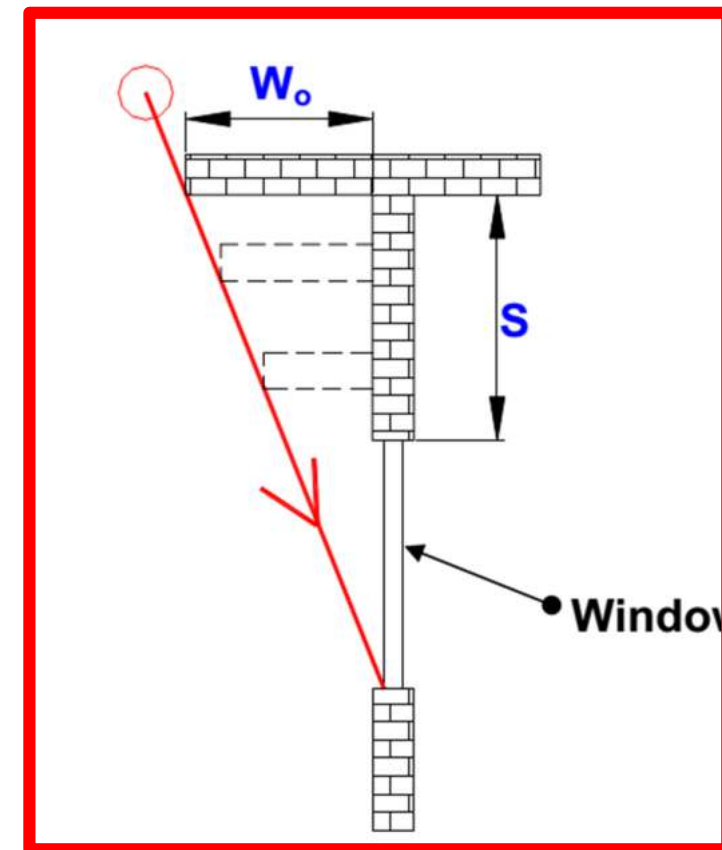


Table 16-5, Typical values of shading coefficients. prepared and presented by ASHRAE Venetianb

Estimation of external loads

Solar Time, h	Direction the sunlit window is facing								
	N	NE	E	SE	S	SW	W	NW	Horiz.
6	0.73	0.56	0.47	0.30	0.09	0.07	0.06	0.07	0.12
7	0.66	0.76	0.72	0.57	0.16	0.11	0.09	0.11	0.27
8	0.65	0.74	0.80	0.74	0.23	0.14	0.11	0.14	0.44
9	0.73	0.58	0.76	0.81	0.38	0.16	0.13	0.17	0.59
10	0.80	0.37	0.62	0.79	0.58	0.19	0.15	0.19	0.72
11	0.86	0.29	0.41	0.68	0.75	0.22	0.16	0.20	0.81
12	0.89	0.27	0.27	0.49	0.83	0.38	0.17	0.21	0.85
13	0.89	0.26	0.26	0.33	0.80	0.59	0.31	0.22	0.85
14	0.86	0.24	0.24	0.28	0.68	0.75	0.53	0.30	0.81
15	0.82	0.22	0.22	0.25	0.50	0.83	0.72	0.52	0.71
16	0.75	0.20	0.20	0.22	0.35	0.81	0.82	0.73	0.58
17	0.78	0.16	0.16	0.18	0.27	0.69	0.81	0.82	0.42
18	0.91	0.12	0.12	0.13	0.19	0.45	0.61	0.69	0.25

Table 16-6, Typical CLF values for glass with interior shading. prepared and presented by ASHRAE

d) Heat transfer rate through glass: This consists of the radiative as well as conductive components. Since no information is available on the value of CLF, it is taken as 1.0. Hence the total heat transfer rate through the glass window is given by:

$$Q_{\text{glass}} = A_{\text{glass}} [U_{\text{glass}}(T_o - T_i) + \text{SHGF}_{\text{max}} \text{SC}] = 2.25[3.12 \times 18 + 300 \times 0.86] = 706.9 \text{ W}$$

(Sensible)

Estimation of external loads

c) Heat transfer due to infiltration:

✓ Heat transfer due to **infiltration** consists of **sensible** and **latent** components.

