

2015-2016 Spring Semester Material and Energy Balance

Enthalpy Balances in Non-Reactive System

Assist. Prof. Dr. Murat Alkan

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10th Weeks

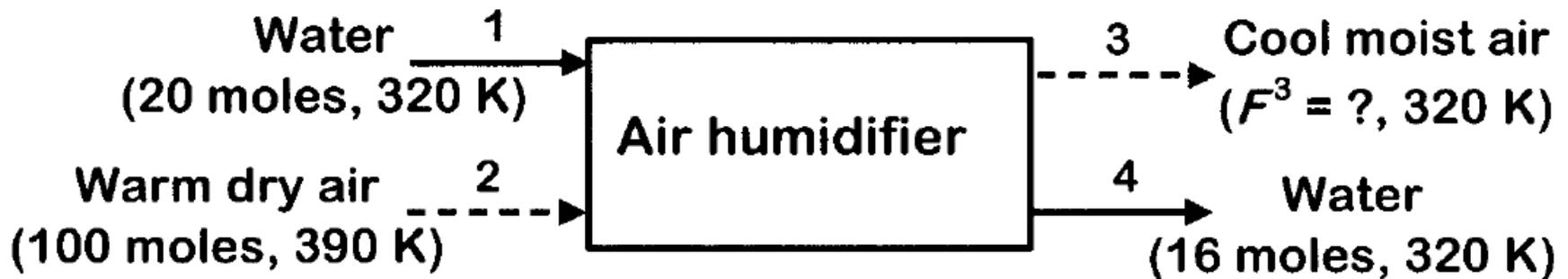
Definitions

- The most common type of energy balance on non-reactive systems is the "heat" balance, in which only the thermal energy (heat) into and out of a process is accounted for. It should properly be referred to as a thermal energy balance, or an enthalpy balance, but it's called a heat balance in common usage.
- assuming no heat loss (i.e. $H_L = 0$), the heat put into a system will equal the heat taken out plus any accumulation.
- In a steady-state system, no heat accumulates. Also, most processes are (or are nearly) isobaric, so enthalpy rather than internal energy is the measure of heat energy.

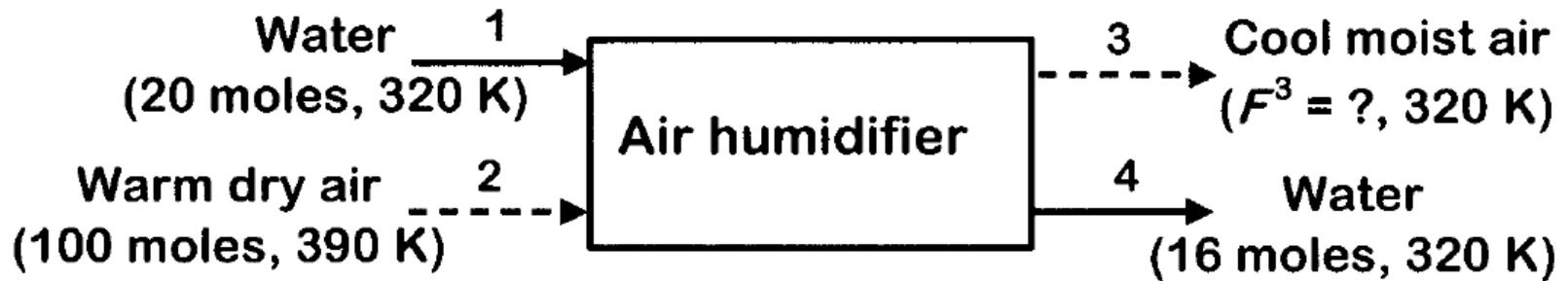
$$H_{\text{instreams}} + H_{\text{reactions}} + H_{\text{surroundings}} + H_{\text{outstreams}} = 0$$

Example: Heat Loss

- Water is sprayed into 100 mol/min of warm dry air to produce cool humidified air. The context of the problem suggests that 320 K is the arithmetically simplest basis temperature for a heat balance.
- The system pressure isn't needed if ideal gas behavior is assumed and dew point and relative humidity aren't involved.
- The objective of this heat balance is to determine the heat loss, if any, from the humidifier device.

