Psychrometrics

1) Ideal Mixing
2) Ideal Gas Air
3) Ideal Gas Water Vapor
4) Adiabatic Saturation

Ideal Gas Law

AVOGADROS LAW

One (1) mole of any gas = 22.4 liters.

6.023×10^{23} molecules/mole of gas at

STP (1 atm and $0^{o}C$)

BOLYES LAW

$$p_1\times v_1 = p_2\times v_2$$

CHARLES LAW

$$\frac{v_1}{v_2}=\frac{T_1}{T_2}$$

$$\frac{p_1}{p_2}=\frac{T_1}{T_2}$$

IDEAL (PERFECT) GAS LAW

$$pv = RT$$

$$pV = mRT$$

p - absolute pressure, psia, kPa

T - absolute temperature, ^{o}R, ^{o}K

$$R=\frac{R^*}{\text{molecular weight}}$$

$$R^* = 1545.15\ \frac{\text{lbf/lbm}^{o}\text{R}}{\text{lbmole}}$$

$$R^* = 8.314\frac{\text{kJ}}{\text{kmole}\,^{o}\text{K}}\ \text{or}\ \frac{\text{kPa m}^3}{\text{kmole}\,^{o}\text{K}}$$

$$\text{mass} = \text{moles}\times\text{Molecular Weight}$$

$$m = n\times\text{Molecular Weight}$$

$$pv = R^*T$$

$$pV = nR^*T$$

The specific volume of air at 75^o F and 14.7 psia

$$v = \frac{RT}{p} = \frac{53.35 \text{ ft lbf/lbm R} \times \left(459.69^o \text{ R} + 75^o \text{ F}\right)}{14.7 \text{ lbf/in}^2 \times 144 \text{ in}^2\text{/ft}^2}$$

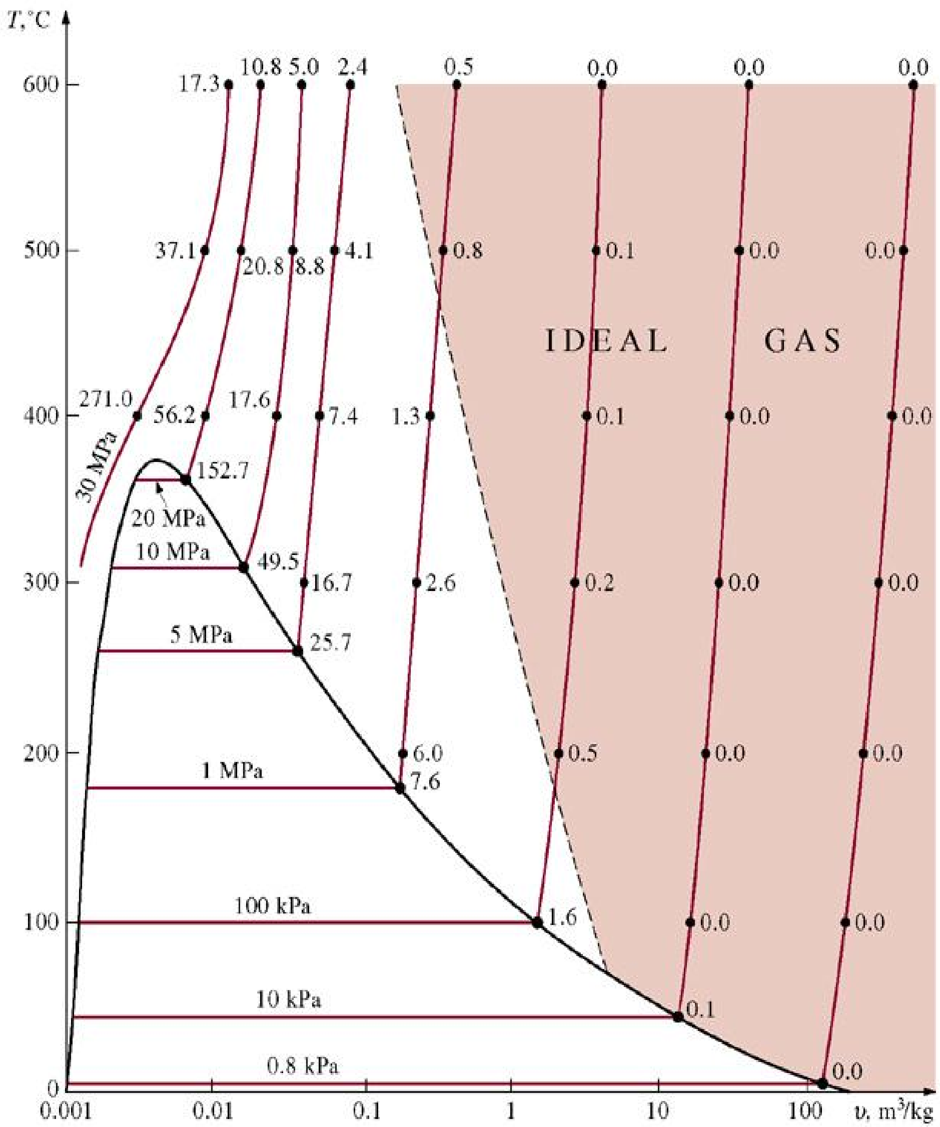
$$v = 13.476 \text{ ft}^3\text{/lb}$$

The specific volume of air at 24^o C and 101.325 kPa

$$v = \frac{RT}{p} = \frac{.287 \text{ kPa m}^3\text{/kg} \times \left(273.15^o \text{ K} + 24^o \text{ C}\right)}{101.325 \text{ kPa}^2}$$

$$v = .8417 \text{ m}^3\text{/kg}$$

$$\left(\frac{\partial T}{\partial p}\right)_h = \text{JT Coefficient}$$



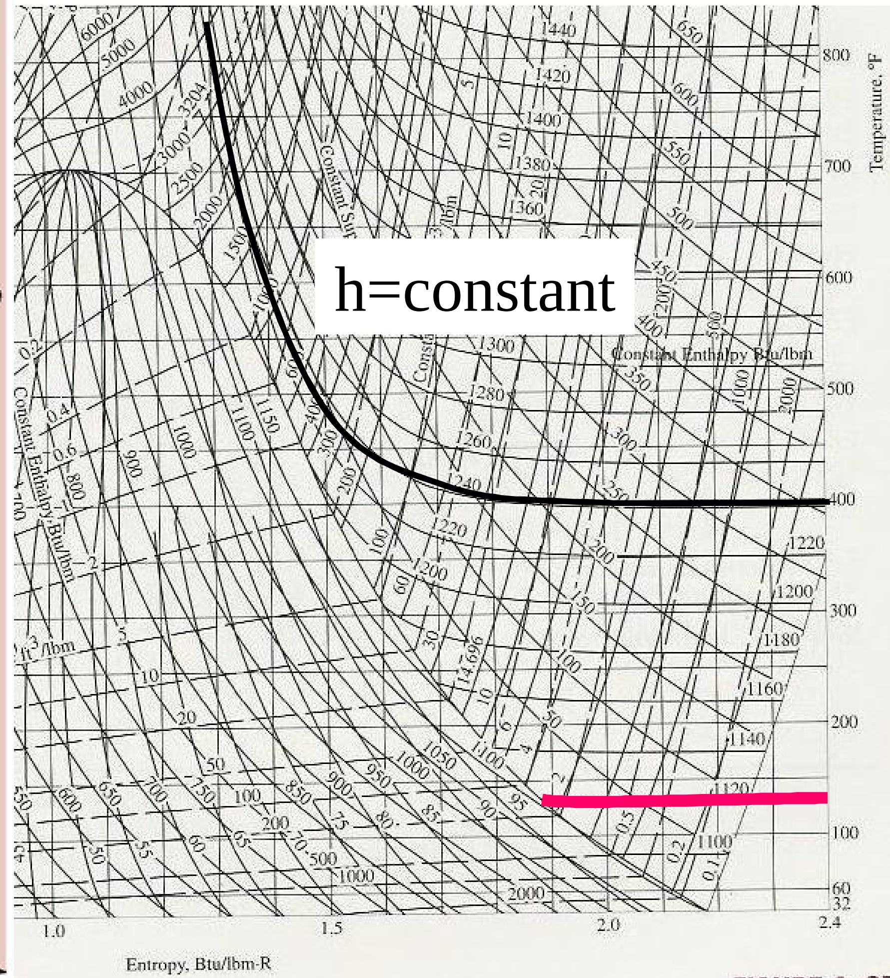


FIGURE A–9E

T-s diagram for water. [*Source:* Joseph H. Keenan, Frederick G. Keyes, Philip G. Hill, and Joan G. Moore, *Steam Tables* (New York: John Wiley & Sons, 1969).]

Specific and Relative Humidity

Basis of calculation - 1 lb_m dry air, 1 kgm dry air

$$\text{Specific Humidity, Mass Fraction, } \chi = \frac{\text{mass water vapor}}{\text{mass dry air}}$$

$$\chi = \frac{\text{mass water vapor}}{\text{mass dry air}} = \frac{\left(pV/RT\right)_{water}}{\left(pV/RT\right)_{air}} = \frac{p_{water}\ MW\ T_{water}}{p_{air}\ MW\ T_{air}}$$

$$\chi = \frac{18\, p_w}{29\left(p_{ambient} - p_w\right)} \qquad (12.43)$$

$$\text{Relative humidity} = \phi = \frac{\text{actual mass water vapor}}{\text{mass water vapor at saturation}}$$

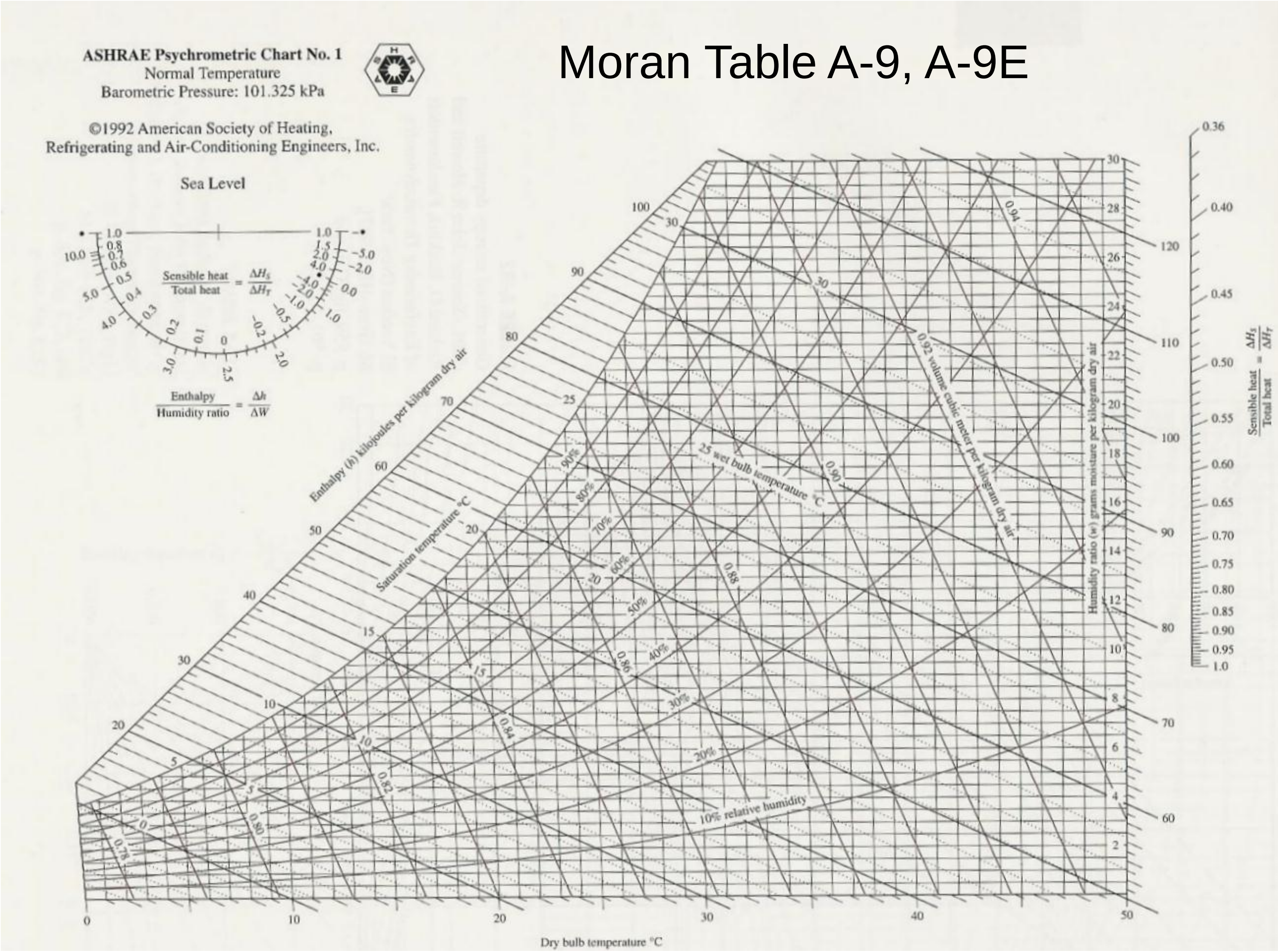
$$\phi = \frac{\text{actual mass water vapor}}{\text{mass water vapor at saturation}} = \frac{\left(pV/RT\right)}{\left(pV/RT\right)_{saturation}}$$

