CCA EXAM

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# ENGINEERING HVAC EQUATIONS

Carbon Auditing Specialist Curriculum

BEYOND SMART CITIES


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The Carbon Auditing Specialist may use HVAC design and engineering formulas to troubleshoot issues in new and existing buildings.


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# BEYOND SMART CITIES

## HVAC and Engineering Equations

**The energy management professional may find certain engineering and HVAC design formulas useful when implementing energy audits, carbon audits, and energy management in new and existing buildings, as well as when diagnosing problems. Following is a list of the most frequently used formulas.**

### GEOMETRY

- Area of circle = $\Pi * r^2$
- Circumference of circle = $\Pi * D$
- Area of rectangle = L * W
- Perimeter of rectangle = 2*L + 2*W

### ELECTRICAL

- V = I * R  Ohm's Law  (single phase)
- P = $I^2$ * R  Ohm's law for power  (single phase)
- kW = (V × A × 1.73 × PF)/1000  (3 phase)  PF = Cos phi
- kW = kVA * PF  PF = Cos phi
- kVA = 1.73 x kV x A  ( 3 phase)

**LIGHTING**

- RCR = (2.5 × cavity height × perimeter)/(area)  General
- RCR = (5 x height x (L + W))/(L*W)  Rectangular room
- Number of lamps = (LUXdesired × area)/(Lumens-per-lamp × Cu × L1 × L2 )
- Lux = Lumens/$d^2$
- Efficacy = Lumens/watt

**HEAT FLOW**

- q = u × A × Δt  W
- q = M × Cp × ΔT  W  sensible heat only
- q = M × Δh  W  sensible and latent heat
- Q cooling = U × A × 24 × CDD  Wh/yr
- Q heating= U × A × 24 × HDD  Wh/yr

**MOTORS**

- Percent load = (NLRPM-RPM)/(NLRPM - FLRPM)
- Synchronous speed = (frequency × 50)/(number of pole pairs)
- kW × Percent load = (V × A × 1.73 × PF × Efficiency)  (3 phase)
- PF = kW/kVA  = Cos phi

**FANS AND FAN LAWS**

- LPSn/LPSo = (RPMn/RPMo)  n=new; o=old
- SPn /SPo = $(RPMn /RPMo )^2$
- kWn/kWo = $(RPMn /RPMo )^3$
- RPM-driven × diameter-driven = RPM-driver × diameter-driver

- Percent OA = (RAT - MAT)/(RAT - OAT)

**MISCELLANEOUS**

- $q = LPS \times 1.2 \times \Delta T$ W (sensible heat for air)
- $q = LPS \times 4.2 \times \Delta t$ kW (sensible heat for water)
- POU energy cost = (output/efficiency) x (cost per unit)
- Density of dry air at standard conditions 1.204 kg/m$^3$
- Specific heat of dry air at standard conditions 1.006 kJ/ kg°C
- Density of water at standard conditions 1 kg/L
- Specific heat of water at standard conditions 4.2 kJ/kg°C
- Density of water 1000 kg/m$^3$

## COOLING AND HEATING EQUATIONS

### For SI:

- **Sensible Heat**

  $HS = cp\ \rho\ q\ \Delta T$
- **Latent Heat**

  $HL = c1\rho q\Delta W$
- **Total Heat**

  $HT = \rho q\Delta h$
- **Sensible Heat Ratio:**

  $SHR = HS/HT$

*Where:*

*$H_S$ = Sensible Heat (kW)*

*$H_L$ = Latent Heat (kW)*

*$H_T$ = Total Heat (kW)*

*$\Delta T$ = Temperature Difference (°K) q = Air Volume Flow ($m^3/s$)*

*$\rho$ = Density of Air (1.202 kg/$m^3$)*

*$c_p$ = **Specific Heat** of Air (1.0 kJ/kg.K)*

*$c_1$ = Air Latent Factor (a typical value 3010)*

*$\Delta W$ = Humidity Ratio Difference (kg water/kg dry air) $\Delta h$ = **Enthalpy** Difference (kJ/kg)*