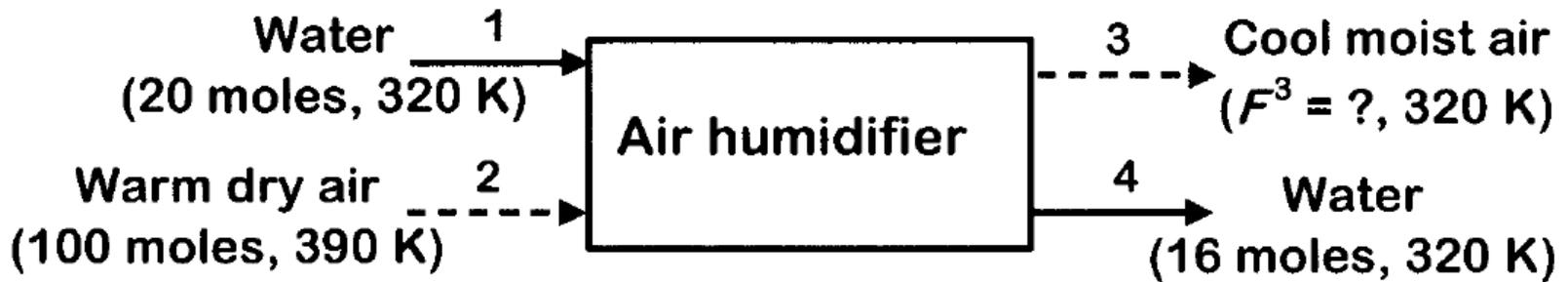


Example: Heat Loss



- What do we need?
- If there is no reaction, where will the energy be calculated?
 - During heating or cooling and,
 - During phase transformation
- Firstly, define the which compounds are heated/cooled and transformed.
- Then, we will look for the thermodynamical data of these compounds.

Example: Heat Loss



- 100 moles air (@390 K) cooled down to 100 moles air (@320K)
- 20-16=4 moles of water vaporized (@320K) $\text{H}_2\text{O}_{(l)} \rightarrow \text{H}_2\text{O}_{(g)}$

• we need the data of

- C_p or ΔH° values of N_2 and O_2 at 390K
- C_p or ΔH° values of N_2 and O_2 at 320K
- $\Delta H^\circ_{\text{vap}}$ value of H_2O at 320K

$$H_{\text{N}_2,320\text{K}}^\circ - H_{\text{N}_2,390\text{K}}^\circ = ?$$

$$H_{\text{O}_2,320\text{K}}^\circ - H_{\text{O}_2,390\text{K}}^\circ = ?$$

• We can use HSC for data

$$H_{\text{H}_2\text{O}_{(g)},320\text{K}}^\circ - H_{\text{H}_2\text{O}_{(l)},320\text{K}}^\circ = ?$$

Example: Heat Loss

Key	Formula: N2(g)	
MainDB	1.	2.
Formula	N2(g)	N2(g)
Structural Formula		
Chemical Name	Nitrogen	Nitrogen
Common Name		
CAN	7727-37-9	7727-37-9
Mol. Weight	28.01	28.01
Melting p. K	63.14	63.14
Boiling p. K	77.36	77.36
T1 K	100.00	350.00
T2 K	350.00	700.00
State	g	g
H kJ/mol	0.000	0.000
S J/(mol*K)	191.610	0.000
A J/(mol*K)	29.298	27.753
B	-1.567	0.605
C	-0.007	0.728
D	3.419	4.960

