MASSEY UNIVERSITY

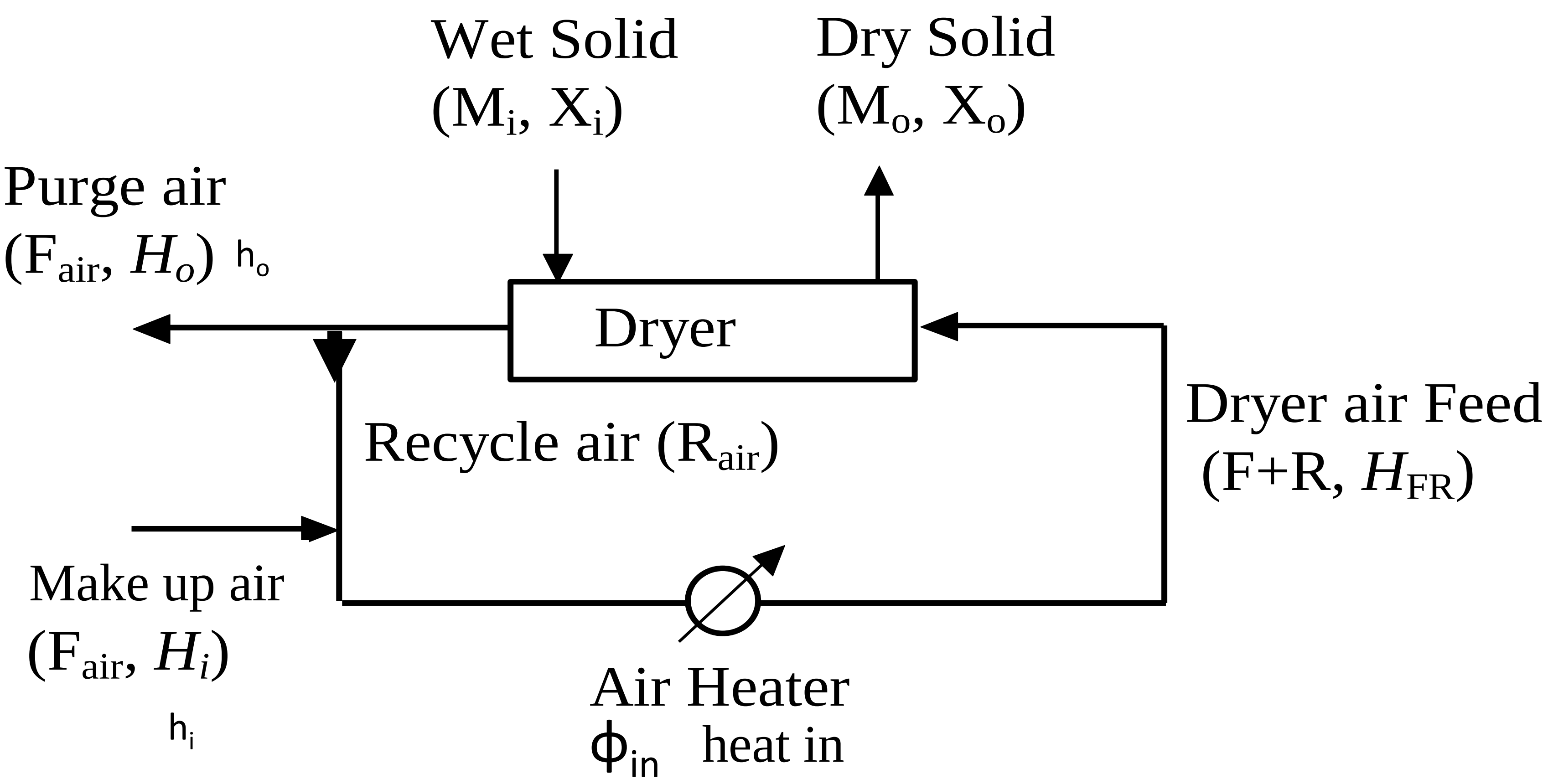
FTE 3013 Process Engineering Operations

Lecture 4

Dryer design:

- Mass and energy balances around the dryer system
- Simplify energy balance by assuming the solid does not heat up appreciably
  - any convective heat loss from the air is returned to the air as latent heat in the evaporated water
  - the air enthalpy remains constant between dryer inlet and outlet.