✓ The **sensible heat transfer rate** due to infiltration is given by:

$$Q_{s,inf} = \dot{m}_o C_{p,m} (T_o - T_i) = \dot{V}_o \rho_o C_{p,m} (T_o - T_i) \quad (16-5)$$

➤ where \dot{V}_o is the infiltration rate (m³/s), ρ_o and $c_{p,m}$ are the density and specific heat of the moist, infiltrated air, respectively. T_o and T_i are the outdoor and indoor dry bulb temperatures.

✓ The **latent heat transfer rate** due to infiltration is given by:

$$Q_{l,inf} = \dot{m}_o i_{fg} (W_o - W_i) = \dot{V}_o \rho_o i_{fg} (W_o - W_i) \quad (16-6)$$

➤ where i_{fg} is the latent heat of **vaporization** of water, W_o and W_i are the outdoor and indoor **humidity ratio**, respectively.

Infiltration rate

1) air change method is given by:

$$\dot{V}_o = (\text{ACH}) \cdot V / 3600 \quad \text{m}^3 / \text{s}$$

ACH is number of air changes per hour and **V** is the gross volume of the conditioned space m^3 . ACH value varies from 0.5 ACH for tight and well-sealed buildings to about 2.0 for loose and poorly sealed buildings. For modern buildings the ACH = 0.2 ACH.

2) crack method is given by:

$$\dot{V}_o = A \cdot C \cdot \Delta P^n \quad \text{m}^3 / \text{s}$$

where **A** is the effective leakage area of the cracks, **C** is a flow coefficient which depends on the type of the crack and the nature of the flow in the crack, **ΔP** is the difference between outside and inside pressure (**$P_o - P_i$**) and **n** is an exponent whose value depends on the nature of the flow in the crack. The value of **n** varies $0.4 \leq n \leq 1.0$. The pressure difference **Δp_a** rises due to the wind (**ΔP_{wind}**), pressure stack effect (**ΔP_{stack}**) and due to building pressurization (**ΔP_{bld}**),

$$\Delta P = \Delta P_{\text{wind}} + \Delta P_{\text{stack}} + \Delta P_{\text{bld}}$$

For the inside conditions of 25°C dry bulb, 50 percent RH:

$$W_i = 9,9167 \times 10^{-3} \text{ kgw/kgda}$$

For the outside conditions of 43°C dry bulb, 24°C wet bulb:

$$W_o = 0.0107 \text{ kgw/kgda, density of dry air} = 1.095 \text{ kg/m}^3$$

e) Heat transfer due to infiltration: The infiltration rate is 0.5 ACH, converting this into mass flow rate, the infiltration rate in kg/s is given by:

$$m_{\text{inf}} = \text{density of air} \times (\text{ACH} \times \text{volume of the room}) / 3600 = 1.095 \times (0.5 \times 3 \times 3 \times 6) / 3600$$

$$m_{\text{inf}} = 8.2125 \times 10^{-3} \text{ kg/s}$$

Sensible heat transfer rate due to infiltration, $Q_{s,\text{inf}}$;

$$Q_{s,\text{inf}} = m_{\text{inf}} c_{\text{pm}} (T_o - T_i) = 8.2125 \times 10^{-3} \times 1021.6 \times (43 - 25) = 151 \text{ W (Sensible)}$$

Latent heat transfer rate due to infiltration, $Q_{l,\text{inf}}$:

$$Q_{l,\text{inf}} = m_{\text{inf}} h_{\text{fg}} (W_o - W_i) = 8.2125 \times 10^{-3} \times 2501 \times (0.0107 - 0.0099) = 16.4 \text{ W (sensible)}$$

6. Calculate the maximum heat transfer rate through a 1.5 m^2 area, unshaded regular double glass facing south during the months of June and December without internal shading and with internal shading consisting of light venetian blinds. Location 32°N