$$\phi = \frac{p_w}{p_g} = \frac{v_g}{v_w} \qquad (12.44)$$

$$H = H_{air} + H_w \qquad BTU/lb_{dryair},\ kJ/kg_{dryair}$$

$$h = h_a + \chi\ h_v = c_p T + \chi\ h_v = c_p T + \chi\ c_{pv} T$$

Metric Psychrometric Chart



Given, 25^{o} C, $\phi = 50\,\%$,

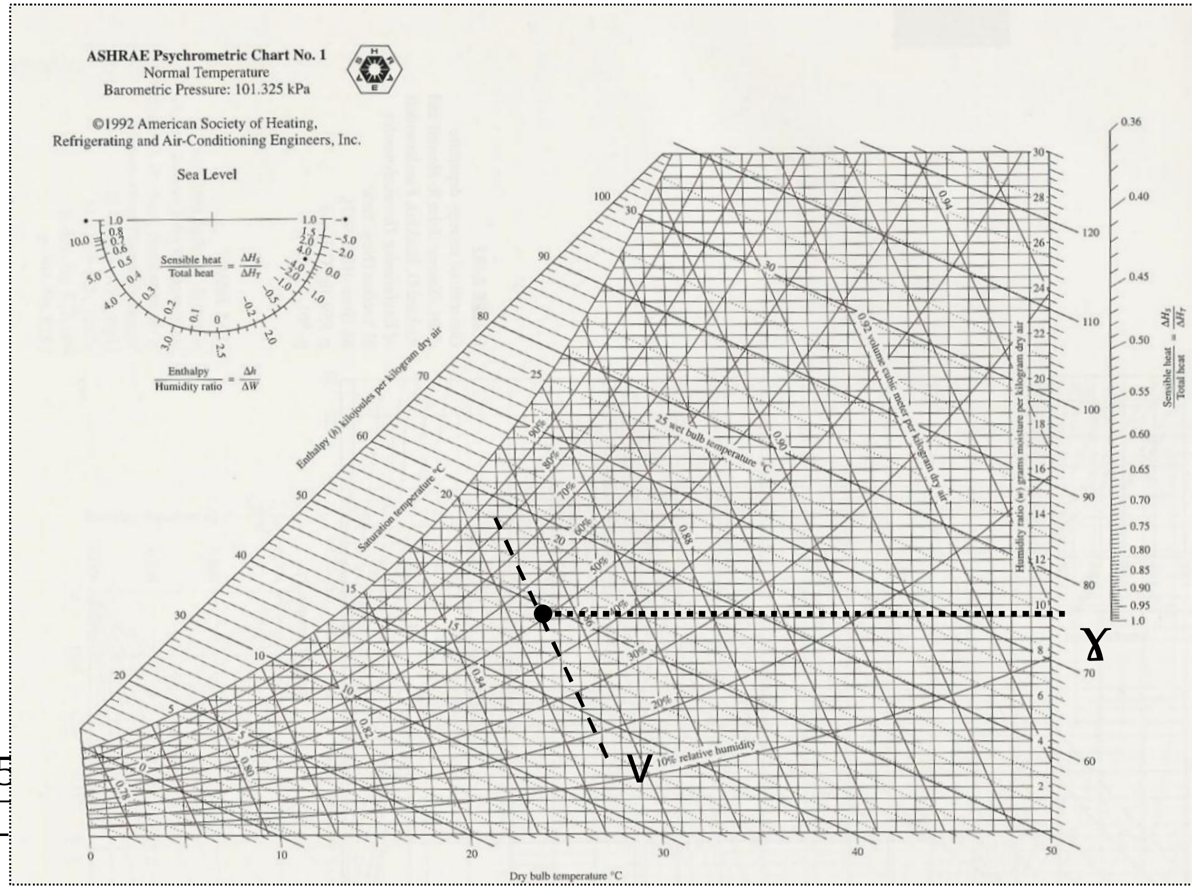
barometer 100 kPa.

Find :

a) p_{air}

c) specific humidity, ɤ

b) specific volume



a) $\phi = \dfrac{p_w}{p_g}$

$p_w = \phi \times p_g = .5 \times 3.1698$

$p_w = 1.5849\ \text{kPa}$

$p_a = p_{atm} - p_w = 98.415\ \text{kPa}$

b) $\gamma = \dfrac{18\ p_v}{29\left(p_{atm} - p_v\right)} = .622\,\dfrac{1.5}{(100 -}$

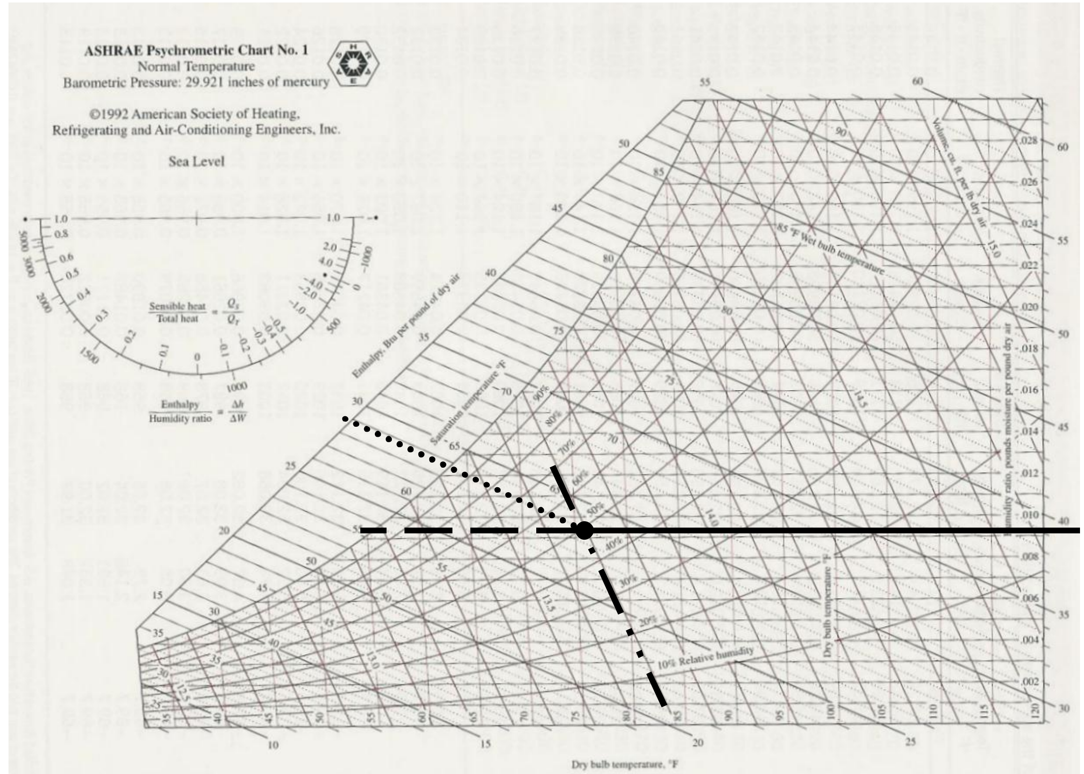
c) $v = v_{air} = R_a T / p_a$

$$v = \frac{.287\,\frac{\text{kPa}}{\text{m}^3\text{K}} \times 289.15\ \text{K}}{(100 - 1.5849)} = .843\ \text{kg/m}^3$$

$v = v_{vapor} = \gamma\, R_v T / p_v$

$$v = .001 \times \frac{.4615\,\frac{\text{kPa}}{\text{m}^3\text{K}} \times 289.15\ \text{K}}{1.5849} = .842\ \text{kg/m}^3$$

$$\text{Given: lb moist air, } 75^{o}\text{F},$$
$$\phi = 50\%, \text{barometer } 14.69 \text{ psia}$$
$$\text{Find: } p_{w}, \omega, v_a, m_a, m_v$$



$$\phi = \frac{p_w}{p_g \text{ at } 75}$$

$$p_w = .5 \times .43016 = .21508 \text{ psia}$$

$$\omega = \frac{18}{29}\frac{p_w}{p_{atm} - p_w} = .622\frac{.21508}{14.69 - .21508}$$

$$\omega = .00924 \text{ lb water / lb dry air}$$

$$V = V_a = V_w$$

$$pv = RT$$

$$V_a = m\frac{RT}{p} = 1\frac{53.35 \times (459.69 + 75)}{(14.69 - .21508) \times 144} = 13.685 \text{ ft}^3$$

$$m_a = \frac{p_a V_a}{RT} = \frac{(14.69 - .21508) \times 144 \times 1\text{ft}^3}{53.35 \times (459.69 + 75)} = .0731 \text{ lb}$$

$$m_v = \frac{p_v V_v}{RT} = \frac{.21508 \times 144 \times 1\text{ft}^3}{85.766 \times (459.69 + 75)} = .000675 \text{ lb}$$

$$\frac{m_v}{m_a} = .00924 \text{ lb water / lb dry air (check)}$$

$$T_{dp} = T \text{ at } p_v = .21508 = 55.11^{o}\text{F}$$

Psychrometric Chart

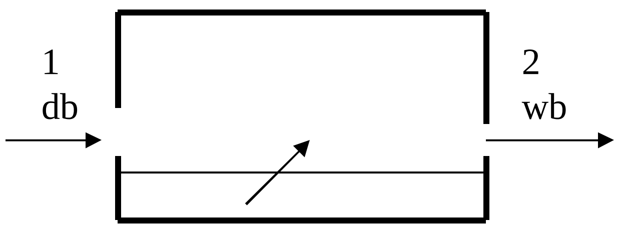
——— $\omega = .093$ lb water/lb dry air

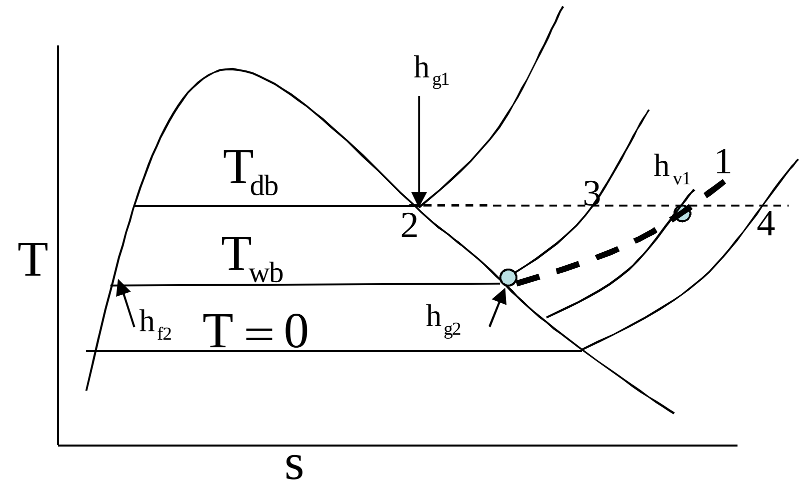
.... $h = 28.5$ BTU/lb dry air

- – – – – $T_{dp} = 55^{o}\text{F}$

— · · — · $v = 13.68 \text{ ft}^3 / lb$

Adiabatic Saturation





basis of calculation 1 mass unit dry air

Steady Flow Energy Equation

$$E_{air+vapor\,in} + E_{water\,added} = E_{air+vapor\,out}$$

$$h_{a1} + \omega_1 h_{v1} + (\omega_2 - \omega_1) h_{fg2} = h_{2a} + \omega_2 h_{v2}$$

substituting,

$$(h_{a1} - h_{a2}) = c_p (T_1 - T_2)$$

$$(h_{v2} - h_{f2}) = h_{fg}$$

$$c_p (T_2 - T_1) + \omega_1 (h_{v1} + h_{f2}) = \omega_2 h_{fg2}$$

$$\omega_1 = \frac{\omega_2 h_{fg2} - c_p (T_2 - T_1)}{(h_{v1} - h_{f2})}$$

$$\omega = \frac{\omega_{wb} h_{fg2} - c_p (T_{db} - T_{wb})}{(h_{v\,db} - h_{f\,wb})}$$