Dryer schematic



Solids mass balance over dryer

- Solids in wet product = Solids in dry product
- Moisture content (X) = kg water/kg dry solid
- Therefore for every 1 kg of dry solid we have X kg of water
- Therefore, (1+X) = kg dry solid + kg water

- Therefore, $\frac{1}{(1+X)} = \frac{kg\ dry\ solid}{(kg\ dry\ solid + kg\ water)}$ = mass fraction of solid

- Therefore, $M_i \frac{1}{(1+X_i)} = M_o \frac{1}{(1+X_o)}$

- Therefore, mass fraction of water = $\frac{X}{(1+X)}$

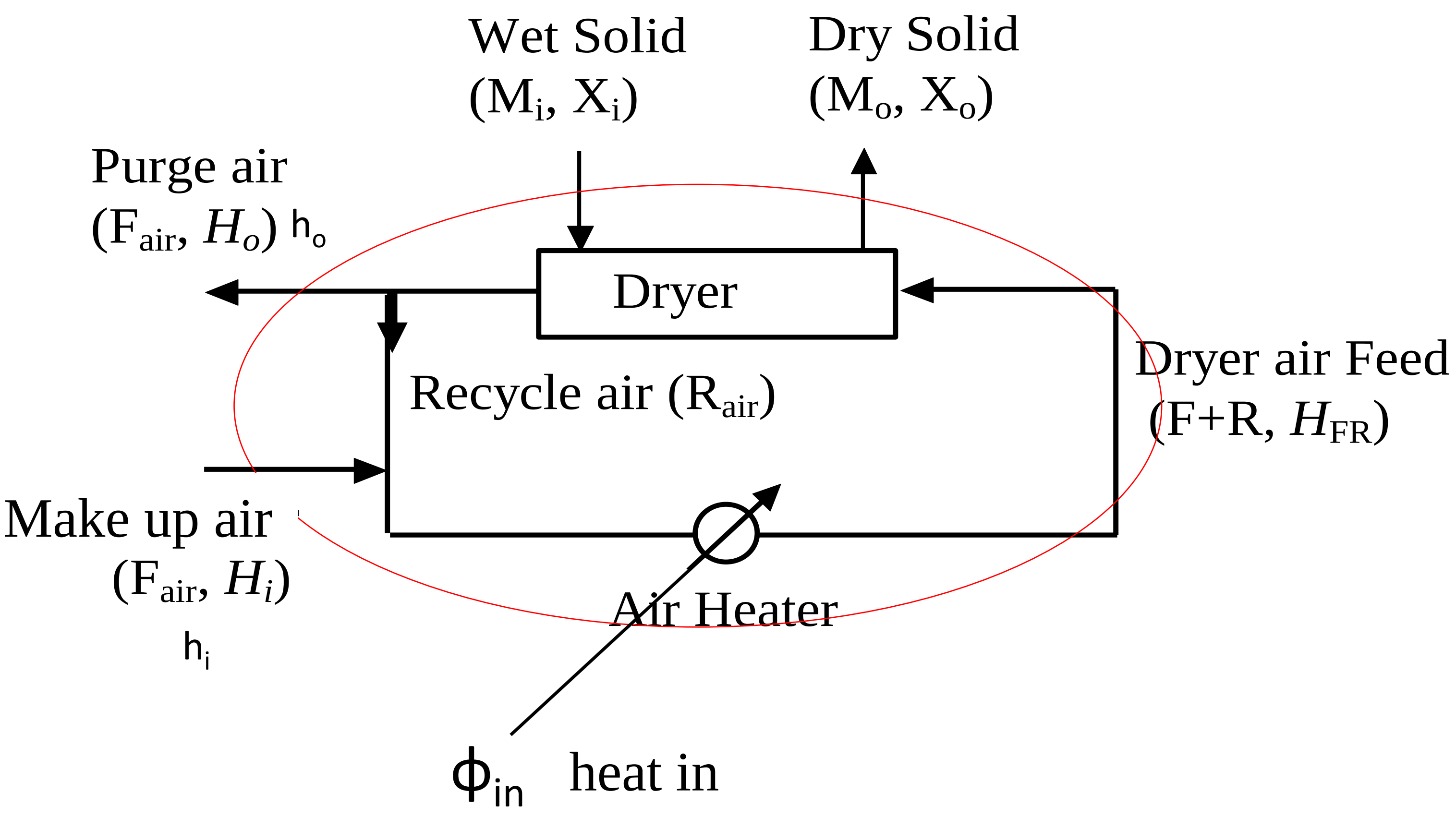
M_i and M_o – mass flow rate of product in or out of dryer

Solids balance

Solid in with the wet product = Solid out with dry product

$$M_i \frac{1}{(1+X_i)} = M_o \frac{1}{(1+X_o)}$$

Water balance for whole dryer system



Nomenclature

F_{air}	flow rate of air (kg/s)
R	flow rate of recycled air (kg/s)
F+R	F_{air} + recycle air (kg/s)
H_i	Humidity of air at inlet to dryer system (makeup air) (kg/kg)
H_o	Humidity of air leaving the dryer system (kg/kg)
H_{FR}	Humidity of air entering dryer (make-up air + recycle air) (kg/kg)
M	mass flow rate of product (kg/s)
X	moisture content of product (kg/kg dry solid)
h_i	enthalpy of air entering (kJ/kg)
h_o	enthalpy of air leaving (kJ/kg)