*SHR = Sensible Heat Ratio*

### For I-P:

- **Sensible Heat**

  $H_S = 1.085 \times CFM \times \Delta T$

- **Latent Heat**

  $H_L = 0.68 \times CFM \times \Delta WGR = 4840 \times CFM \times \Delta WLB$

- **Total Heat**

$H_T = 4.5 \times CFM \times \Delta h$

## • Sensible Heat Ratio

$SHR = H_S / H_T$

*Where:*

*$H_S$ = Sensible Heat (Btu/hr)*

*$H_L$ = Latent Heat (Btu/hr)*

*$H_T$ = Total Heat (Btu/hr)*

*$\Delta T$ = Temperature Difference (°F)*

*$\Delta WGR$. = Humidity Ratio Difference (Gr.$H_2O$/Lb.DA)*

*$\Delta WLB$. = Humidity Ratio Difference (Lb.$H_2O$/Lb.DA)*

*$\Delta h$ = Enthalpy Difference (Btu/Lb.DA)*

*CFM = Air Flow Rate (Cubic Feet per Minute) SHR = Sensible Heat Ratio*

## Thermal Resistance R-Values/U-Values

## A. Thermal Value (R-Value)

$R = t / k$

## B. Thermal Transmittance (U-Value)

$U = 1 / \Sigma R$

*Where:*

### *For SI:*

*k = Thermal Conductivity (W/(m·K))*

*R = Thermal Resistance ((m2·K)/W)*

*U = Thermal Transmittance (W/(m2·K)) t = Thickness (m)*

*ΣR = Sum of the Individual R-Values*

### *For I-P:*

*k = Thermal Conductivity (Btu./hr. ft. °F.)*
*R = Thermal Resistance (hr. ft2. °F./Btu.)*
*U = Thermal Transmittance (Btu./hr. ft2. °F.) t = Thickness (ft)*

## WATER SYSTEM EQUATIONS

### For SI:

$H = \rho \cdot q \cdot cp \cdot \Delta T$

$q\ (Evap) = H\ (\rho \cdot cp \cdot \Delta T)$

*Where:*
*H = Total Heat (kW)*
*q = Water Flow Rate ($m^3/s$)*
*ρ = Density of Water (997 $kg/m^3$)*

*Cp = Specific Heat of Water (4.187 kJ/kg.K) ΔT = Temperature Difference (°K)*

### For I-P:

$H = (GPM \cdot \Delta T) / 24$

$GPM\ (Evap) = (H \cdot 24) / \Delta T$

$GPM\ (Cond) = (H \cdot 30) / \Delta T$

*Where:*
*H = Total Heat (Tons of Refrigerant)*
*ΔT = Temperature Difference (°F)*
*GPM = Water Flow Rate (Gallons per Minute)*
*$GPM\ (Evap)$. = Evaporator Water Flow Rate (Gallons per Minute)*

*$GPM\ (Cond)$. = Condenser Water Flow Rate (Gallons per Minute)*

## AIR CHANGE RATE EQUATIONS

### For SI:

$ACH = (q \cdot 3600) / V$

*Where:*
*ACH. = Air Change Rate per Hour*

*q = Air Volume Flow ($m^3/s$)*
*V = Space Volume ($m^3$)*

### For I-P:

ACH = (CFM • 60) / V

*Where:*

*ACH. = Air Change Rate per Hour*

*CFM = Air Volume Flow (cubic feet per minute)*

*V = Space Volume (ft3)*

**Mixed Air Temperature**

$$T_{MA} = \left(T_{RA} \cdot \left(\frac{Q_{RA}}{Q_{SA}}\right)\right) + T_{OA} \cdot \left(\frac{Q_{OA}}{Q_{SA}}\right)$$

*Where:*

***For SI:***

*$Q_{SA}$= Supply Air (L/s)*

*$Q_{RA}$ = Return Air (L/s)*

*$Q_{OA}$ = Outside Air (L/s)*

*$T_{MA}$ = Mixed Air Temperature (°C) $T_{RA}$ = Return Air Temperature (°C) $T_{OA}$ = Outside Air Temperature (°C)*

## *For I-P:*

*$Q_{SA}$= Supply Air (CFM)*

*$Q_{RA}$ = Return Air (CFM)*

*$Q_{OA}$ = Outside Air (CFM)*

*$T_{MA}$ = Mixed Air Temperature (°F) $T_{RA}$ = Return Air Temperature (°F) $T_{OA}$ = Outside Air Temperature (°F)*

# DUCTWORK EQUATIONS

## • Total Pressure

$p_t = p_s + p_v$ $p_s$ = Static Pressure (Pa)

Where:

$p_t$ = Total Pressure (Pa)

$p_v$ = Velocity Pressure (Pa)

## • Velocity

V=Q / A

*Where:*

***For SI:***

*V = Fluid Mean Velocity (m/s)*
*Q = Volumetric Flow Rate (m3/s)*
*A = Cross-Sectional Area of Duct (m2)*