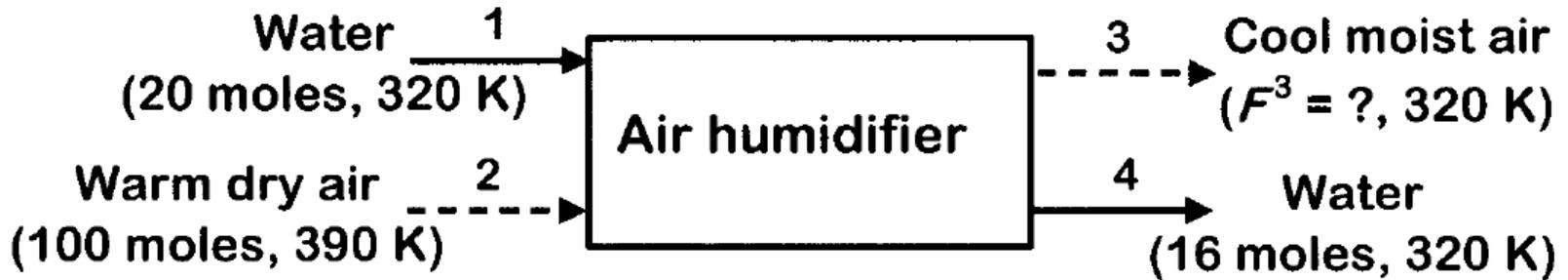
Key	Formula: O2(g)	
MainDB	1.	2.
Formula	O2(g)	O2(g)
Structural Formula		
Chemical Name	Oxygen	Oxygen
Common Name		
CAN	7782-44-7	7782-44-7
Mol. Weight	32.00	32.00
Melting p. K	54.36	54.36
Boiling p. K	90.20	90.20
T1 K	100.00	298.15
T2 K	298.15	700.00
State	g	g
H kJ/mol	0.000	0.000
S J/(mol*K)	205.149	0.000
A J/(mol*K)	29.780	22.060
B	-6.177	20.887
C	-0.021	1.621
D	15.997	-8.207

Results				
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	T	Cp	H	S
1	H2O(l)=H2O(g)			
2	T	deltaH	deltaS	deltaG
3	K	kJ	J/K	kJ
4	320.000	43.093	115.934	5.994
5				
6	Formula	FM	Conc.	Amount
7		g/mol	wt-%	mol
8	H2O(l)	18.015	100.000	1.000
9		g/mol	wt-%	mol
10	H2O(g)	18.015	100.000	1.000

$$C_p = A + B \times 10^{-3} \cdot T + \frac{C \times 10^5}{T^2} + D \times 10^{-6} \cdot T^2 \quad H_{320} - H_{390} = n \cdot \int_{390}^{320} C_p \cdot dT$$

$$H_{320} - H_{390} = n \cdot \left[\left(A \cdot T \Big|_{390}^{320} \right) + \left(\frac{B \times 10^{-3}}{2} \cdot T^2 \Big|_{390}^{320} \right) + \left((-C \times 10^5) \cdot \frac{1}{T} \Big|_{390}^{320} \right) + \left(\frac{D \times 10^{-6}}{3} \cdot T^3 \Big|_{390}^{320} \right) \right]$$

Example: Heat Loss



$$H_{N_2,320K}^\circ - H_{N_2,390K}^\circ = -161.327 \text{ kJ}/\text{min}$$

$$H_{O_2,320K}^\circ - H_{O_2,390K}^\circ = -43.712 \text{ kJ}/\text{min}$$

$$\Delta H_{air} = H_{Air,320K}^\circ - H_{Air,390K}^\circ = -205.039 \text{ kJ}/\text{min}$$

$$\Delta H_{wat.} = H_{H_2O(g),320K}^\circ - H_{H_2O(l),320K}^\circ = 172.372 \text{ kJ}/\text{min}$$