Water balance for whole dryer system

Water in with wet product + Water in with dry air	=	Water out with dry product + Water out with moist air

$$M_i \frac{X_i}{(1+X_i)} + F_{air} H_i = M_o \frac{X_o}{(1+X_o)} + F_{air} H_o$$

Rearrange:

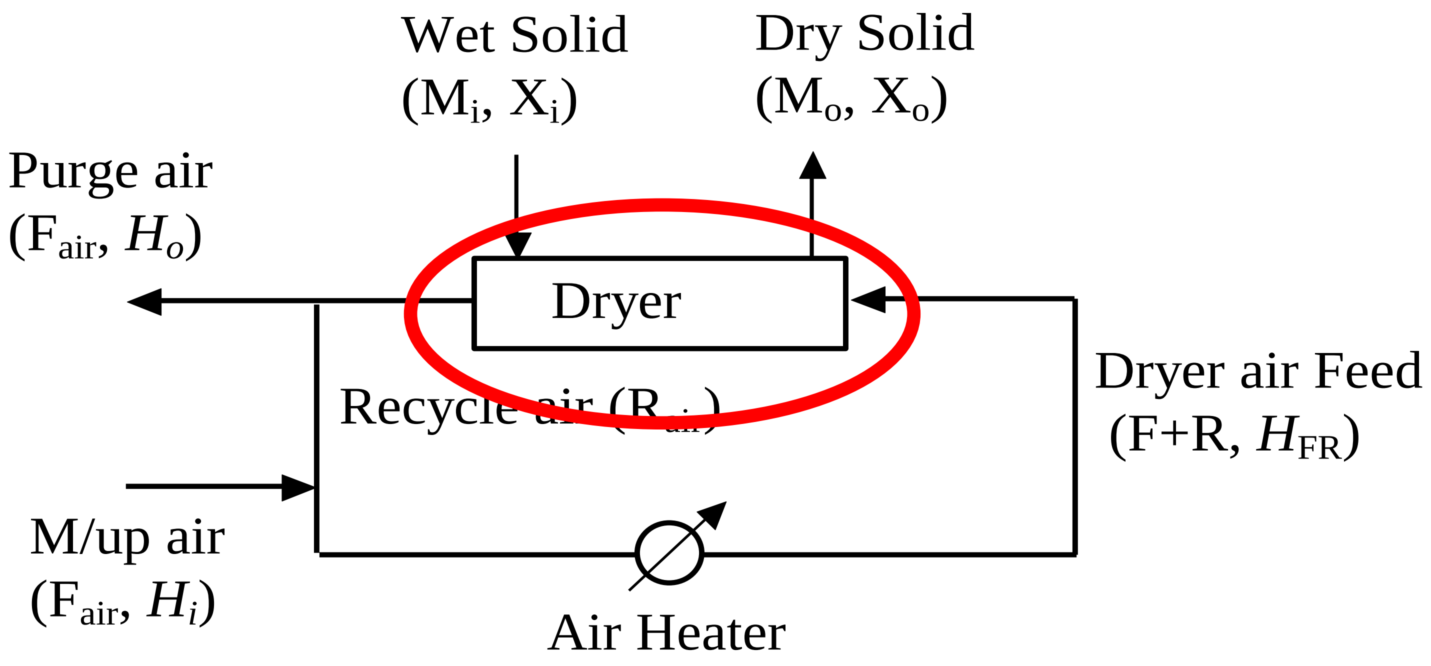
$$M_i \frac{X_i}{1+X_i} - M_O \frac{X_O}{1+X_O} = F_{air}(H_O - H_i)$$

m_v m_v

The water that entered with the wet solids leaves with the drying air which now has a higher humidity.

m_v is the rate of evaporation of water from the wet solid.

Water balance for dryer + recycle



Water balance for dryer + recycle

Water in wet product + Water in dryer feed air (including recycled air)	=	Water out dry product + Water out dryer exit air

$$M_i \frac{X_i}{(1+X_i)} + (F+R)_{air} H_{FR} = M_o \frac{X_o}{(1+X_o)} + (F+R)_{air} H_o$$