Table 16-4 and 16-5

Ans.: For the month of June the SHGF_{max} from Table 33.1 is 190 W/m^2 . Using the values of shading coefficients from Table 33.2, the heat transfer rate is:

Without internal shading ($\text{SC} = 0.9$):

$$Q_{\text{sg}} = A.(\text{SHGF}_{\text{max}}).(\text{SC}) = 1.5 \times 190 \times 0.9 = 256.5 \text{ W} \quad (\text{Ans.})$$

With internal shading ($\text{SC} = 0.51$):

$$Q_{\text{sg}} = A.(\text{SHGF}_{\text{max}}).(\text{SC}) = 1.5 \times 190 \times 0.51 = 145.35 \text{ W} \quad (\text{Ans.})$$

These values for the month of December ($\text{SHGF}_{\text{max}} = 795 \text{ W/m}^2$) are:

Without internal shading: $Q_{\text{sg}} = 1073.25 \text{ W} \quad (\text{Ans.})$

With internal shading: $Q_{\text{sg}} = 608.175 \text{ W} \quad (\text{Ans.})$

8. A large air conditioned building with a total internal volume of $1,00,000 \text{ m}^3$ is maintained at 25°C (DBT) and 50% RH, while the outside conditions are 35°C and 45% RH. It has a design occupancy of 10,000 people, all non-smoking. The infiltration rate through the building is equal to 1.0 ACH. Estimate the heat transfer rate due to ventilation and infiltration. Assume the barometric pressure to be 1 atm.

Ans.: From psychrometric chart:

For inside conditions: 24°C (DBT) and 50% RH:

$$W_i = 0.0093 \text{ kgw/kgda}, h_i = 47.656 \text{ kJ/kgda}$$

For outside conditions: 35°C (DBT) and 45% RH:

$$W_o = 0.01594 \text{ kgw/kgda}, h_o = 75.875 \text{ kJ/kgda} \text{ and } v_a = 0.89519 \text{ m}^3/\text{kg}$$

Heat transfer due to ventilation:

From Table 33.3, assume a ventilation requirement of **3.5 l/s/person**. Hence the total OD air required is:

Table 16-5a

$$V_{o,v} = 3.5 \times 10,000 = 35000 \text{ l/s} = 35 \text{ m}^3/\text{s}$$

Hence the mass flow rate of ventilated air is:

$$m_{o,v} = 35 / 0.89519 = 39.1 \text{ kg/s}$$

Sensible heat transfer rate due to ventilation is given by:

$$Q_{s,v} = m_{o,v} c_{pm} (t_o - t_i) = 39.1 \times 1.0216 \times (35 - 25) = 399.5 \text{ kW}$$

Latent heat transfer rate due to ventilation is given by:

$$Q_{l,v} = m_{o,v} h_{fg} (W_o - W_i) = 39.1 \times 2501 \times (0.01594 - 0.0093) = 649.3 \text{ kW}$$

Hence total heat transfer rate due to ventilation is:

$$Q_{t,v} = Q_{s,v} + Q_{l,v} = 1048.8 \text{ kW} \quad (\text{Ans.})$$

Heat transfer rate due to infiltration:

Infiltration rate, $V_{inf} = 1 \text{ ACH} = 1,00,000/3600 = 27.78 \text{ m}^3/\text{s}$

Hence mass flow rate of infiltrated air is:

$$m_{inf} = V_{inf}/v_a = 27.78/0.89519 = 31 \text{ kg/s}$$

Hence using expressions similar to ventilation, the sensible, latent and total heat transfer rates due to infiltration are found to be:

$$Q_{s,inf} = 316.7 \text{ kW} \quad (\text{Ans.})$$

$$Q_{l,inf} = 514.8 \text{ kW} \quad (\text{Ans.})$$

$$Q_{t,inf} = 831.5 \text{ kW} \quad (\text{Ans.})$$

It can be seen from the above example that the total load on the air conditioning system is very high (= **1880.3 kW = 534.6 TR**).