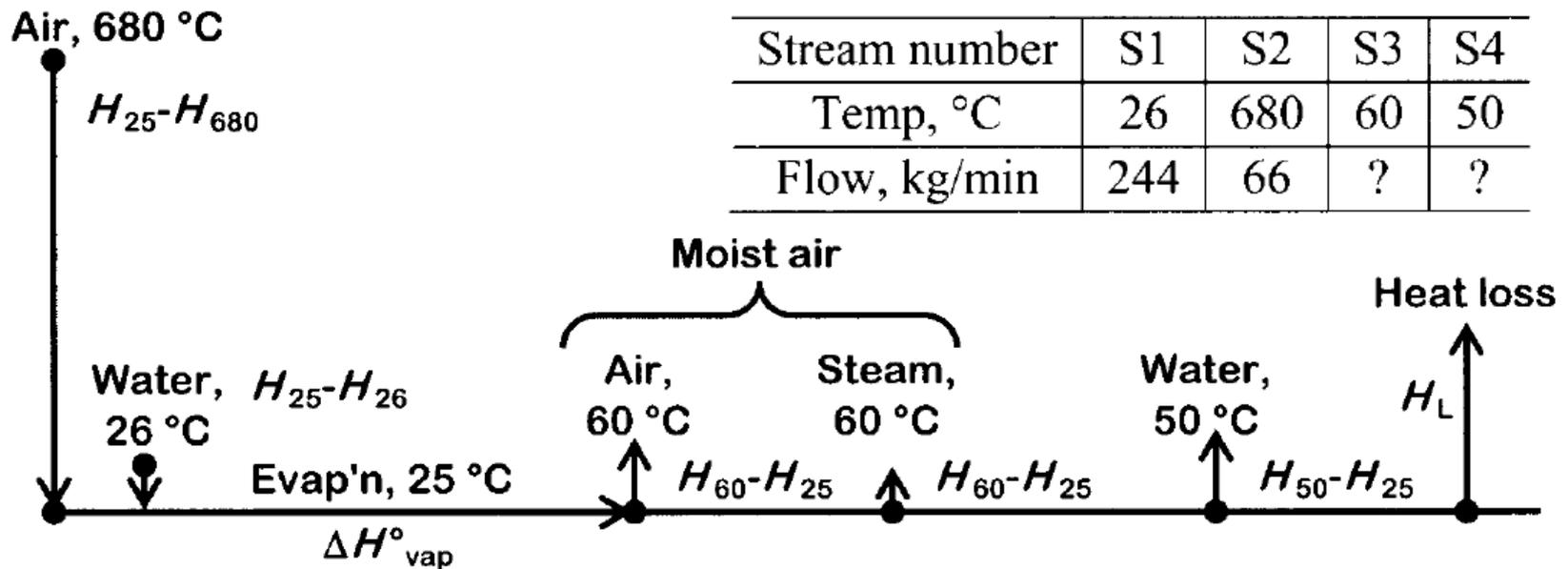
$$\text{Total Heat} = 0 = \Delta H_{wat.} + \Delta H_{air} + \Delta H_{loss}$$

$$0 = 172.372 - 205.039 + \Delta H_{loss}$$

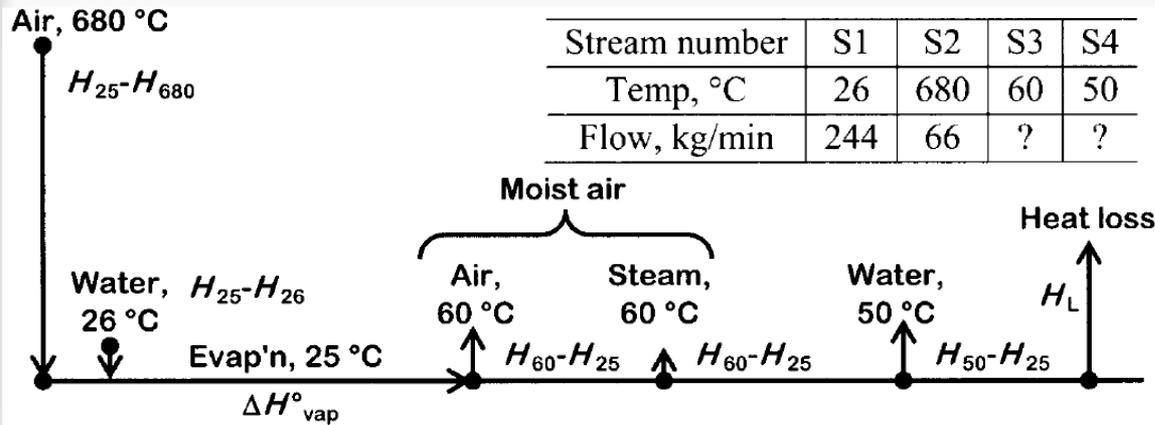
$$\Delta H_{loss} = 32.667 \text{ kJ}/\text{min}$$

Example: Heat Loss

- The use of 25 °C as a basis temperature is illustrated for a different version of the above example. Again, cold water is used to cool hot air and at the same time, humidify it. The heat loss was measured to be 7360 kJ/min. The procedure is to cool all instreams to 25 °C, evaporate W kg of water at 25 °C, and heat all outstreams.
- Calculate the flow rate of the moist air and water.