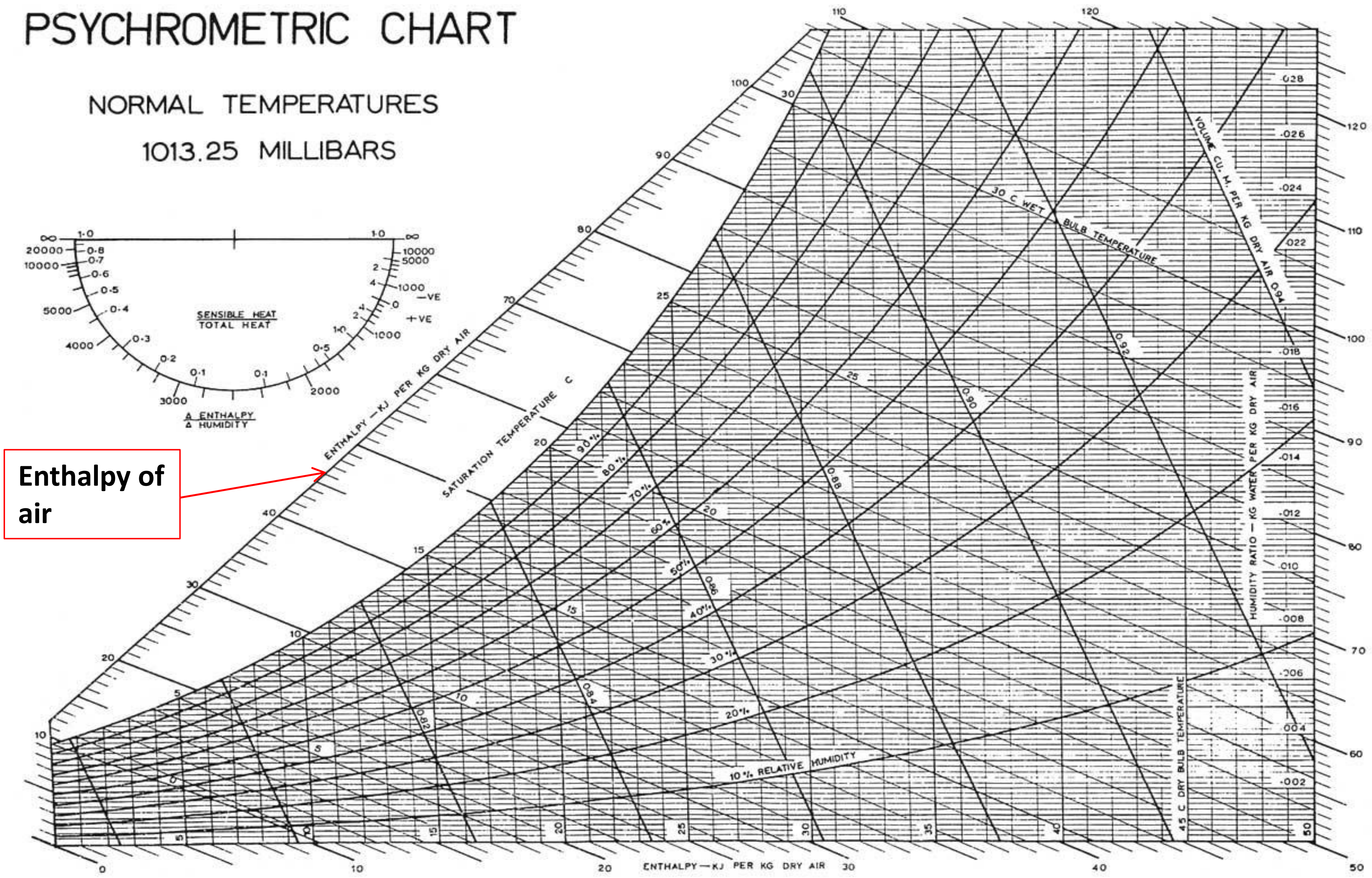
Enthalpy balance

Heat in with dry air + Heater duty	=	Heat out with moist air

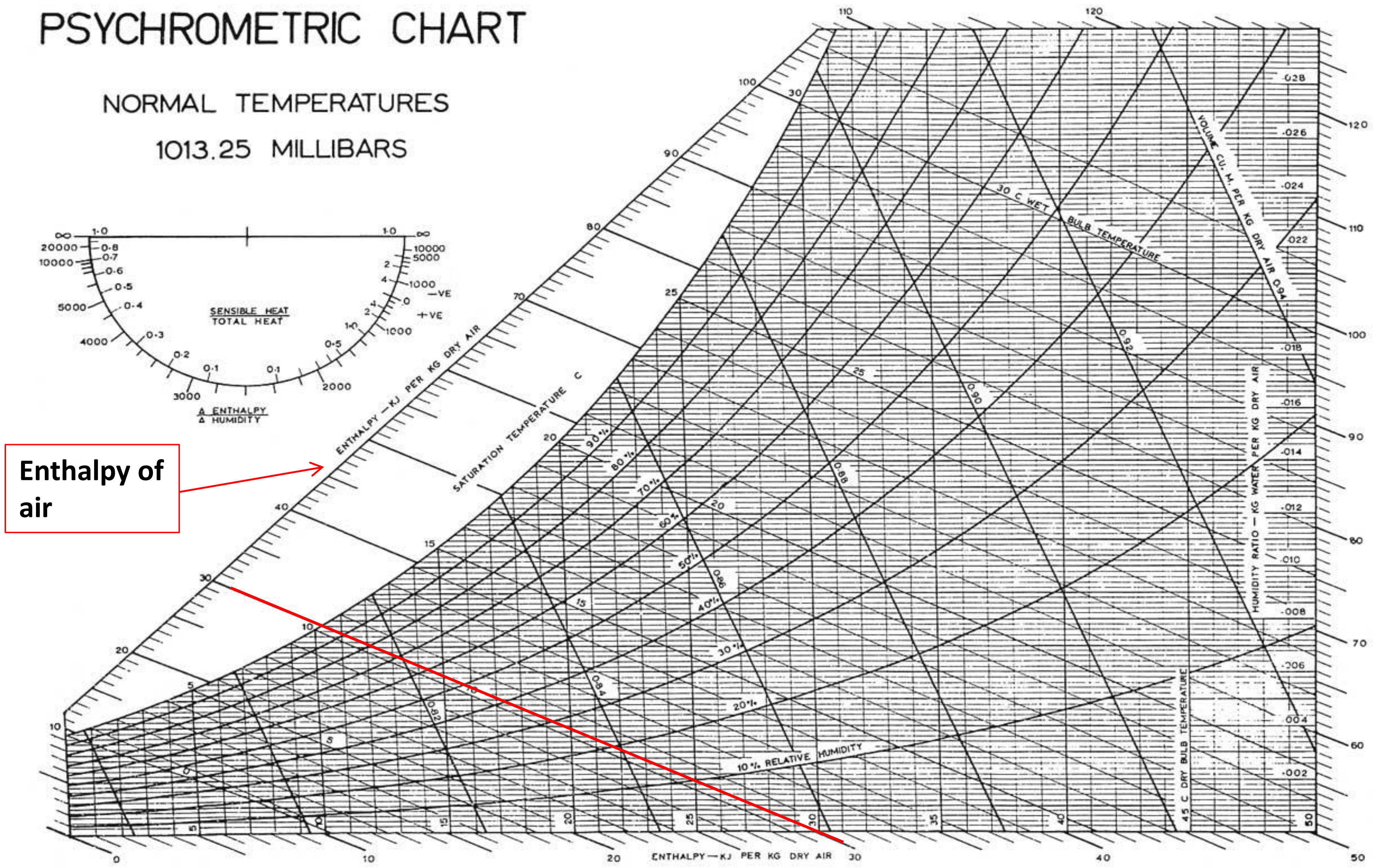
h_i and h_o from psychrometric chart

$$F_{air} h_i + \phi_{in} = F_{air} h_o$$

where $$h_o = h_{FR}$$ (constant air enthalpy in dryer)



Enthalpy of air


PSYCHROMETRIC CHART
NORMAL TEMPERATURES
1013.25 MILLIBARS
SENSIBLE HEAT / TOTAL HEAT
Δ ENTHALPY / Δ HUMIDITY
ENTHALPY — KJ PER KG DRY AIR
SATURATION TEMPERATURE C
30 C WET BULB TEMPERATURE
VOLUME CU. M. PER KG DRY AIR 0.94
HUMIDITY RATIO — KG WATER PER KG DRY AIR
10 % RELATIVE HUMIDITY
45 C DRY BULB TEMPERATURE
ENTHALPY — KJ PER KG DRY AIR
Enthalpy of air

Ideal Heat Load

- *The ideal amount of heat required to evaporate the water*

$$\phi_{ideal} = \left[M_i \frac{X_i}{(1+X_i)} - M_o \frac{X_o}{(1+X_o)} \right] h_{fg}$$

- *Remember*

$$\phi_{ideal} = m_v h_{fg}$$

Efficiency

- *Drying efficiency*

$$\eta = \frac{\phi_{ideal}}{\phi_{in}} = \frac{\phi_{ideal}}{\phi_{actual}}$$

ϕ_{in} (or ϕ_{actual}) is the heat input from the air heater

