BEYOND SMART CITIES

ENGINEERING HVAC EQUATIONS

Energy modeling specialists can use engineering and HVAC design formulas to implement new building energy modeling processes and diagnose problems.

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HVAC and Engineering Equations

Certain engineering and HVAC design formulas may be useful to energy modeling specialists when implementing building energy modeling processes in new buildings, as well as when diagnosing problems. Below is a list of the most commonly 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)

ΔT = Temperature Difference (°K) q = Air Volume Flow (m^3/s)

ρ = 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)

*ΔW = Humidity Ratio Difference (kg water/kg dry air) Δh = **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)

ΔT = Temperature Difference (°F)

ΔWGR. = Humidity Ratio Difference (Gr.H_2O/Lb.DA)

ΔWLB. = Humidity Ratio Difference (Lb.H_2O/Lb.DA)

Δh = 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(