Example: Heat Loss



Stream number	S1	S2	S3	S4
Temp, °C	26	680	60	50
Flow, kg/min	244	66	?	?

- What do we need?
- Find heated or cooled compounds
- Find transformed compounds

1 Cooling Process

- 66 kg/min Air (@ 680°C) cooled down to 66 kg/min Air (@ 25°C)
- 244 kg/min water (@ 26°C) cooled down to 244 kg/min water (@ 25°C)

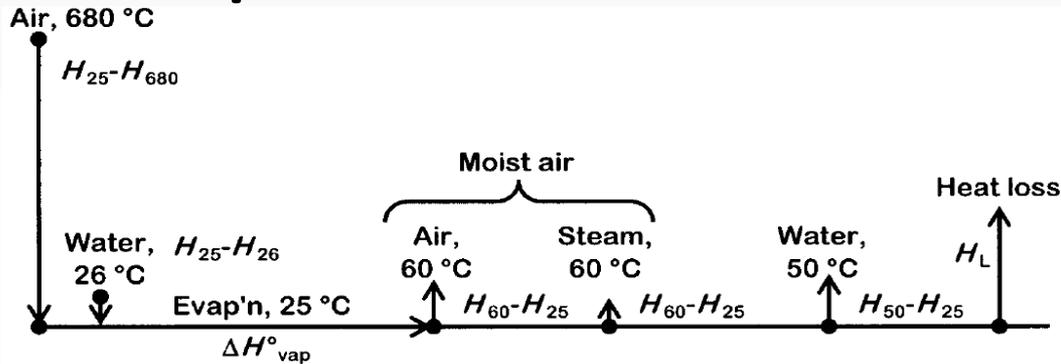
2 Vaporing process

- X kg/min water (@ 25°C) evaporated to X kg/min water vapor (@ 25°C)

3 Heating Process

- 66 kg/min Air (@ 25°C) heated up to 66 kg/min Air (@ 60°C)
- X kg/min water vapor (@ 25°C) heated up to X kg/min water vapor (@ 60°C)
- 244-X kg/min water (@ 25°C) heated up to 244-X kg/min water (@ 50°C)

Example: Heat Loss



Stream number	S1	S2	S3	S4
Temp, °C	26	680	60	50
Flow, kg/min	244	66	?	?

Heat term	ΔH°_{vap} H ₂ O(l) at 25 °C	$H_{680}-H_{25}$ dry air	C_p H ₂ O(g)	C_p H ₂ O(l)	C_p dry air
Value	2440	700	1.869	4.184	1.009

1 Cooling Process

- 66 kg/min Air (@ 680°C) cooled down to 66 kg/min Air (@ 25°C)
- 244 kg/min water (@ 26°C) cooled down to 244 kg/min water (@ 25°C)

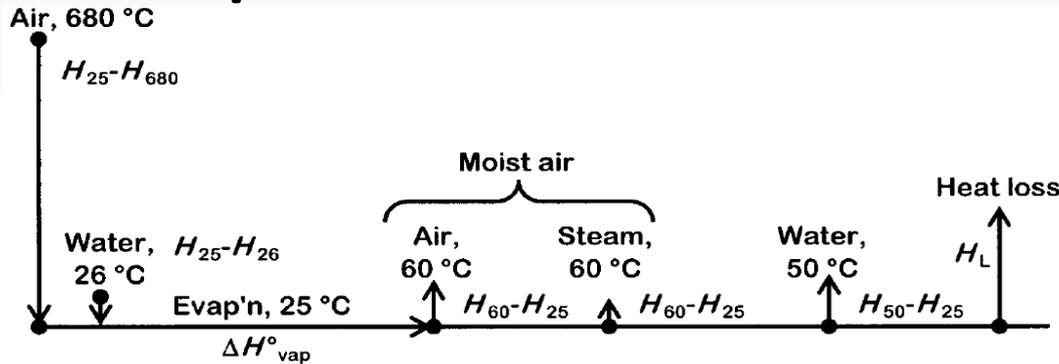
2 Vaporizing process

- X kg/min water (@ 25°C) evaporated to X kg/min water vapor (@ 25°C)

3 Heating Process

- 66 kg/min Air (@ 25°C) heated up to 66 kg/min Air (@ 60°C)
- X kg/min water vapor (@ 25°C) heated up to X kg/min water vapor (@ 60°C)
- 244-X kg/min water (@ 25°C) heated up to 244-X kg/min water (@ 50°C)

Example: Heat Loss



Stream number	S1	S2	S3	S4
Temp, °C	26	680	60	50
Flow, kg/min	244	66	?	?