Summary of Equations

Solids balance

$$M_i \frac{1}{(1+X_i)} = M_o \frac{1}{(1+X_o)}$$

Water balance (dryer only)

$$M_i \frac{X_i}{(1+X_i)} + F_{air} H_i = M_o \frac{X_o}{(1+X_o)} + F_{air} H_o$$

If we rearrange Water balance

$$\left[M_i \frac{X_i}{(1+X_i)} - M_o \frac{X_o}{(1+X_o)}\right] = F_{air}(H_O - H_i)$$

Water balance (entire system

$$M_i \frac{X_i}{(1+X_i)} + (F+R)_{air} H_{FR} = M_o \frac{X_o}{(1+X_o)} + (F+R)_{air} H_o$$

Enthalpy balance

$$F_{air} h_i + \emptyset_{in} = F_{air} h_o$$

$$\emptyset_{ideal} = m_v h_{fg}$$

$$\emptyset_{ideal} = \left[M_i \frac{X_i}{(1+X_i)} - M_o \frac{X_o}{(1+X_o)}\right] h_{fg}$$

Efficiency

$$\eta = \frac{\emptyset_{ideal}}{\emptyset_{in}} = \frac{\emptyset_{ideal}}{\emptyset_{actual}}$$

MASSEY UNIVERSI

Typical solution procedure

1. Use the overall solid balance to determine the missing flow rate M_i or M_o.

2. Use the Overall water balance and Dryer water balance equations to determine two other missing air variables, probably a flow-rate (F_{air}) and a humidity (H).