1) h_{v1} = saturation vapor enthalpy @$(T = T_{db}, p = p_v)$

2) $h_{v1} = h_g @ T_{db}$

3) $h_{v1} = h_g @ T_{wb} + .45 \times (T_{db} - T_{wb})$

4) $h_{v1} = h_g @ 0\,F + .44 \times (T_{db} - T_{wb}) = 1061.8 + .44 \times (T_{db})$

for 75F db, 70 F wb

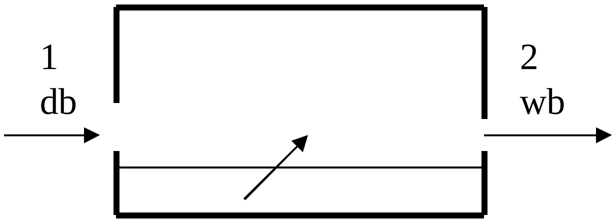
1) h_{v1} = 1094.07 BTU/ lb dry air   Exact

2) h_{v1} = 1093.9 BTU/lb dry air   easiest to use

3) h_{v1} = 1094.05BTU/lb dry air   most accurate

4) h_{v1} = 1094.80BTU/lb dry air

Adiabatic Saturation



basis of calculation 1 mass unit dry air

Steady Flow Energy Equation

$$E_{air+vapor\,in} + E_{water\,added} = E_{air+vapor\,out}$$

$$h_{a1} + \omega_1 h_{v1} + (\omega_2 - \omega_1) h_{fg2} = h_{2a} + \omega_2 h_{v2}$$

substituting,

$$(h_{a1} - h_{a2}) = c_p (T_1 - T_2)$$

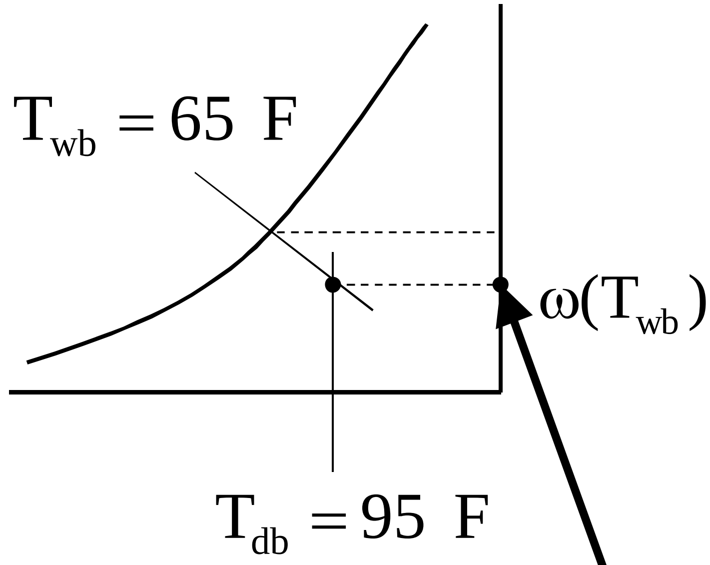
$$(h_{v2} - h_{f2}) = h_{fg}$$

$$c_p (T_1 - T_2) + \omega_1 (h_{v1} + h_{f2}) = \omega_2 h_{fg2}$$

$$\omega_1 = \frac{\omega_2 h_{fg2} - c_p (T_1 - T_2)}{(h_{v1} - h_{f2})}$$

$$\omega = \frac{\omega_{wb} h_{fg2} - c_p (T_{db} - T_{wb})}{(h_{v\,db} - h_{f\,wb})}$$

95 F db
65 F wb
14.7 atm
Specific Humidity ?

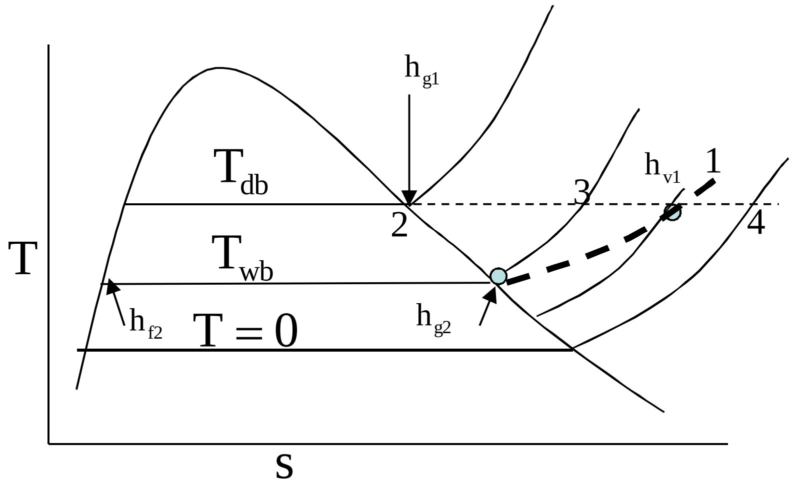


	T	p	h_f	h_{fg}	h_g
T_{db}	95				1102.6
T_{wb}	65	.30578	33.08	1056.5	

$$\omega(T_{wb}) = .622 \times \frac{p_{saturation}(T_{wb})}{p_{atm} - p_{saturation}(T_{wb})} = .622 \times \frac{.30578}{14.7 - .30578} = .0132 \text{ lb water /lb dry air}$$

$$\omega(T_{db}) = \frac{\omega(T_{wb}) \times h_{fg}(T_{wb}) + c_p(T_{wb} - T_{db})}{h_g(T_{db}) - h_f(T_{wb})}$$

$$\omega(T_{db}) = \frac{.0132 \times 1056.5 + .24 \times (65 - 96)}{1102.6 - 33.08} = \frac{13.946 - 7.2}{1069.52} = .0063 \text{ lb water /lb dry air}$$



$$1)\ h_{v1} = \text{saturation vapor enthalpy} @(T = T_{db}, p = p_v)$$

$$2)\ h_{v1} = h_g @ T_{db}$$

$$3)\ h_{v1} = h_g @ T_{wb} + .45 \times (T_{db} - T_{wb})$$

$$4)\ h_{v1} = h_g @ 0\,F + .44 \times (T_{db} - T_{wb}) = 1061.8 + .44 \times (T_{db})$$

for 75F db, 70 F wb

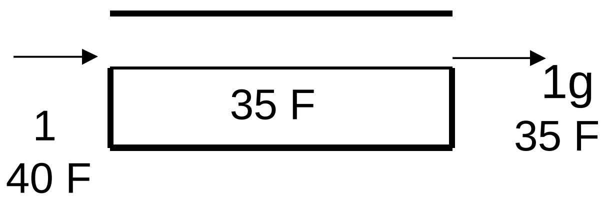
1) $h_{v1} = 1094.07$ BTU/ lb dry air   Exact

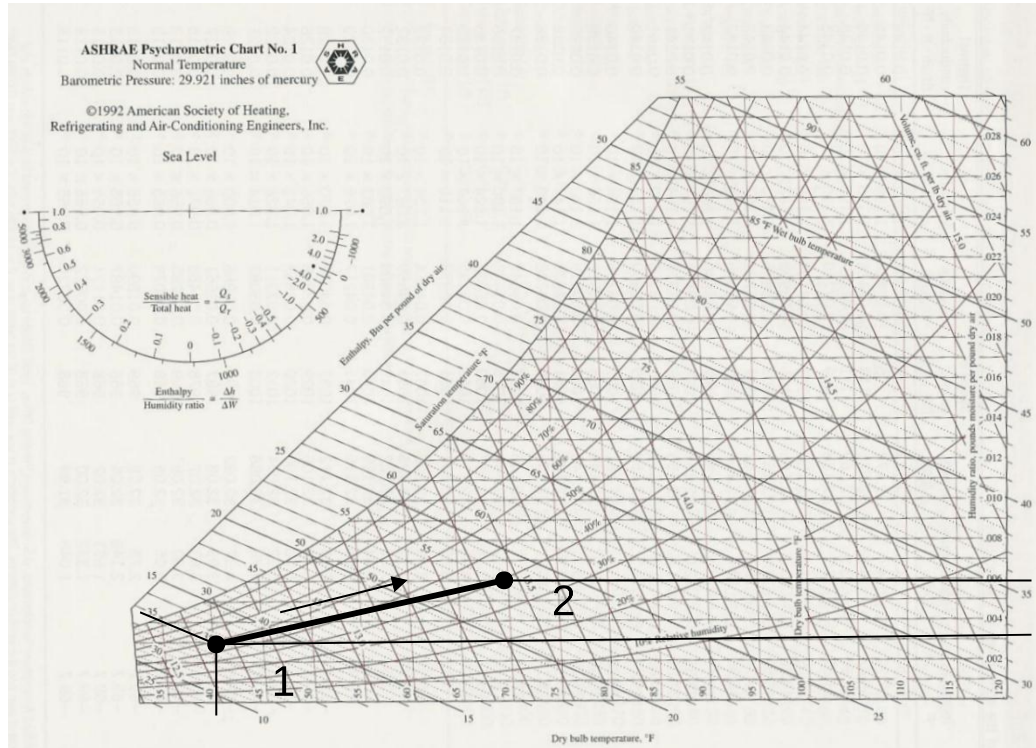
2) $h_{v1} = 1093.9$ BTU/lb dry air   easiest to use

3) $h_{v1} = 1094.05$BTU/lb dry air   most accurate

4) $h_{v1} = 1094.80$BTU/lb dry air

Air at 40 F db, 35F wb is heated and humidified to 70 F db, 40 % relative humidity at 14.7 psia. Find the mass of water added.





$$\omega_{1g} = .622\frac{.09998}{14.7 - .09998} = .00426$$

$$\omega_1 = \frac{c_p(T_1 - T_2) + \omega_{g1} h_{fg} \text{at } 35}{h_v \text{ at } 40 - h_l \text{ at } 35}$$

$$\omega_1 = \frac{.24(35 - 40) + .00426 \times 1073.5}{1078.7 - 3.004}$$

$$\omega_1 = .00314 \text{ lb water/ lb dry air}$$

$$\omega_2 = .622\frac{p_v}{p_{atm} - p_v}$$

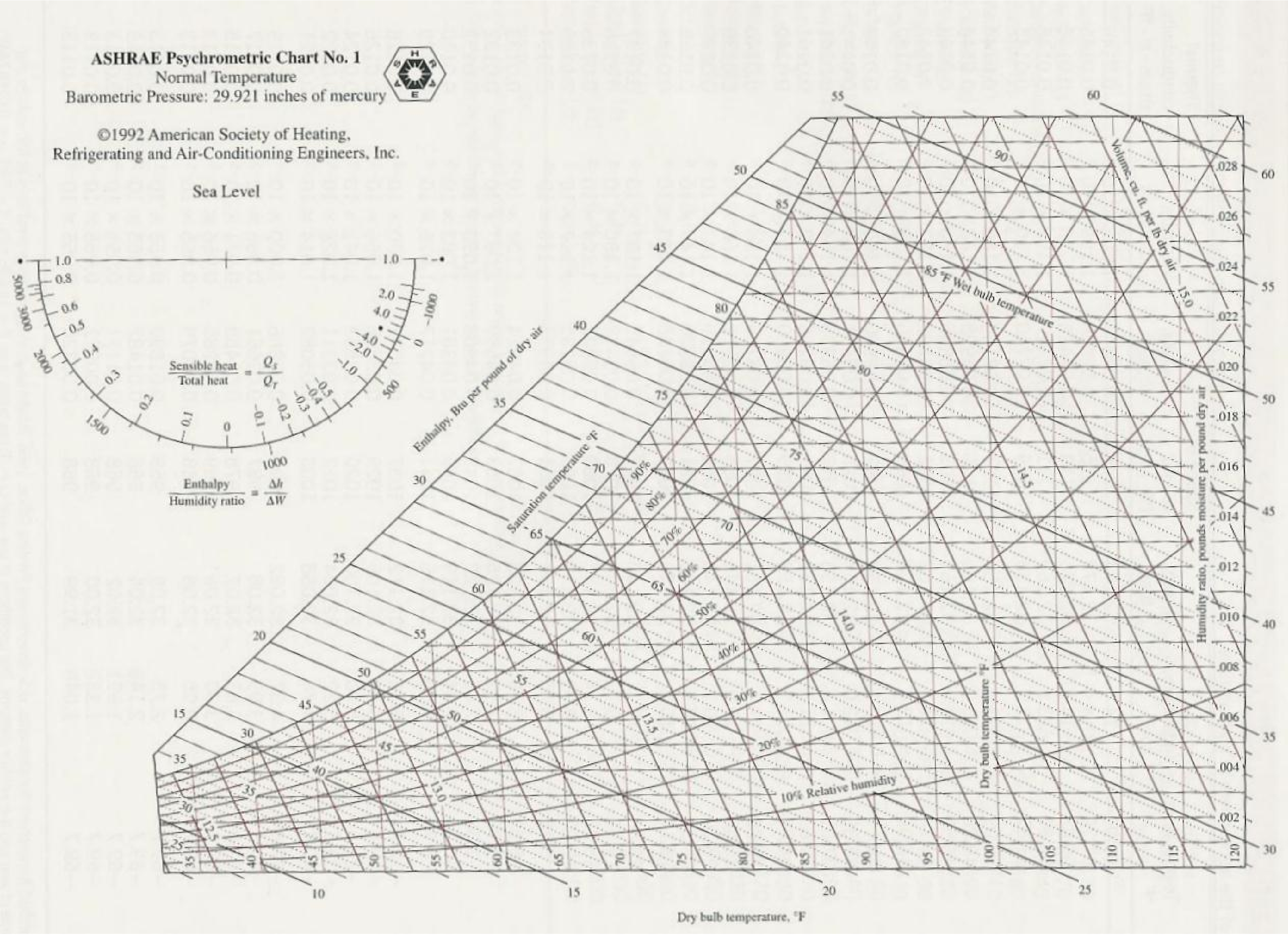
$$p_{v2} = \phi \times p_{g2} = .4 \times .36335 = .1453 \text{ in Hg}$$

$$\omega_2 = .622\frac{.1453}{14.7 - .1453} = .00621$$

water added

$$\omega_2 - \omega_1 = .00649 - .00326 = .00323\frac{\text{lb water}}{\text{lb dry air}}$$