Function	Occupancy per 100 m ² floor area	OD air requirement per person (L/s)	
		Smoking	Non-smoking
Offices	7	10	2.5
Operation theatres	20	-	15
Lobbies	30	7.5	2.5
Class rooms	50	-	8.0
Meeting places	60	17.5	3.5

Table 33.3: Typical outdoor air requirements for ventilation

Table 16-5a, Typical outdoor air requirements for ventilation

Estimation of external loads

d) Miscellaneous external loads:

- In addition to the **above loads**, if the **cooling coil** has a **positive by-pass factor**, then some amount of **ventilation air** directly **enters** the conditioned space, in which case it becomes a **part of the building cooling load**.
- In addition, **sensible** and **latent** heat transfer to the building also occurs due to heat transfer and air leakage in the **supply ducts**.
- The **power input** of the supply **air fan** becomes a part of the **external sensible load** on the building, **initially** it is assumed that the supply fan **adds about 5%** of the room **sensible cooling load** where cooling loads are then **estimated**. Then this value is **corrected** in the end when the **actual** fan selection is done.

Estimation of Internal Loads

□ **The internal loads consist of load due to:**

- ✓ **Occupants**
- ✓ **Lighting**
- ✓ **Equipment**
- ✓ **Appliances**
- ✓ **Products stored**
- ✓ **Processes being performed in the conditioned space.**

Estimation of Internal Loads

a) Load due to occupants:

- ❑ This consists of both **sensible** and **latent** heat components.
- ❑ The **rate** at which the **sensible** and **latent** heat transfer take place depends mainly on the **population** and activity level of the occupants.
- ❑ This **portion** of the heat transfer is in the form of **radiation**,
- ❑ The **sensible** heat transfer to the conditioned space due to the **occupants** is given by the equation:
$$Q_{s,occupants} = (\text{No. of People}).(\text{Sensible heat gain/person}).\text{CLF} \quad (17-1)$$
- ❑ The **fraction** of the total heat gain that is **sensible** depends on the conditions of the **indoor** environment.

Estimation of external loads

Activity	Total heat gain, W	Sensible heat gain fraction
Sleeping	70	0.75
Seated, quiet	100	0.60
Standing	150	0.50
Walking @ 3.5 kmph	305	0.35
Office work	150	0.55
Teaching	175	0.50
Industrial work	300 to 600	0.35

Table 17-1, Total heat gain, sensible heat gain fraction from occupants

Estimation of Internal Loads

a) Load due to occupants:

- ❑ The value **CLF** for **occupants** depends on:
 - ✓ The **hours** after the entry of the **occupants** into the conditioned space,
 - ✓ The total **hours** spent in the conditioned space
 - ✓ The **type** of the building.
- ❑ Values of **CLF** have been obtained for **different types** of buildings and have been tabulated in ASHRAE handbooks.
- ❑ Since the **latent** heat gain from the **occupants** is instantaneous the CLF for **latent** heat gain is 1.0, thus the **latent** heat gain due to **occupants** is given by:

$$Q_{l,occupants} = (\text{No. of People}).(\text{Latent heat gain/person}) \quad (17-2)$$

Estimation of Internal Loads

b) Load due to lighting:

- ❑ Lighting adds **sensible** heat to the conditioned space.
- ❑ This heat transfer consists of both **radiation** and **convection**.
- ❑ The cooling load due to **lighting** system is given by:

$$Q_{s,lighting} = (\text{Installed wattage}).(\text{Usage factor}).(\text{Ballast factor}).CLF \quad (17-3)$$

- ❑ The **usage factor** accounts for any lamps that are installed but are **not** switched on at the **time** at which load calculations are performed.
- ❑ The **ballast factor** accounts the load imposed by **ballasts** used in **fluorescent lights**. Taken as 1.25 for **fluorescent lights**, and 1.0 for **incandescent lamps**.
- ❑ The values of CLF is a **function** of the **number of hours** after the lights are turned on, **type of lighting fixtures** and the **hours** of operation of the lights.