Heat term	$\Delta H^\circ_{\text{vap}} \text{ H}_2\text{O}(l) \text{ at } 25^\circ\text{C}$	$H_{680}-H_{25} \text{ dry air}$	$C_p \text{ H}_2\text{O}(g)$	$C_p \text{ H}_2\text{O}(l)$	$C_p \text{ dry air}$
Value	2440	700	1.869	4.184	1.009

1 Cooling Process

- $\Delta H_{\text{air}} = -46200 \text{ kJ/min}$
- $\Delta H_{\text{water}} = -1020 \text{ kJ/min}$

$$\Delta H_{\text{loss}} = 7360 \text{ kJ/min}$$

2 Vaporizing process

- $\Delta H_{\text{vap}} = 2440 \cdot X \text{ kJ/min}$

$$\text{Total Heat} = 0 = \Delta H_{\text{wat.}} + \Delta H_{\text{air}} + \Delta H_{\text{loss}}$$

$$X = 5 \text{ kg/min}$$

3 Heating Process

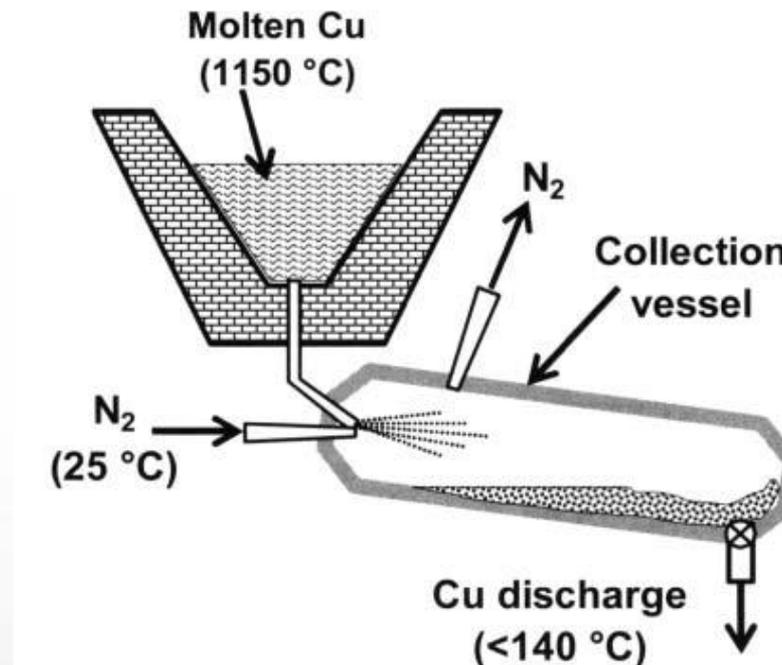
- $\Delta H_{\text{air}} = -2330 \text{ kJ/min}$
- $\Delta H_{\text{vap}} = 65.4 \cdot X \text{ kJ/min}$
- $\Delta H_{\text{water}} = 25520 - 104.6 \cdot X \text{ kJ/min}$

$$S3 = 66 + 5 = 71 \text{ kg/min}$$

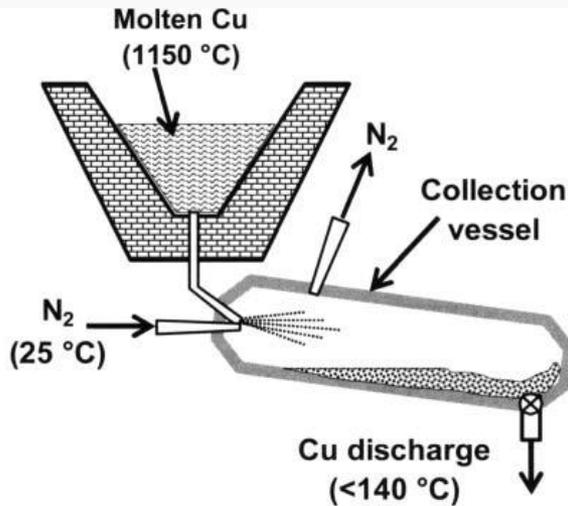
$$S4 = 244 - 5 = 239 \text{ kg/min}$$

Example: Copper Atomization (Adiabatic Process)