USCU Psychrometric Chart



T_{db}

T_{wb}

p_{atm}

p_{vapor}

p_{air}

h

v

ɤ

ϕ

ENTHALPY

$$h = h_{air} + ɤ\, h_{vapor}$$

$$h_{vapor} = h_g @ T_{db}$$

$$h = .24 \times T_{db} + ɤ \times (1061.8 + .44 \times T_{db}) \quad (1)$$

$$h = 1.005 \times T_{db} + ɤ \times (1061.8 + 1.8 \times T_{db})$$

SPECIFIC HUMIDITY

$$p_{atm} = p_{vapor} + p_{air}$$

$$ɤ = \frac{18}{29}\frac{p_{vapor}}{p_{air}} = .622 \frac{p_{vapor}}{p_{atm} - p_{vapor}} \quad (2)$$

$$ɤ = \frac{(ɤ \times h_{fg})_{wb} + c_{pair}(T_{wb} - T_{db})}{h_{\substack{vapor \\ db}} - h_{\substack{liquid \\ wb}}} \quad (3)$$

RELATIVE HUMIDITY

$$\phi = \frac{p_{vapor}}{p_{saturation} @ T_{db}} \quad (4)$$

SPECIFIC VOLUME

$$v = v_{air} = 1 \times \frac{RT_{db}}{p_{air}} \quad (5)$$

$$v = v_{vapor} = ɤ \times \frac{R_{air} T_{db}}{p_{vapor}} \quad (6)$$

To Build a Psychrometric Chart

select p_{atm}

repeatedly select h and ɤ

with h find T_{db} from (1)

with ɤ find p_{vapor} from (2)

with ɤ find T_{wb} from (3) by itteration

with p_{vapor} find ű from (4)

with T_{db}, p_{vapor} find v from (5)

Common HVAC State Point Specifications

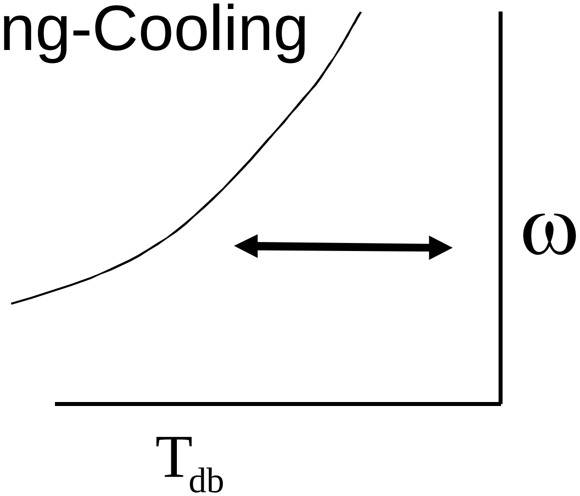
T_{wb} and T_{db}

ϕ and T_{db}

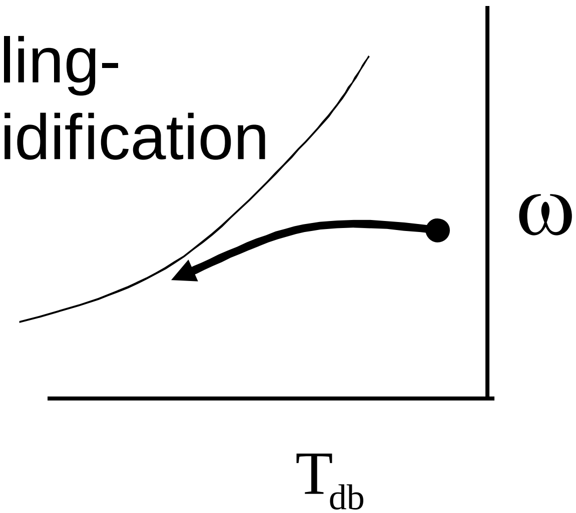
	Metric	English
c_p air	1.005	.24
$c_{p\ liquid\ water}$	4.18	1.0
$c_{p\ water\ vapor}$	1.8	.44

PSYCHROMETRIC PROCESSES

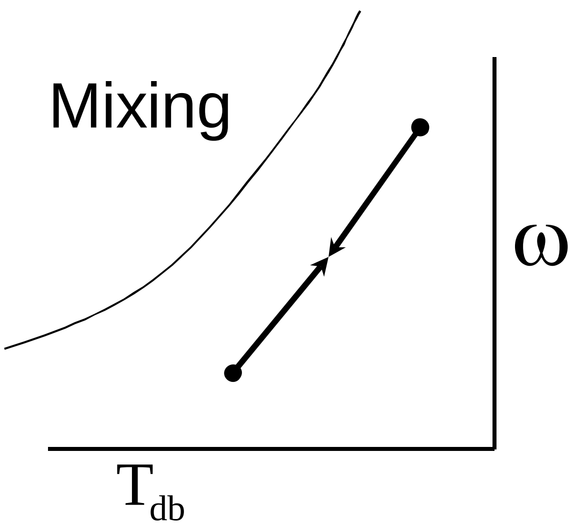
Heating-Cooling



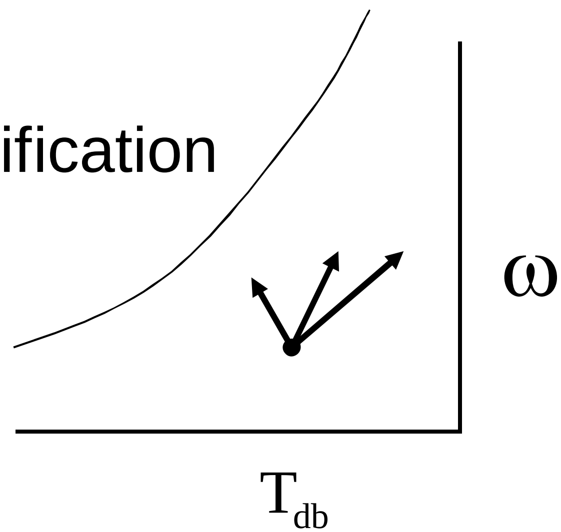
Cooling-
Dehumidification



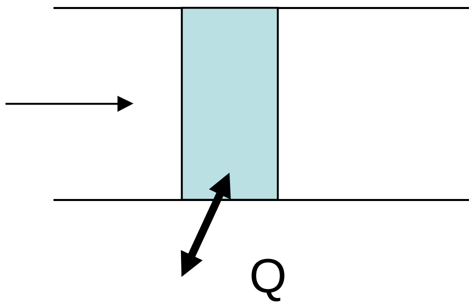
Mixing

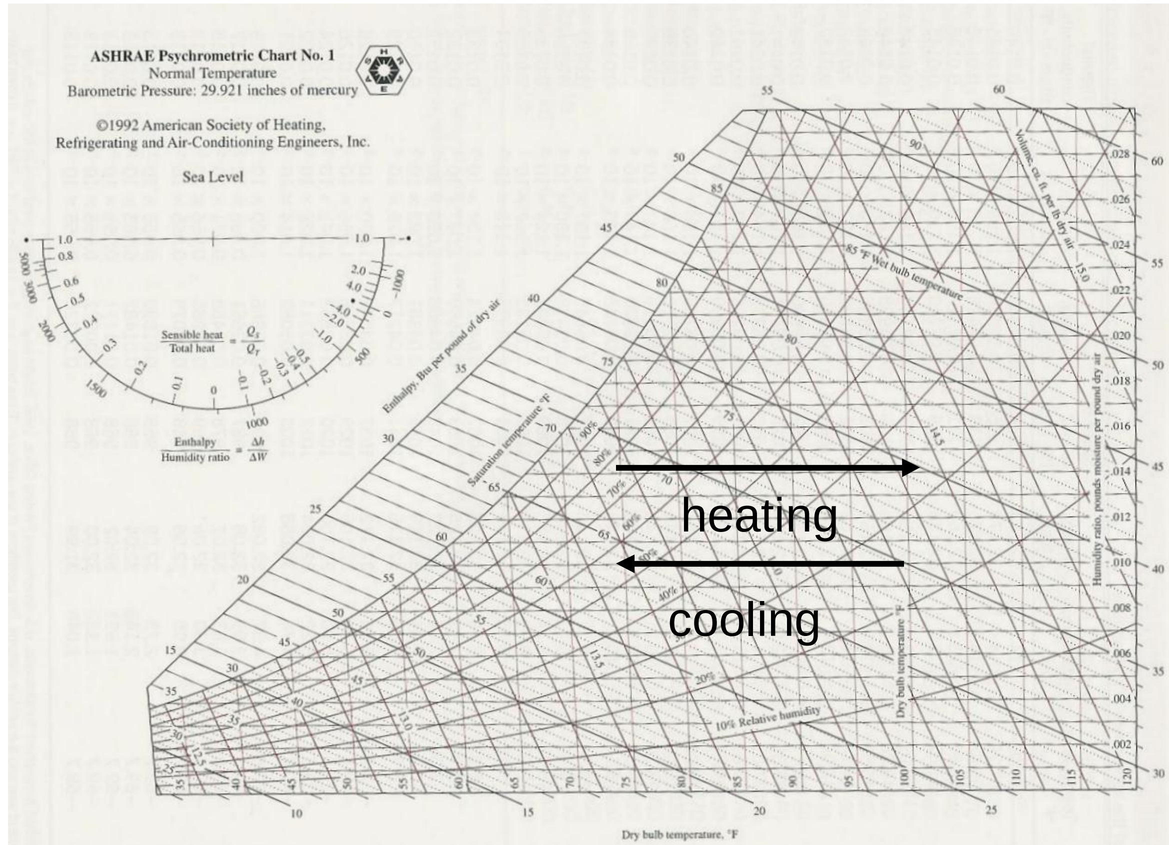


Humidification



Heating Cooling





$\omega = \text{constant}$

$p_w = \text{constant}$

$\phi, T_{\text{dry bulb}}, v = \text{varying}$

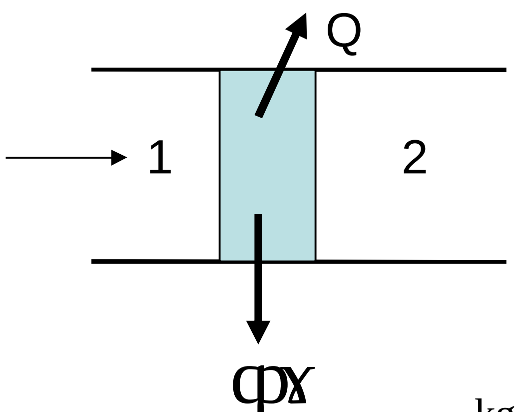
$Q = \Delta H = \Delta H_{\text{air}} + \Delta H_{\text{water}}$