3. Use the psychrometric chart to obtain air enthalpies (h).

4. Use the energy balance to calculate the required heat to the heater (ϕ).

5. Calculate the ideal heat required to evaporate the water that was evaporated and hence the efficiency.

Example 7: Dryer mass and energy balances (with recycle)

A dryer is used to dry 690 kg/hr of wet solid with a moisture content 2.7 kg/kg to a final moisture content of 0.3 kg/kg.

Air is to be fed to the dryer at 80^{o}C with a humidity of 0.035 kg/kg. An air flow in the dryer of 14 kg/s can be maintained. Make up air is available at 25^{o}C with a humidity of 0.0016 kg/kg.

Determine the outlet air conditions (outlet temperature and humidity), the amount of air recycled (recycle rate) and the thermal efficiency

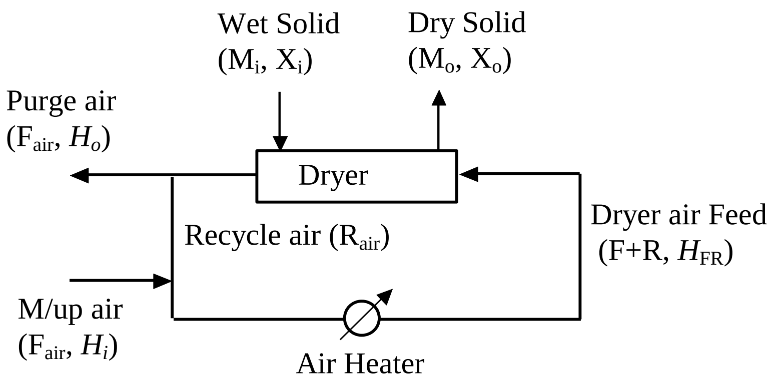
$$M_i \frac{1}{(1+X_i)} = M_o \frac{1}{(1+X_o)}$$

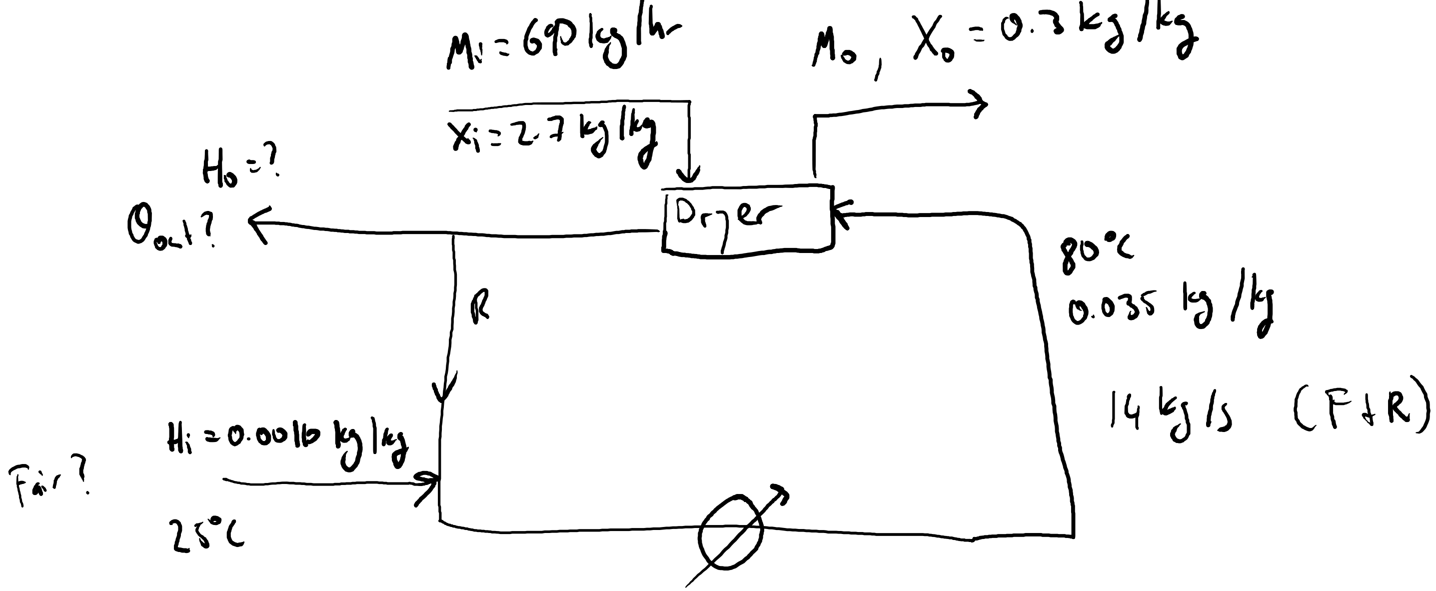
$$M_i \frac{X_i}{(1+X_i)} + (F+R)_{air} H_{FR} = M_o \frac{X_o}{(1+X_o)} + (F+R)_{air} H_o$$

$$\phi_{ideal} = \left[M_i \frac{X_i}{(1+X_i)} - M_o \frac{X_o}{(1+X_o)} \right] h_{fg}$$