### *For I-P:*

*V = Fluid Mean Velocity (FPM)*
*Q = Volumetric Flow Rate (CFM)*
*A = Cross-Sectional Area of Duct (ft2)*

## Fan Affinity Laws

A. Flow Rate

$$Q_1 = Q_2 \cdot (\frac{N_1}{N_2})$$

B. Static Pressure

$$P_1 = P_2 \cdot \left(\frac{N_1}{N_2}\right)^2$$

C. Electrical Power

$$W_1 = W_2 \cdot \left(\frac{N_1}{N_2}\right)^3$$

*Where:*

*Where:*

### *For SI:*

*Q = Volumetric Flow Rate (m3/s)*
*N = Rotational Speed, Revolutions Per Minute (RPM) P = Static Pressure (Pa)*
*W = Electrical Power (W*

### *For I-P:*

*Q = Volumetric Flow Rate (CFM)*
*N = Rotational Speed, Revolutions Per Minute (RPM) P = Static Pressure (in.wg)*
*W = Electrical Power (W)*

## Pump Affinity Laws (At Constant Pump Impeller Diameter)

*Where:*

- Flow Rate

$$Q_1 = Q_2 \cdot (\frac{N_1}{N_2})$$

- Pump Head

$$P_1 = P_2 \cdot \left(\frac{N_1}{N_2}\right)^2$$

- Electrical Power

$$W_1 = W_2 \cdot \left(\frac{N_1}{N_2}\right)^3$$

*Where:*

### *For SI:*

*Q = Volumetric Flow Rate (m3/s)*
*N = Rotational Speed, Revolutions Per Minute (RPM) P = Pump Head (bar)*
*W = Electrical Power (W)*

### *For I-P:*

*Q = Volumetric Flow Rate (GPM)*
*N = Rotational Speed, Revolutions Per Minute (RPM) P = Static Pressure (ft.wg)*
*W = Electrical Power (W)*

**Pump Net Positive Suction Head (NPSH) Calculations**

$NPSH_{AVAIL} > NPSH_{REQ'D}$

Net Positive Suction Head Available:

$NPSH_{AVAIL} = H_A \pm H_S - H_F - H_{VP}$

*Where:*

### *For SI:*

*$NPSH_{AVAIL}$ = Net Positive Suction Available at Pump (m)*
*$NPSH_{REQ'D}$ = Net Positive Suction Required at Pump (m)*
*$H_A$ = Pressure at Liquid Surface (m—10.2 m for Water at Atmospheric Pressure) $H_S$ = Height of Liquid Surface Above (+) or Below (−) Pump (m)*
*$H_F$ = Friction Loss between Pump and Source (m)*
*$H_{VP}$ = Absolute Pressure of Water Vapor at Liquid Temperature (m)*

### *For I-P:*

*$NPSH_{AVAIL}$ = Net Positive Suction Available at Pump (ft)*
*$NPSH_{REQ'D}$ = Net Positive Suction Required at Pump (ft)*
*$H_A$ = Pressure at Liquid Surface (ft—34 ft for Water at Atmospheric Pressure)*

*$H_S$ = Height of Liquid Surface Above (+) or Below (−) Pump (ft)*
*$H_F$ = Friction Loss between Pump and Source (ft)*
*$H_{VP}$ = Absolute Pressure of Water Vapor at Liquid Temperature (ft)*

## EFFICINECIES

## For SI:

### • Coefficient of Performance (COP)

COP = Total Cooling Capacity (W) /(Compressor Input Power (W) + Condenser Fan Input Power (W) )

- **Energy Efficiency Ratio (EER)**

$$\text{EER} = \frac{\text{Net Cooling Capacity (W)} \cdot 3.413}{\text{Total Input Power (W)}}$$

**For I-P:**

- **Coefficient of Performance (COP)**

$$\text{COP} = \frac{\text{Total Cooling Capacity (BTU/h)}}{(\text{Compressor (W)} + \text{Condenser Fan (W)}) \cdot 3.413}$$

- **Energy Efficiency Ratio (EER)**

EER = Net Cooling Capacity (BTU/h) / Total Input Power (W)

## Cooling Towers and Heat Exchangers

**APPROACH** (COOLING TOWER) = LWT – AWB

APPROACH (HEAT EXCHANGER) = $EWT_{HS} - LWT_{CS}$

RANGE = EWT – LWT

*Where:*

### *For SI:*

*EWT = Entering Water Temperature (°C) LWT = Leaving Water Temperature (°C) AWB = Ambient Wet Bulb Temperature (°C) HS = Hot Side*