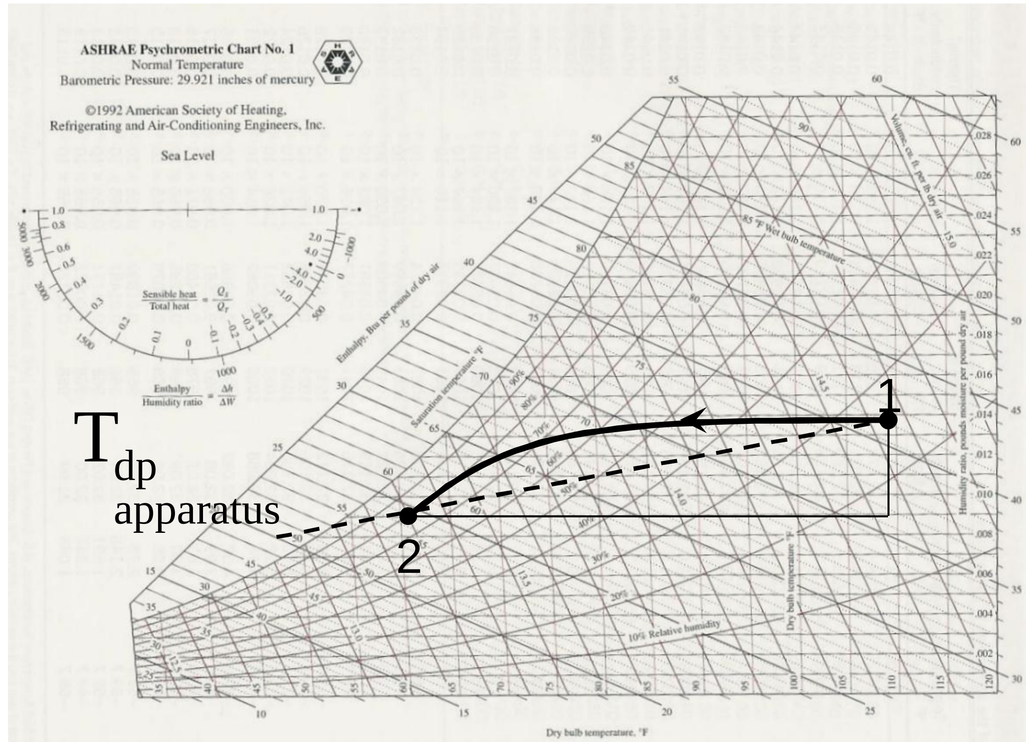
$Q = m_{\text{dry air}}\ \Delta h_{\text{air}} + m_{\text{dry air}}\ \omega\ \Delta h_{\text{water vapor}}$

$Q = m_{\text{dry air}}\ c_p\ \Delta T + m_{\text{dry air}}\omega\ \ c_{\text{p water}}\Delta T,\ \text{kJ, BTU}$

$Q = m_{\text{dry air}}\ .24\ \Delta T + m_{\text{dry air}}\omega\ \ .45\ \Delta T,\ \text{kJ, BTU}$

Cooling Dehumidification





$$\text{condensate} = \gamma_1 - \gamma_2, \quad \frac{\text{kg water}}{\text{kg dryair}}$$

$$Q = \varphi H_{dryair} + \varphi H_{water\ vapor} + \varphi H_{condensate}$$

$$\frac{q}{m_{dryair}} = \varphi h_{air} + \gamma_2 \varphi h_{water\ vapor} + (\gamma_1 - \gamma_2)\left((h_{1_{vapor}} - h_{1_{liquid}}) + (h_{1_{liquid}} - h_{2_{liquid}})\right)$$

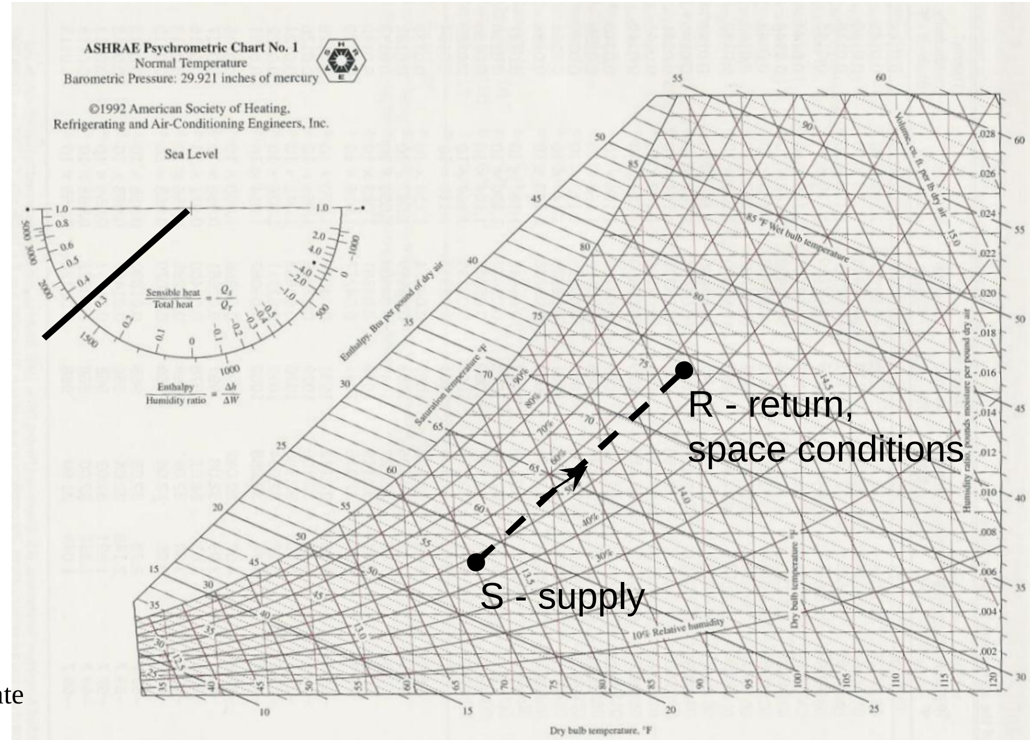
$$\frac{q_{sensible}}{m_{dry\ air}} = \varphi h_{air} + \gamma_2 (h_{v1} - h_{v2}) + (\gamma_1 - \gamma_2)(h_{1_{liquid}} - h_{2_{liquid}})$$

$$Q_{sensible} = c_{p_{air}} \varphi T_{dry\ air} + \gamma_2 c_{p\ water\ vapor} \varphi T_{dry\ air} + (\gamma_1 - \gamma_2) c_{p\ liquid\ water} \varphi T_{dry\ air}$$

$$Q_{latent} = (\gamma_1 - \gamma_2)(h_{1_{vapor}} - h_{1_{liquid}}) = (\gamma_1 - \gamma_2) h_{fg_1}$$

$$\text{Sensible Heat Factor, SHF} = \frac{Q_{sensible}}{Q_{sensible} + Q_{latent}}$$

Conditioned Space



$$\text{water gain} = \Delta\gamma\,,\quad \frac{\text{mass water}}{\text{mass dryair}}$$

$$Q = \phi H_{\text{dry air}} + \phi H_{\text{water vapor}} + \phi H_{\text{condensate}}$$

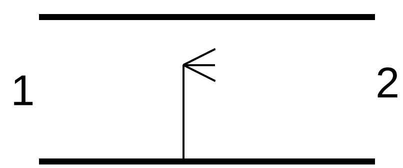
$$\frac{q_{\text{sensible}}}{m_{\text{dry air}}} = \phi h_{\text{air}} + \gamma_S \phi h_{\text{water vapor}} + \left(\gamma_R h_{R\text{ vapor}} - \gamma_S h_{S\text{ vapor}}\right)$$

$$\frac{q_{\text{sensible}}}{m_{\text{dry air}}} = \phi h_{\text{air}} + \gamma_S \phi h_{\substack{\text{water}\\\text{vapor}}} = c_{\substack{p\\\text{air}}}\ \phi T_{\text{dry air}} + \gamma_S c_{\substack{p\\\text{water}\\\text{vapor}}}\ \phi T_{\text{dry air}} + \left(\gamma_R - \gamma_S\right) c_{\substack{p\\\text{liquid}\\\text{water}}}\ \phi T_{\text{dry air}}$$

$$\frac{q_{\text{latent}}}{m_{\text{dry air}}} = (\gamma_R - \gamma_S)(h_{\substack{R\\\text{vapor}}} - h_{\substack{R\\\text{liquid}}}) = (\gamma_R - \gamma_S) h_{\substack{fg\\R}}$$

$$\text{Sensible Heat Factor, SHF} = \frac{Q_{\text{sensible}}}{Q_{\text{sensible}} + Q_{\text{latent}}}$$

Adiabatic Humidification



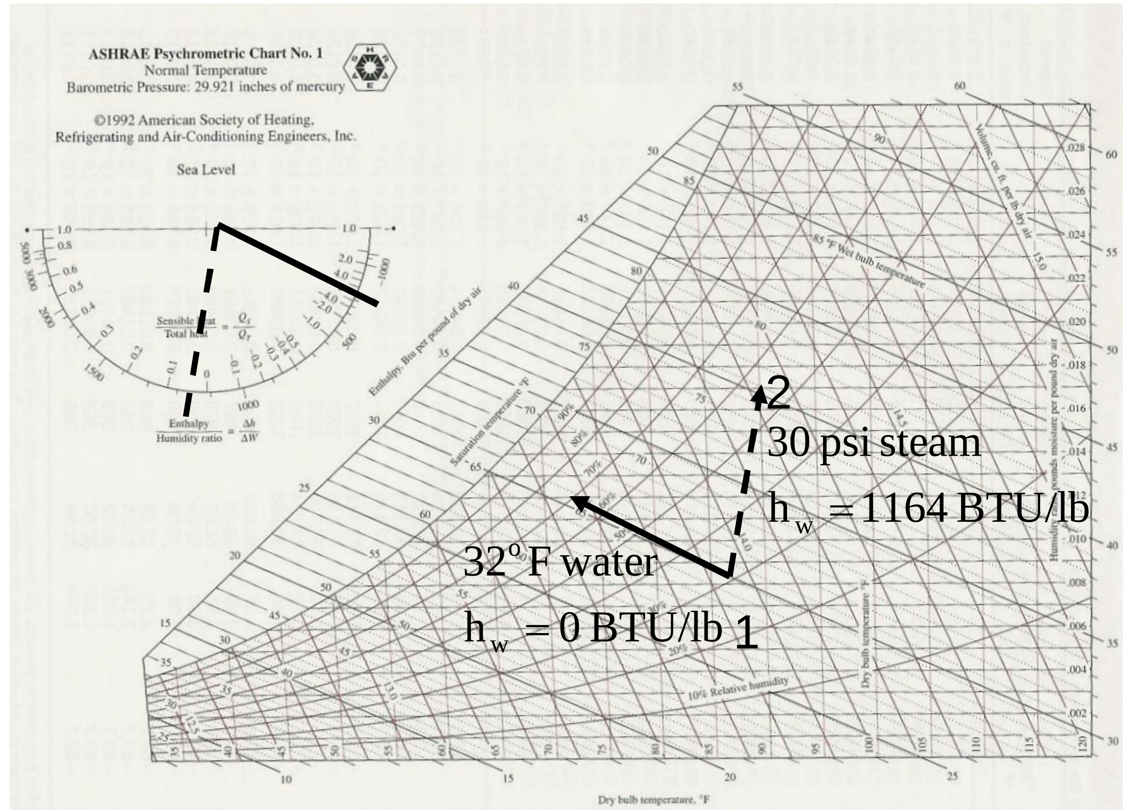
$$H_1 + H_w = H_2$$

$$m_a h_1 + m_a h_w = m_a h_2$$

$$h_1 + (\gamma_2 - \gamma_1) h_w = h_2$$

$$\frac{h_2 - h_1}{\gamma_2 - \gamma_1} = h_w$$

$$\frac{\varphi h}{\varphi \gamma} = h_w$$



$$Q_{\text{sensible}} = m_{\text{dry air}} \varphi h_{\text{air}} + m_{\text{dry air}} \gamma_1 \varphi h_{\text{water vapor}}$$

$$Q_{\text{latent}} = (\gamma_2 - \gamma_1)\left(h_{2\,\text{vapor}} - h_{1\,\text{vapor}}\right) \text{steam humidification}$$

$$Q_{\text{latent}} = (\gamma_2 - \gamma_1)\left(h_{2\,\text{vapor}} - h_{1\,\text{liquid}}\right) \text{water wash}$$