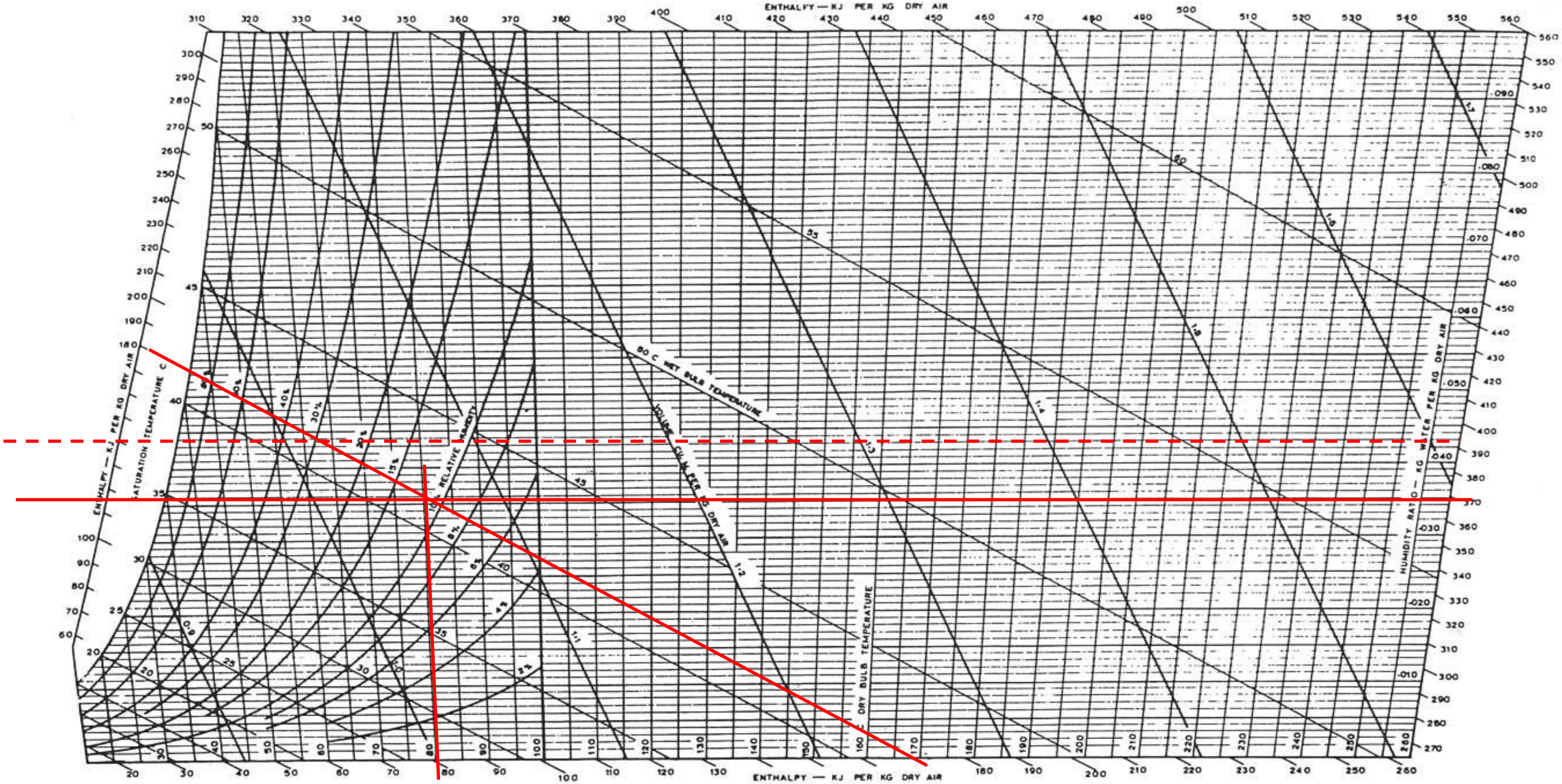
$$\eta = \frac{\phi_{ideal}}{\phi_{in}} = \frac{\phi_{ideal}}{\phi_{actual}}$$