Estimation of Internal Loads

c) Load due to equipment and appliances:

- ❑ These may add both **sensible** and **latent** loads to the conditioned space.
- ❑ The **sensible** load may be in the form of **radiation** and/or **convection**.
- ❑ The internal **sensible** load due to equipment and appliances is given by:

$$Q_{s,appliances} = (\text{Installed wattage}).(\text{Usage factor}).CLF \quad (17-4)$$

- ❑ The internal **latent** load due to equipment and appliances is given by:

$$Q_{l,appliances} = (\text{Installed wattage}).(\text{Latent heat fraction}) \quad (17-5)$$

Appliance	Sensible load, W	Latent load, W	Total load, W
Coffee brewer, 0.5 gallons	265	65	330
Coffee warmer, 0.5 gallons	71	27	98
Toaster, 360 slices/h	1500	382	1882
Food warmer/m ² plate area	1150	1150	2300

Table 17-2, Typical appliance load

Estimation of Internal Loads

c) Load due to equipment and appliances:

- ❑ For other equipment such as **computers**, **printers** etc, the load is in the form of **sensible** heat transfer and is estimated based on the **rated power consumption**, with CLF of 1.0 due to their negligible radiative heat transfer
- ❑ Electric motors **efficiencies** should be taken into account when they kept **inside** the **conditioned space**,
- ❑ Though the estimation of cooling load due to **appliance and equipment** appears to be **simple** as given by the equations, a large amount of **uncertainty** is introduced on account of the **usage factor** and the difference between **rated** (nameplate) power consumption at **full loads** and actual power consumption at part loads.
- ❑ Estimation using **nameplate power** input may lead to overestimation of the loads, if the equipment operates at **part load** conditions **most** of the time.

Internal loads:

a) Load due to occupants: The sensible and latent load due to occupants are:

$$Q_{s,occ} = \text{no.of occupants} \times \text{SHG} = 4 \times 90 = 360 \text{ W}$$

$$Q_{l,occ} = \text{no.of occupants} \times \text{LHG} = 4 \times 40 = 160 \text{ W}$$

b) Load due to lighting: Assuming a CLF value of 1.0, the load due to lighting is:

$$Q_{lights} = 33 \times \text{floor area} = 33 \times 18 = 594 \text{ W (Sensible)}$$

c) Load due to appliance:

$$Q_{s,app} = 600 \text{ W (Sensible)}$$

$$Q_{l,app} = 300 \text{ W (Latent)}$$

Estimation of the Cooling Capacity of the System

- ❑ In order to find the required **cooling capacity** of the system, the following factors should be considered
 - ✓ The **sensible** and **latent** loads due to ventilation
 - ✓ Leakage losses in the return air ducts
 - ✓ **Heat added** due to return air fan

Total sensible and latent loads are obtained by summing-up all the sensible and latent load components (both external as well as internal) as:

$$Q_{s,\text{total}} = 300.38 + 710.6 + 388.8 + 706.9 + 151 + 360 + 594 + 600 = 3811.68 \text{ W} \quad (\text{Ans.})$$

$$Q_{l,\text{total}} = 16.4 + 160 + 300 = 476.4 \text{ W} \quad (\text{Ans.})$$

Total load on the building is:

$$Q_{\text{total}} = Q_{s,\text{total}} + Q_{l,\text{total}} = 3811.68 + 476.4 = 4288.08 \text{ W} \quad (\text{Ans.})$$

Room Sensible Heat Factor (RSHF) is given by:

$$\text{RSHF} = Q_{s,\text{total}}/Q_{\text{total}} = 3811.68/4288.08 = 0.889 \quad (\text{Ans.})$$

To calculate the required cooling capacity, one has to know the losses in return air ducts. Ventilation may be neglected as the infiltration can take care of the small ventilation requirement. Hence using a safety factor of 1.25, the required cooling capacity is:

$$\text{Required cooling capacity} = 4288.08 \times 1.25 = 5360.1 \text{ W} \approx 1.5 \text{ TR} \quad (\text{Ans.})$$