$$q_l = \varphi h = \varphi x\ h_{fg}$$

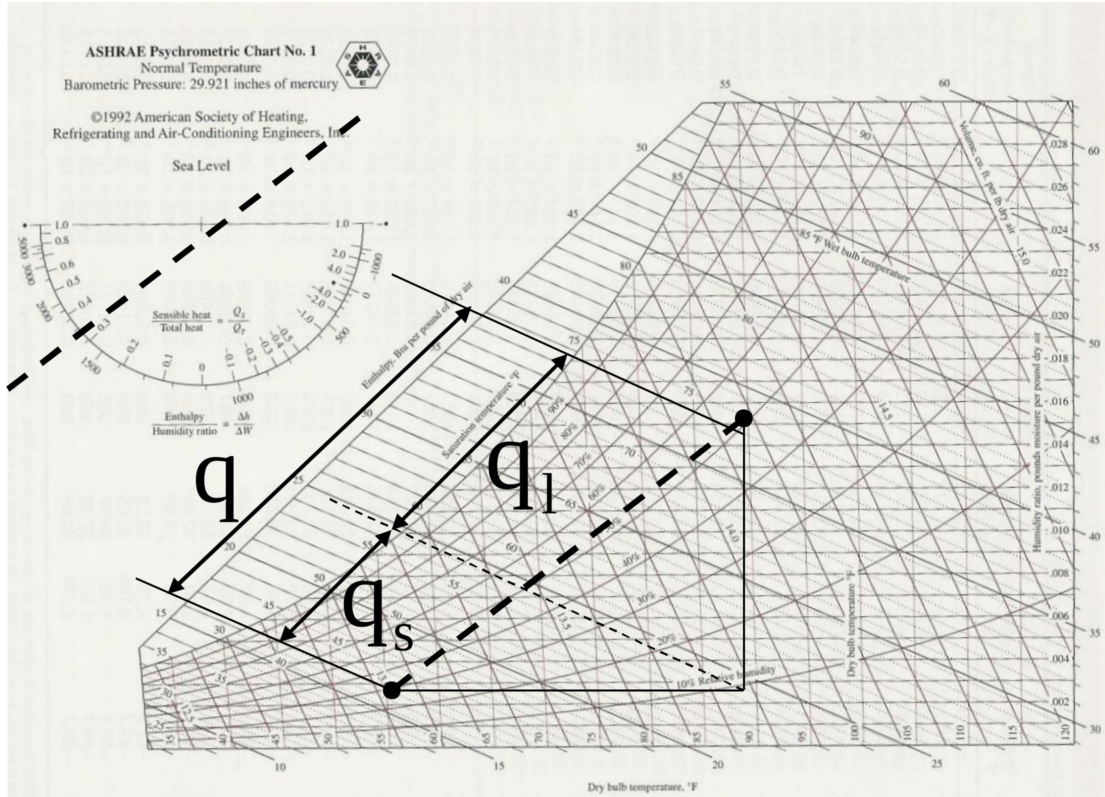
$$q_s = \varphi h_s = \varphi h - \varphi h_l$$

$$SHF = \frac{q_s}{q_l + q_s}$$

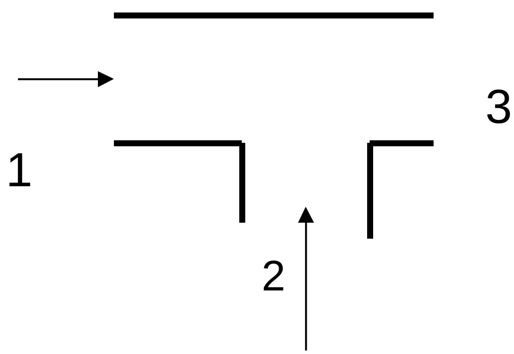
$$SHF = \frac{\varphi h - \varphi x\ h_{fg}}{\varphi x\ h_{fg} + \varphi h - \varphi x\ h_{fg}}$$

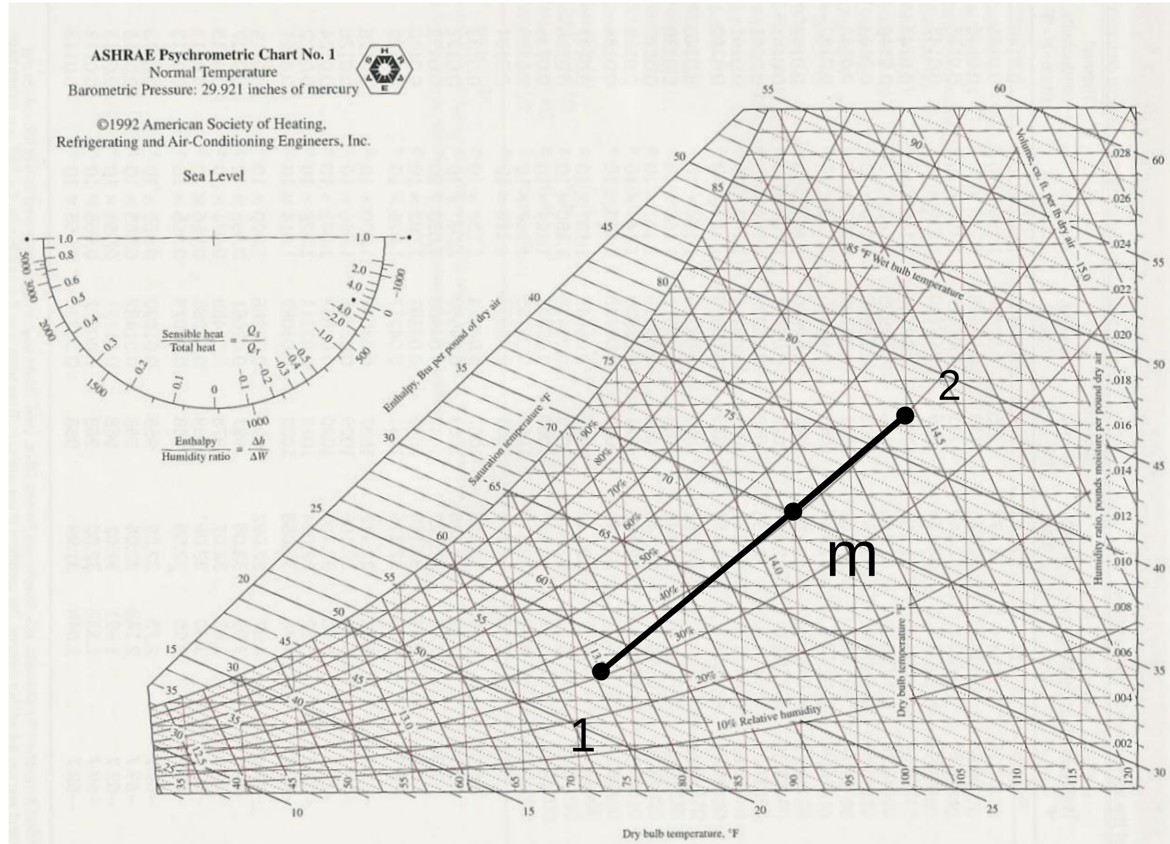
$$SHF = \frac{\frac{\varphi h}{\varphi x} - h_{fg}}{\frac{\varphi h}{\varphi x} + h_{fg} - h_{fg}}$$

$$\frac{\varphi h}{\varphi x} = \frac{h_{fg}}{SHF - 1}$$



Mixing





$$H_m = H_1 + H_2$$

$$m_m h_m = m_1 h_1 + m_2 h_2$$

$$h_m = \frac{m_1}{(m_1 + m_2)_3} h_1 + \frac{m_2}{(m_1 + m_2)} h_2$$

$$\gamma_m = \frac{m_1}{(m_1 + m_2)} \gamma_1 + \frac{m_2}{(m_1 + m_2)} \gamma_2$$

$$\varphi q_{1\rightarrow m} = \varphi q_{1\rightarrow m}$$

$$m_1 c_p (T_m - T_1) = m_2 c_p (T_2 - T_m)$$

$$\frac{m_1}{m_2} = \frac{(T_2 - T_m)}{(T_m - T_1)}$$

10 cubic meters per second of 10 C db, 5 C wb air is mixed with 6 cubic meters per second of air at 25 C db and 18 C wb. Compute the mixture conditions and compare them to results from the psychrometric chart.

Pt 1 -10 c db, 5 c wb

$$\gamma_{g1} = \frac{.622 p_v @\ T_{wb}}{p_{atm} - p_v}$$

$$\gamma_{g1} = \frac{.622 \times .8725\ \text{kPa}}{101.325\ \text{kPa} - .8725\ \text{kPa}} = .0054\ \text{kg/kg}$$

$$\gamma_1 = \frac{c_{pa}\left(T_{wb} - T_{db}\right) + \left(\gamma_{g1} \times h_{fg}\right) @T_{wb}}{h_v @T_{db} - h_w @T_{wb}}$$

$$\gamma_1 = \frac{1.005\ \text{kJ/kgK}\ (5-10) + (.0054\ \text{kg/kg} \times 2489.1\ \text{kJ/kg})}{2510.1\ \text{kJ/kg} - 21.02\ \text{kJ/kg}}$$

$$\gamma_1 = .00338\ \text{kg/kg}$$

$$m_{a1} = \frac{p_a V}{RT} = \frac{(101.325\ \text{kPa} - .8725\ \text{kPa}) \times 10\ \text{m}^3/\text{sec}}{.287\ \text{kPa m}^3/\text{kg} \times (273.15 + 10)}$$

$$m_{a1} = 12.36\ \text{kg/sec}$$

$$m_{v1} = \frac{p_a V}{RT} = \frac{(.8725\ \text{kPa}) \times 10\ \text{m}^3/\text{sec}}{.4615\ \text{kPa m}^3/\text{kg} \times (273.15 + 10)} = .0668\ \text{kg/sec}$$

$$m_m = 12.36 + .0668 = 12.427\ \text{kg/sec}$$

$$h_1 = c_{pa}\left(T_{db}\right) + \gamma_1 \times h_{v1}$$

$$h_1 = 1.005\ \text{kJ/kg K} \times 10 + .00338\ \text{kg/kg} \times 2519.2\ \text{kJ/kg}$$

$$h_1 = 18.56\ \text{kJ/kg}$$

Chart, Pt 2 25 C db, 18 C wb

$$\gamma_2 = 10\ \text{g/kg}$$

$$v_2 = .858\ \text{m}^3/\text{kg}$$

$$m_2 = \frac{6}{.858\ \text{m}^3/\text{kg}} = 7\ \text{kg/sec}$$

$$h_2 = 50.9\ \text{kJ/kg}$$

Calculated Mixing

$$m_m \gamma_m = m_1 \gamma_1 + m_2 \gamma_2$$

$$m_m = m_1 + m_2$$

$$\gamma_m = \frac{m_1}{m_m}\gamma_1 + \frac{m_2}{m_m}\gamma_2$$

$$\gamma_m = \frac{12.36}{19.36} \times .00338 + \frac{7}{19.36} \times .010$$

$$\gamma_m = .00577\ \text{kg/kg}$$

$$h_m = \frac{12.36}{19.36} \times 18.56\ \text{kJ/kg} + \frac{7}{19.36} \times 50.9\ \text{kJ/kg}$$