*CS = Cold Side*

### *For I-P:*

*EWT = Entering Water Temperature (°F) LWT = Leaving Water Temperature (°F) AWB = Ambient Wet Bulb Temperature (°F) HS = Hot Side*

*CS = Cold Side*

## External Heat Gain

**Fenestration Transmission**

## For SI:

$$q_c = UA(T_{out} - T_{in})$$

*where*

| | |
|---|---|
| $q$ | = fenestration transmission heat gain, W |
| $U$ | = overall U-factor, including frame and mounting orientation from Table 4 of Chapter 15, W/(m$^2$·K) |
| $A$ | = window area, m$^2$ |
| $T_{in}$ | = indoor temperature, °C |
| $T_{out}$ | = outdoor temperature, °C |

## For I-P:

$$q_c = UA(T_{out} - T_{in})$$

*where*

| | |
|---|---|
| $q$ | = fenestration transmission heat gain, Btu/h |
| $U$ | = overall U-factor, including frame and mounting orientation from Table 4 of Chapter 15, Btu/h·ft$^2$·°F |
| $A$ | = window area, ft$^2$ |
| $T_{in}$ | = indoor temperature, °F |
| $T_{out}$ | = outdoor temperature, °F |

# Internal Heat Gain

## Occupants

## For SI:

$$q_s = q_{s,per} N$$

$$q_l = q_{l,per} N$$

*where*

$q_s$ = occupant sensible heat gain, W

$q_l$ = occupant latent heat gain, W

$q_{l,per}$ = latent heat gain per person, W/person; see Table 1

$N$ = number of occupants

## For I-P:

$$q_s = q_{s,per} N$$

$$q_l = q_{l,per} N$$

*where*

$q_s$ = occupant sensible heat gain, Btu/h

$q_l$ = occupant latent heat gain, Btu/h

$q_{l,per}$ = latent heat gain per person, Btu/h·person; see Table 1

$N$ = number of occupants

# Lighting
## For SI:

$$q_{el} = WF_{ul}F_{sa}$$

*where*

$q_{el}$ = heat gain, W
$W$ = total light wattage, W
$F_{ul}$ = lighting use factor
$F_{sa}$ = lighting special allowance factor

## For I-P:

$$q_{el} = 3.41WF_{ul}F_{sa}$$

*where*

$q_{el}$ = heat gain, Btu/h
$W$ = total light wattage, W
$F_{ul}$ = lighting use factor
$F_{sa}$ = lighting special allowance factor
3.41 = conversion factor

# Ventilation and Infiltration Air Heat Gain
## For SI:

$$q_s = 1230Q_s\Delta t$$
$$q_l = 1.20 \times 2500Q_s\,\Delta W = 3000Q_s\,\Delta W$$

*where*

$q_s$ = sensible heat gain due to infiltration, W
$q_l$ = latent heat gain due to infiltration, W
$Q_s$ = infiltration airflow at standard air conditions, L/s
$t_o$ = outdoor air temperature, °C
$t_i$ = indoor air temperature, °C
$W_o$ = outdoor air humidity ratio, kg/kg
$W_i$ = indoor air humidity ratio, kg/kg
1230 = air sensible heat factor at standard air conditions, (W·s)/($m^2$·K)
3000 = air latent heat factor at standard air conditions, (W·s)/($m^2$·K)

## For I-P:

$$q_s = 1.10 Q_s \, \Delta t$$

$$q_l = 60 \times 0.075 \times 1076 Q_s \, \Delta W = 4840 Q_s \, \Delta W$$

*where*

| | | |
|---|---|---|
| $q_s$ | = | sensible heat gain due to infiltration, Btu/h |
| $q_l$ | = | latent heat gain due to infiltration, Btu/h |
| $Q_s$ | = | infiltration airflow at standard air conditions, cfm |
| $t_o$ | = | outdoor air temperature, °F |
| $t_i$ | = | indoor air temperature, °F |
| $W_o$ | = | outdoor air humidity ratio, lb/lb |
| $W_i$ | = | indoor air humidity ratio, lb/lb |
| 1.10 | = | air sensible heat factor at standard air conditions, Btu/h·cfm( |
| 4840 | = | air latent heat factor at standard air conditions, Btu/h·cfm( |