Estimation of the Cooling Capacity of the System

a) Load on the system due to ventilated air:

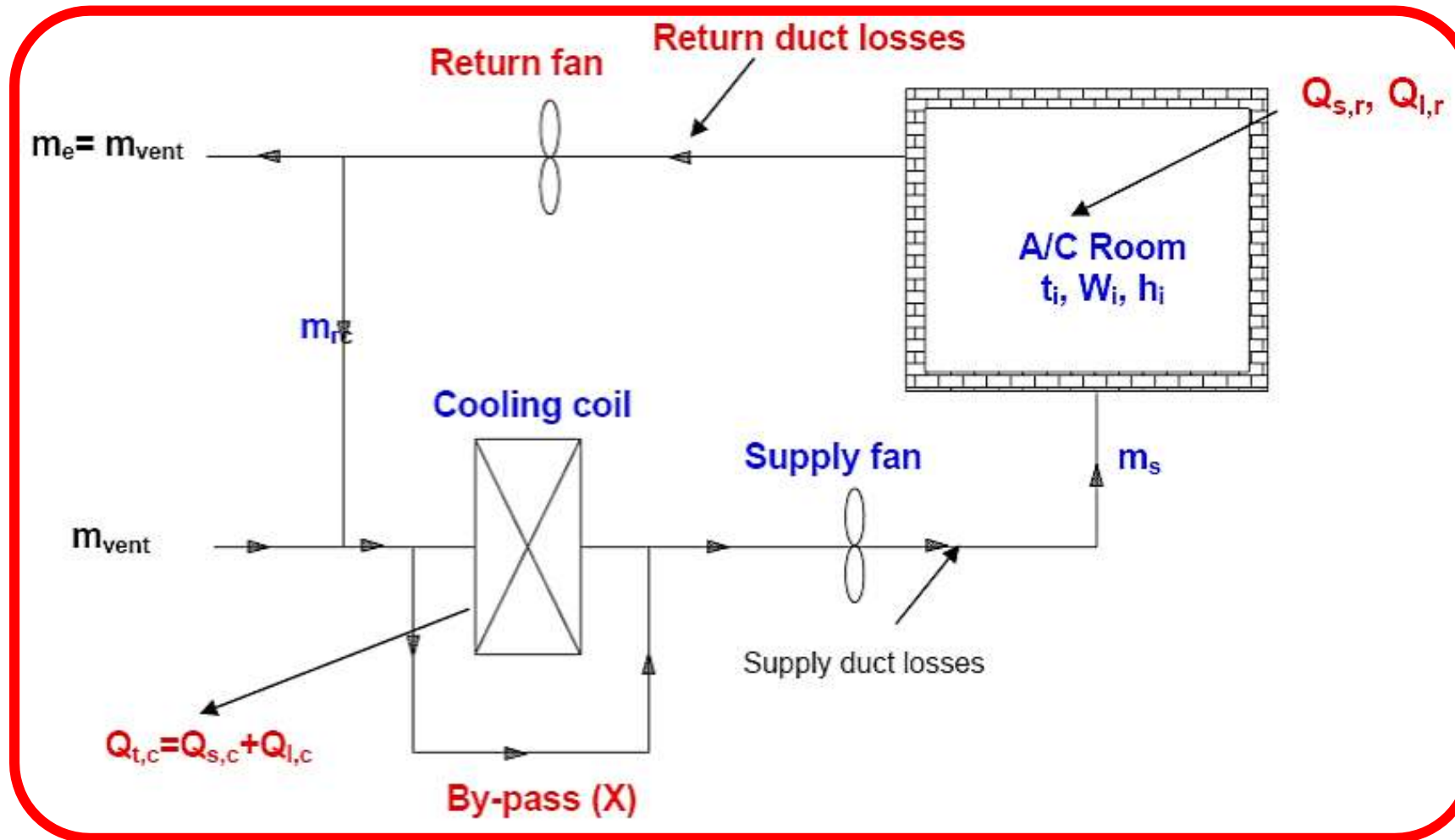


Figure 17-1, A typical summer air conditioning system with a cooling coil of non-zero by-pass factor