$$h_m = 30.25\ \text{kJ/kg}$$

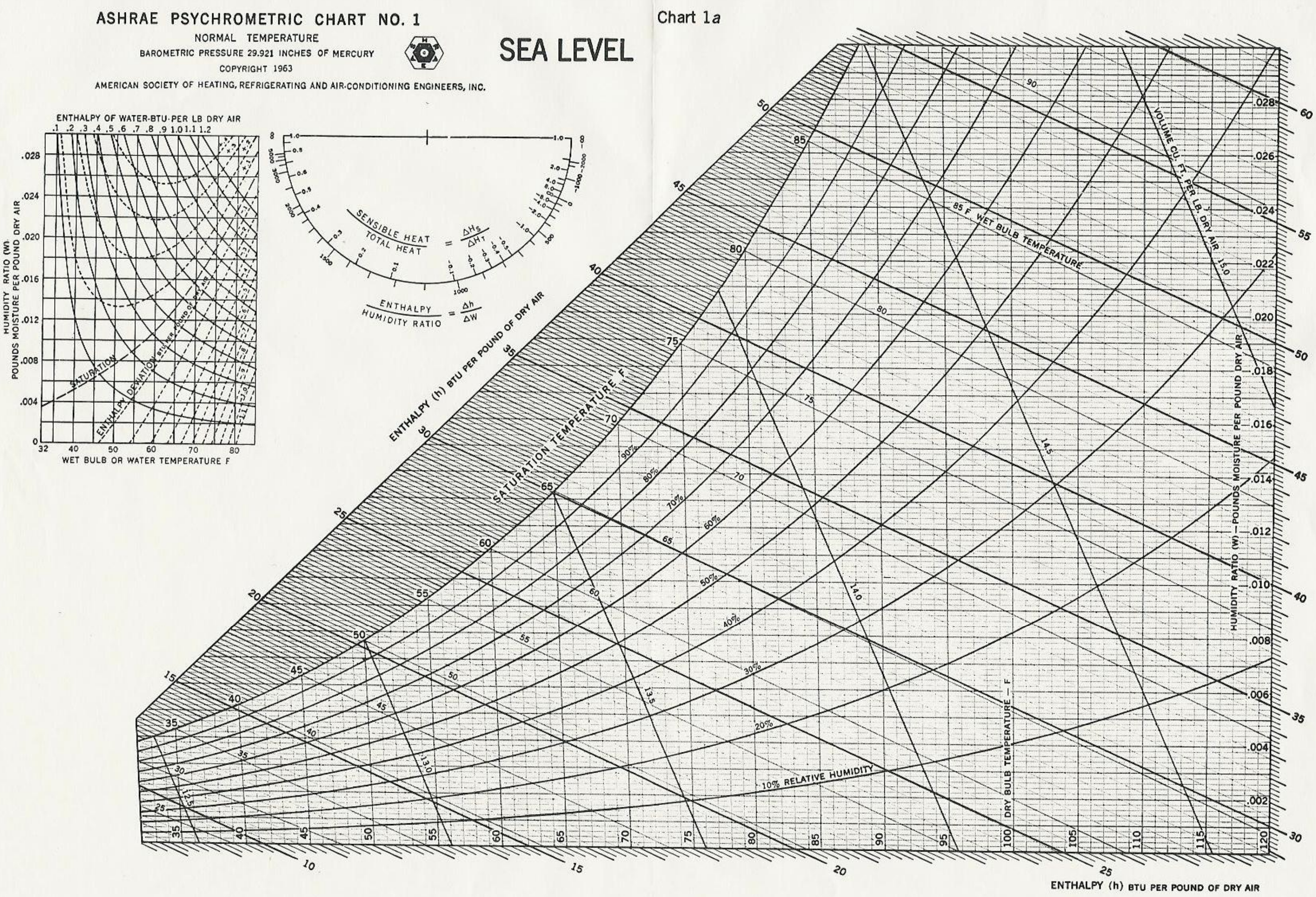
Chart Mixing

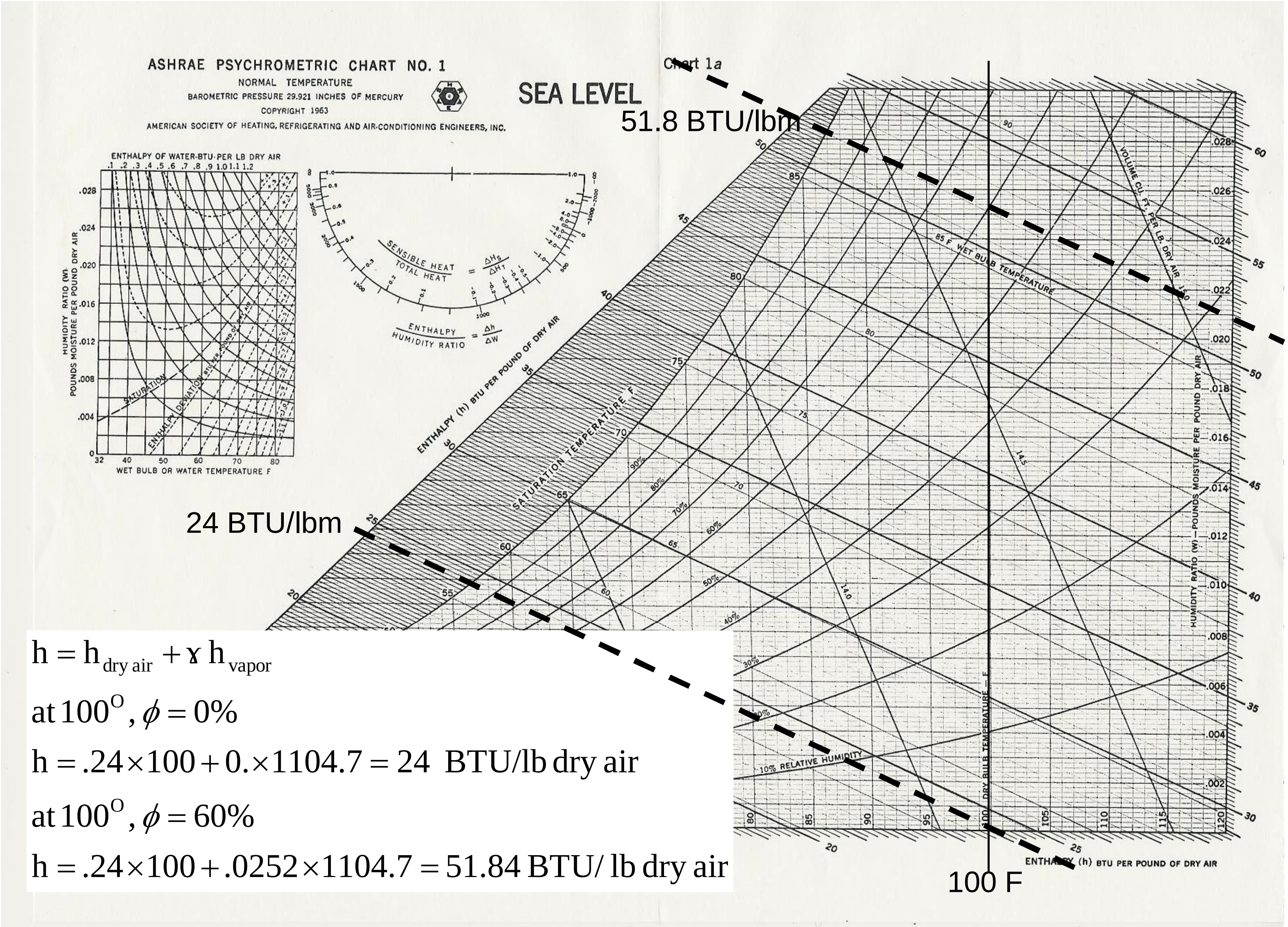
distance from point 2 to point m

$$2.65\ \text{in} \times \frac{12.361}{19.428} = 1.686\ \text{in}$$

read $\gamma_m = 6\text{g/kg}$ and $h_m = 30.5\ \text{kJ/kg}$

Chart 1a


ASHRAE PSYCHROMETRIC CHART NO. 1
NORMAL TEMPERATURE
BAROMETRIC PRESSURE 29.921 INCHES OF MERCURY
COPYRIGHT 1963
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SEA LEVEL
ENTHALPY OF WATER-BTU-PER LB DRY AIR
HUMIDITY RATIO (W) POUNDS MOISTURE PER POUND DRY AIR
WET BULB OR WATER TEMPERATURE F
SATURATION
ENTHALPY DEVIATION
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔHT
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
ENTHALPY (h) BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - F
85 F WET BULB TEMPERATURE
VOLUME CU. FT. PER LB. DRY AIR
10% RELATIVE HUMIDITY
DRY BULB TEMPERATURE - F
HUMIDITY RATIO (W) - POUNDS MOISTURE PER POUND DRY AIR
ENTHALPY (h) BTU PER POUND OF DRY AIR



$$h = h_{\text{dry air}} + \gamma\, h_{\text{vapor}}$$

$$\text{at } 100^{O},\ \phi = 0\%$$

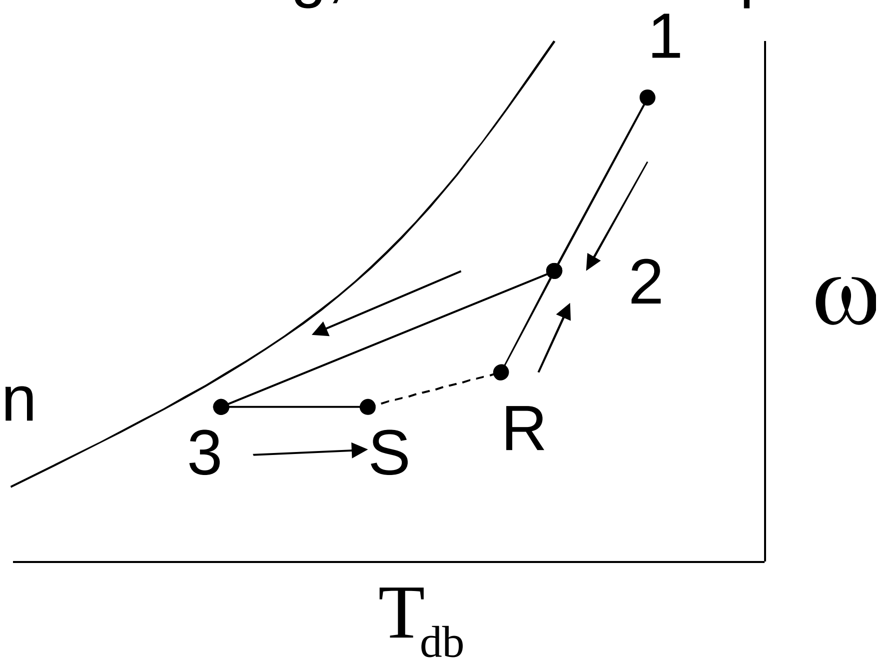
$$h = .24 \times 100 + 0. \times 1104.7 = 24 \ \text{BTU/lb dry air}$$

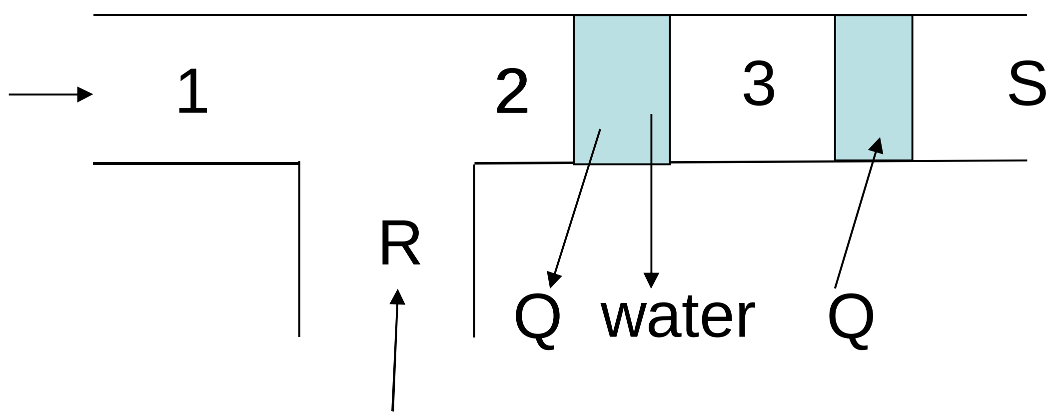
$$\text{at } 100^{O},\ \phi = 60\%$$

$$h = .24 \times 100 + .0252 \times 1104.7 = 51.84 \ \text{BTU/ lb dry air}$$

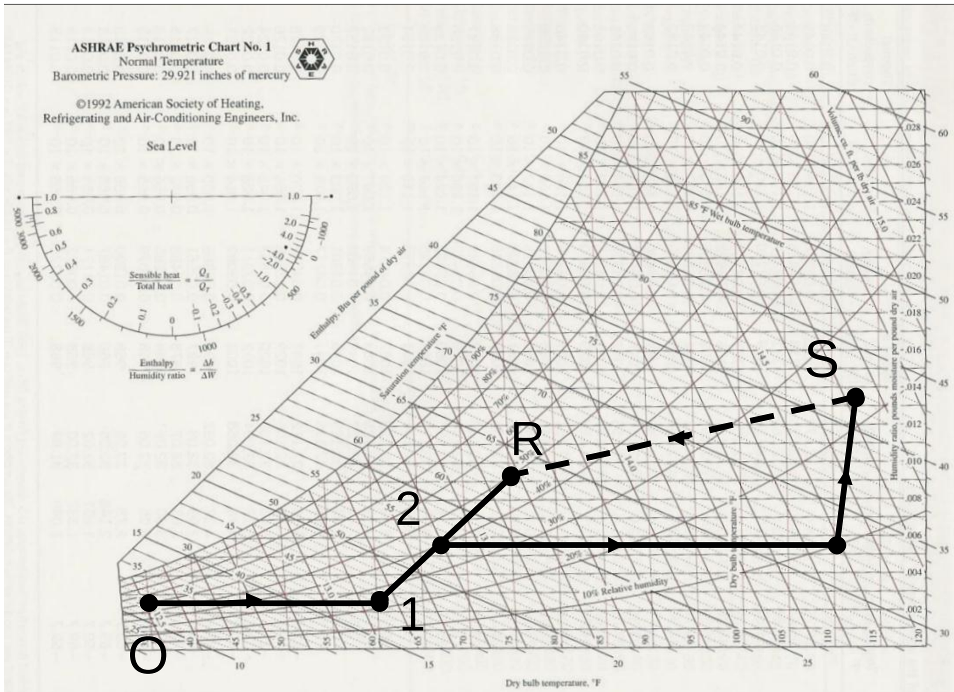
<u>Combined Processes</u> - mixing, cooling and dehumidification, reheating, conditioned space.