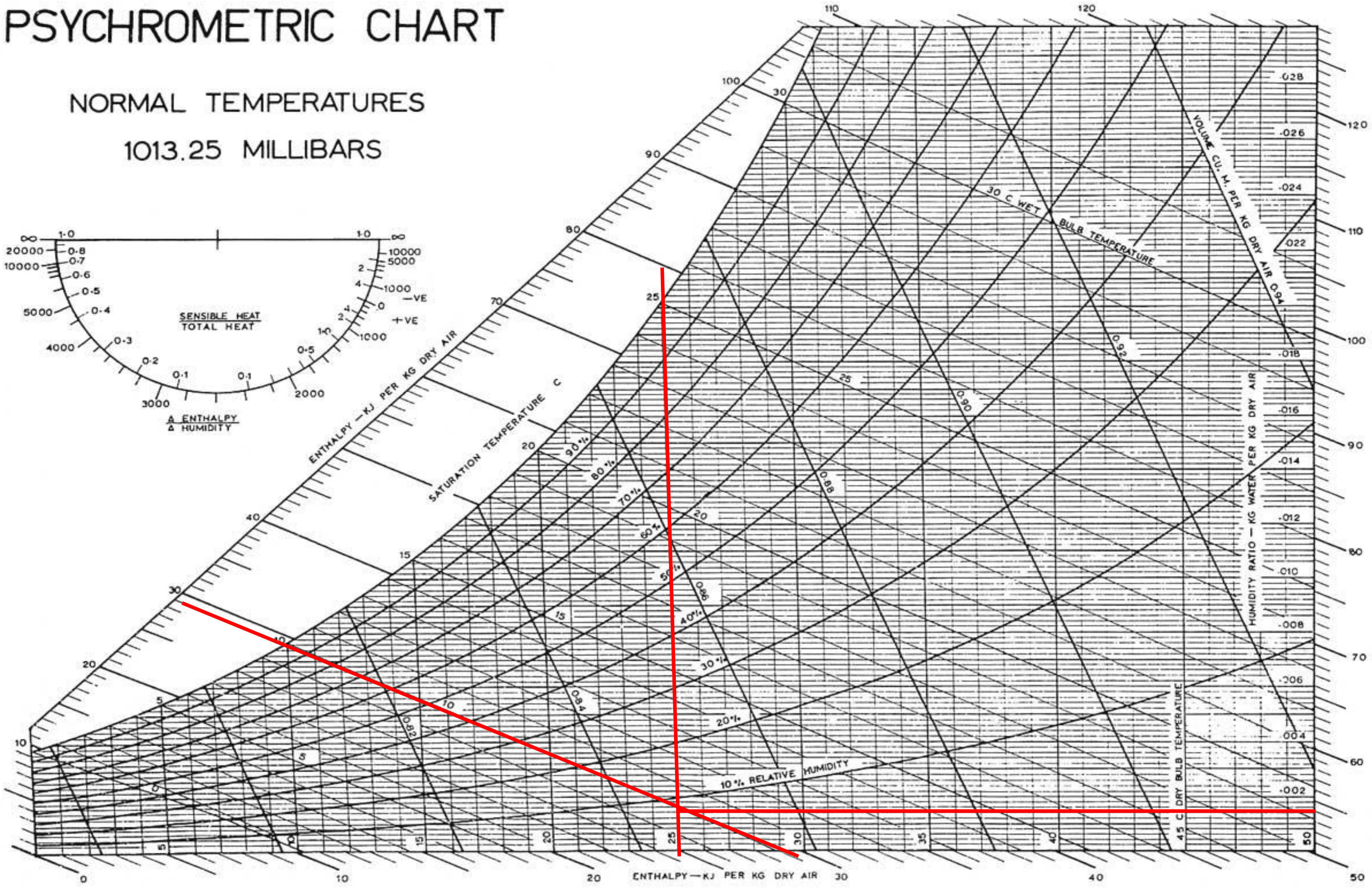
Draw the system





PSYCHROMETRIC CHART HIGH TEMPERATURES 1013.25 MILLIBARS




PSYCHROMETRIC CHART
NORMAL TEMPERATURES
1013.25 MILLIBARS
SENSIBLE HEAT / TOTAL HEAT
Δ ENTHALPY / Δ HUMIDITY
ENTHALPY — KJ PER KG DRY AIR
SATURATION TEMPERATURE C
30 C WET BULB TEMPERATURE
VOLUME CU. M. PER KG DRY AIR
HUMIDITY RATIO — KG WATER PER KG DRY AIR
10 % RELATIVE HUMIDITY
45 C DRY BULB TEMPERATURE

Example 8: Dryer mass and energy balances (with recycle)

0.5 kg/s of a heat sensitive protein product with an initial moisture content of 1.5 kg water/kg solid is to be dried to a final moisture content of 0.7 kg water/kg solid.

Drying air is fed to the dryer at 80^{o}C and 0.015 kg/kg humidity. Moist air is to be purged at a rate sufficient to give an exit humidity of 0.032 kg/kg and make-up air is supplied at 25^{o}C and 60% relative humidity.

Calculate the required flowrate of make-up air, the flowrate of air through the dryer and the thermal efficiency of the dryer.