Estimation of the Cooling Capacity of the System

a) Load on the system due to ventilated air:

- The cooling load on the coil due to **sensible** heat transfer of the ventilated air is given by:

$$Q_{s,vent} = \dot{m}_{vent} (1-X) \cdot C_{p,m} (T_o - T_i) = \dot{V}_{vent} \rho_o (1-X) \cdot C_{p,m} (T_o - T_i) \quad (17-6)$$

- The cooling load on the coil due to **latent** heat transfer of the ventilated air is given by:

$$Q_{l,vent} = \dot{m}_{vent} (1-X) \cdot i_{fg} (W_o - W_i) = \dot{V}_{vent} \rho_o (1-X) \cdot i_{hg} (W_o - W_i) \quad (17-7)$$

where \underline{W}_o and \underline{W}_i are the humidity ratios of the ambient and conditioned air, respectively and \underline{i}_{fg} is the latent heat of vaporization of water and \underline{X} is **the by-pass factor of the coil**

Estimation of the Cooling Capacity of the System

b) Load on the coil due to leakage in return air duct and due to return air fan:

- ❑ The **sensible** heat transfer to the return duct due to heat transfer from the surroundings to the return duct depends on:
 - ✓ The surface area of the duct that is exposed to outside air (A_{exposed})
 - ✓ The amount of insulation (U_{ins})
 - ✓ The temperature difference between outdoor air and return air

$$Q_{s,duct} = U_{\text{ins}} \cdot A_{\text{exposed}} (T_o - T_i) \quad (17-8)$$

- ❑ The amount of **sensible** and **latent** heat transfer rates due to **air leakage** from or to the system depends on the **effectiveness** of the sealing provided and the condition of the **outdoor** air and return air.

Estimation of the Cooling Capacity of the System

□ The total **sensible** load on the coil ($Q_{s,c}$) is:

$$Q_{s,c} = Q_{s,r} + Q_{s,vent} + Q_{s,return duct} \quad (17-9)$$

□ The total **latent** load on the coil ($Q_{l,c}$) is:

$$Q_{l,c} = Q_{l,r} + Q_{l,vent} + Q_{l,return duct} \quad (17-10)$$

□ The **required cooling capacity** of the system which is equal to the total load on the coil is obtained from the equation:

$$\text{Required Cooling Capacity } Q_{t,c} = Q_{s,c} + Q_{l,c} \quad (17-11)$$

□ One can also calculate the **sensible heat factor for the coil** (CSHF) and **draw** the process line on the **psychrometric** chart and find the required coil **Apparatus Dew Point Temperature** (coil ADP) from the aforementioned data

Estimation of the Cooling Capacity of the System

- ❑ The method discussed above is based on **Cooling Load Temperature Difference** CLTD/CLF as suggested by ASHRAE.
- ❑ It can be seen that with the **aid** of suitable input data and building specifications one can manually **estimate** the **cooling** load on the building and the required **cooling** capacity of the system.
- ❑ A suitable **safety factor** is normally used in the end to account for **uncertainties** in occupants, equipment, external infiltration, external conditions etc.
- ❑ This relatively simple method offers **reasonably** accurate results for **most** of the buildings.
- ❑ For more accurate results one has to resort actual building simulation taking into account on all **relevant factors** that affect the **cooling** load.

Heating Load Calculations

- ❑ Conventionally, **steady state conditions** are assumed for estimating the building **heating** loads and the internal heat sources are **neglected**.
- ❑ One has to estimate only the **sensible** and latent heat losses from the building walls, roof, ground, windows, doors, due to infiltration and ventilation.
- ❑ Equations **similar** to those used for **cooling** load calculations are used with the difference that the **CLTD** values are simply replaced by the design temperature difference between the conditioned space and outdoors.
- ❑ Since a **steady state is assumed**, the required heating **capacity** of the system is equal to the **total heat loss** from the building.
- ❑ Depending on the **specific case** one has to select a **suitable and economically** justifiable method for estimating **heating loads**.