1 Outside air
R Return air from conditionded space
2 After mixing
3 After dehumidifucation
S Supply

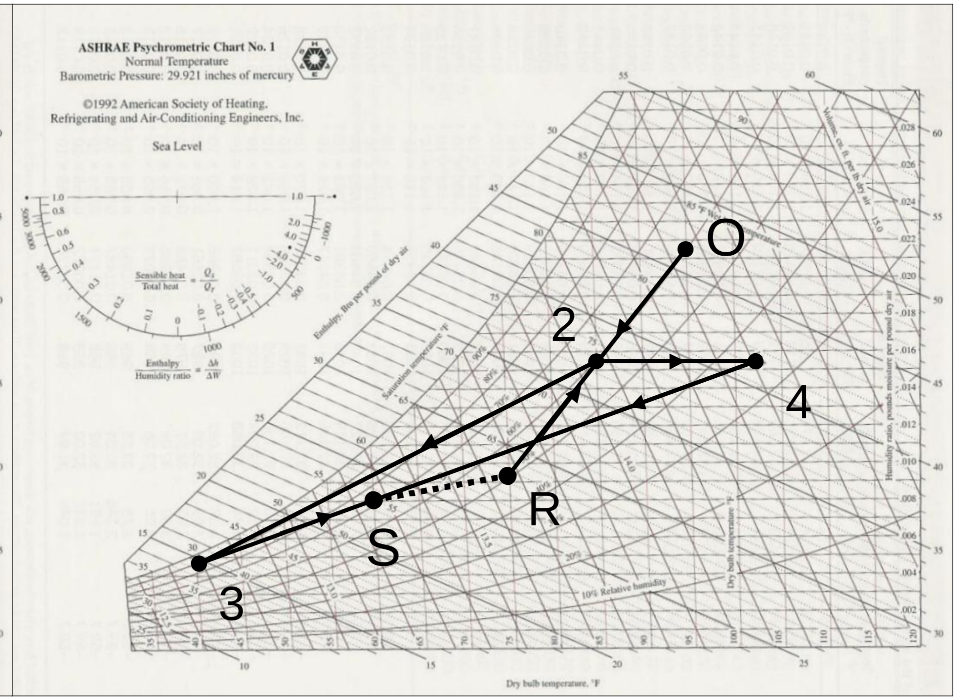




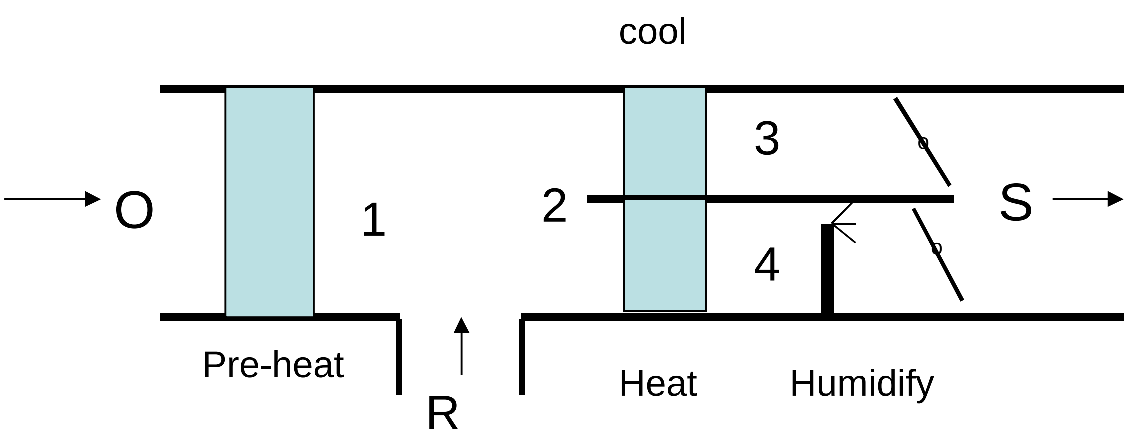
Combined Air Processes



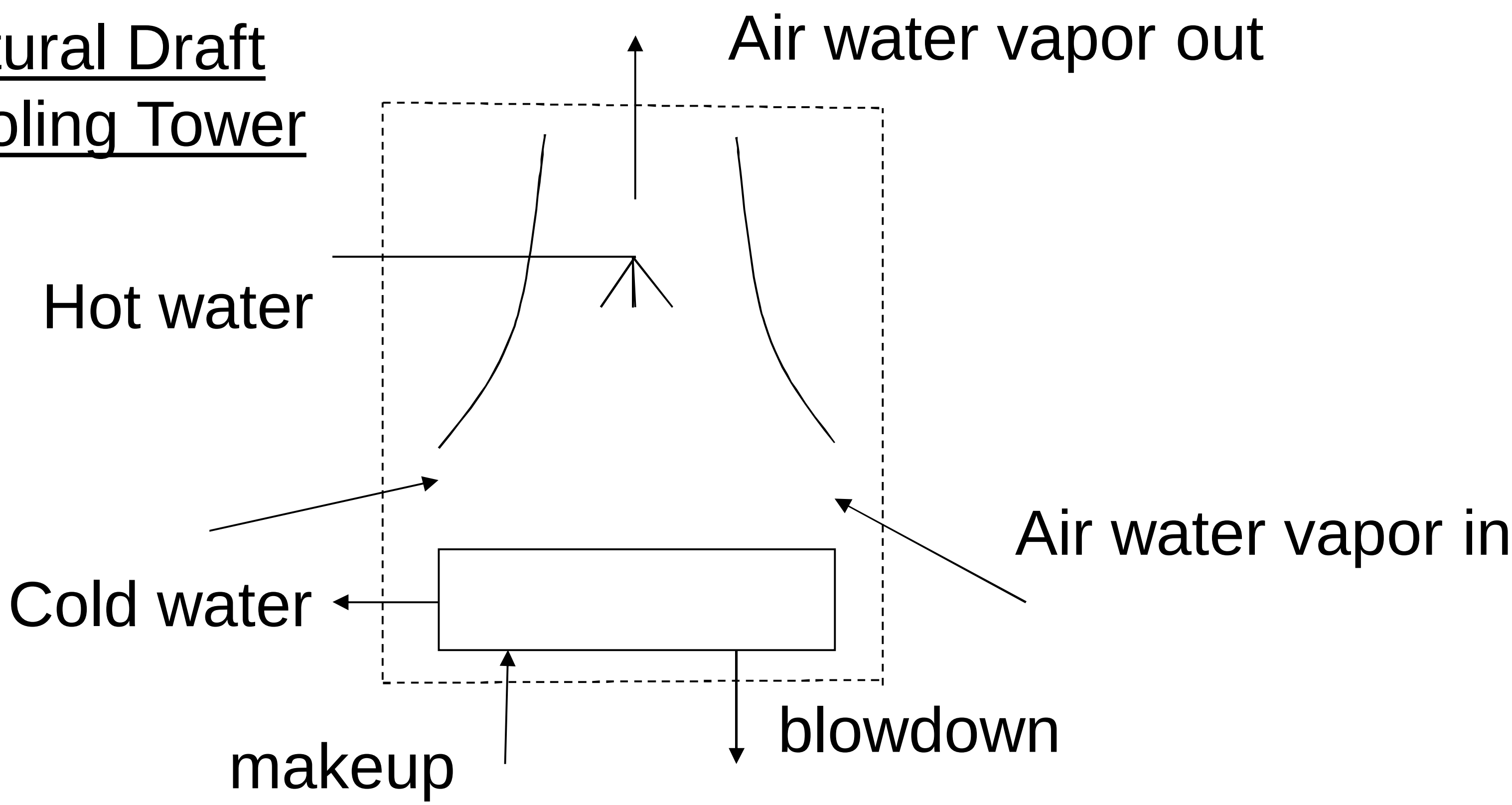
Winter - Heating



Summer - Cooling



Natural Draft Cooling Tower



Mass Balance

$$m_{air\,in} = m_{air\,out}$$

mass water in – mass water out

$$m_{hot\ water} + m_{makeup} + m_{air}\gamma_{in}$$
$$= m_{cold\ water} + m_{blow\ down} + m_{air}\gamma_{out}$$

$$m_{makeup} = m_{air}(\gamma_{out} - \gamma_{in})$$

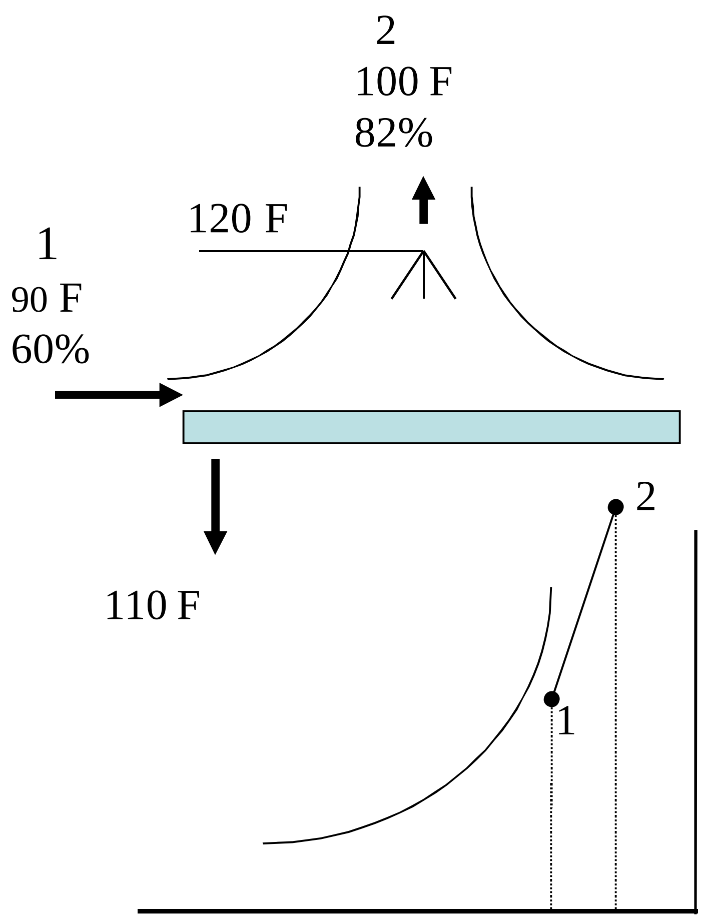
Energy Balance

net energy lost by liquid water =

energy gained by air + water vapor

Cooling Tower Example

An evaporative counterflow air cooling tower removes 1×10^6 BTU/hr from a water flow. The temperature of the water is reduced from 120^o F to 110^o F. Air enters the cooling tower at 90^o F and 60% relative humidity, and the air leaves at 100^o and 82% relative humidity. Calculate a) the air flow rate and b) the quantity of makeup water.



$$\omega_1 = \frac{18\times.6\times p_{g90^oF}}{29\times\left(14.3-.6\times p_{g90^oF}\right)} = \frac{18\times.6\times.69904}{29\times\left(14.3-.6\times.69904\right)}$$

$$\omega_1 = .01876 \text{ lb water/lb dry air}$$

$$\omega_2 = \frac{18\times.82\times.95052}{29\times\left(14.3-.82\times.95052\right)} = .03578 \text{lb water/lb dry air}$$

Mass and Energy Balance

$$\Delta Q_{air} = \Delta Q_{water} = 1{,}000{,}000 \text{ BTU/hr}$$

Assume makeup and blowdown at 110^o F

$$Q_{dryair} = m_a c_p \Delta T = m_a\times.24\times(100-90) = 2.4\times m_a$$

$$Q_{\omega_1} = m_a\times\omega_1\times c_p\times\Delta T = m_a\times.01876\times.45\times(100-90)$$

$$Q_{\omega_1} = .0844\times m_a$$

$$Q_{\Delta\omega} = m_a\times(\omega_2-\omega_1)\times\left(h_{v100^oF}-h_{f120^oF}\right)$$

$$Q_{\Delta\omega} = m_a\times(.03578-.01876)\times(1104.7-88.)$$

$$Q_{\Delta\omega} = 17.3\times m_a$$

$$1{,}000{,}000 = Q_{drtair} + Q_{\omega_1} + Q_{\Delta\omega} = 19.78\times m_a$$

$$m_a = 50{,}556 \text{ lb dry air/hr}$$

$$\text{mass air} = m_a + \omega_1\times m_a = (1+\omega_1)\times m_a = 51{,}504 \text{lb/hr}$$

$$\text{make up} = m_a\times(\omega_2-\omega_1) = 51{,}504\times(.03578-.01876)$$

$$\text{make up} = 876.6 \text{ lb/hr}$$