- Copper powder is prepared by atomizing molten copper with nitrogen. **The heat loss through the walls of the powder collection vessel is negligible.** The average flow rate of molten Cu is 30 kg/min.
- Make a system balance to calculate the flow rate of N_2 required at the average flow rate of Cu to attain a powder temperature of $120\text{ }^\circ\text{C}$



Example: Copper Atomization (Adiabatic Process)



$$H_{Cu,1150^{\circ}C}^{\circ} = 44.978 \text{ kJ/mol}$$

$$H_{N_2,85^{\circ}C}^{\circ} = 1.749 \text{ kJ/mol}$$

$$H_{Cu,120^{\circ}C}^{\circ} = 2.367 \text{ kJ/mol}$$

$$H_{N_2,25^{\circ}C}^{\circ} = 0 \text{ kJ/mol}$$

$$MW_{Cu} = 63.55 \text{ g/mol}$$

$$MW_{N_2} = 28.01 \text{ g/mol}$$

$$\Delta H_{Cu} + \Delta H_{N_2} = 0$$

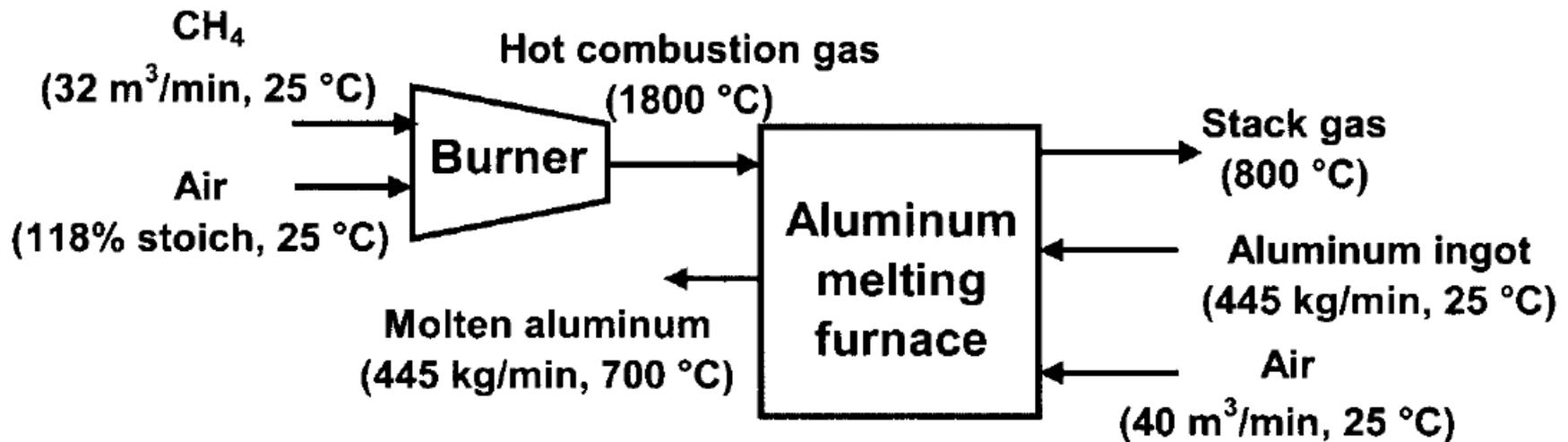
$$\Delta H_{Cu} + \Delta H_{N_2} = n_{Cu} \cdot [H_{Cu,120^{\circ}C}^{\circ} - H_{Cu,1150^{\circ}C}^{\circ}] + n_{N_2} \cdot [H_{N_2,85^{\circ}C}^{\circ} - H_{N_2,25^{\circ}C}^{\circ}] = 0$$

$$472.07 \cdot [2.367 - 44.978] + n_{N_2} \cdot [1.749 - 0] = 0$$

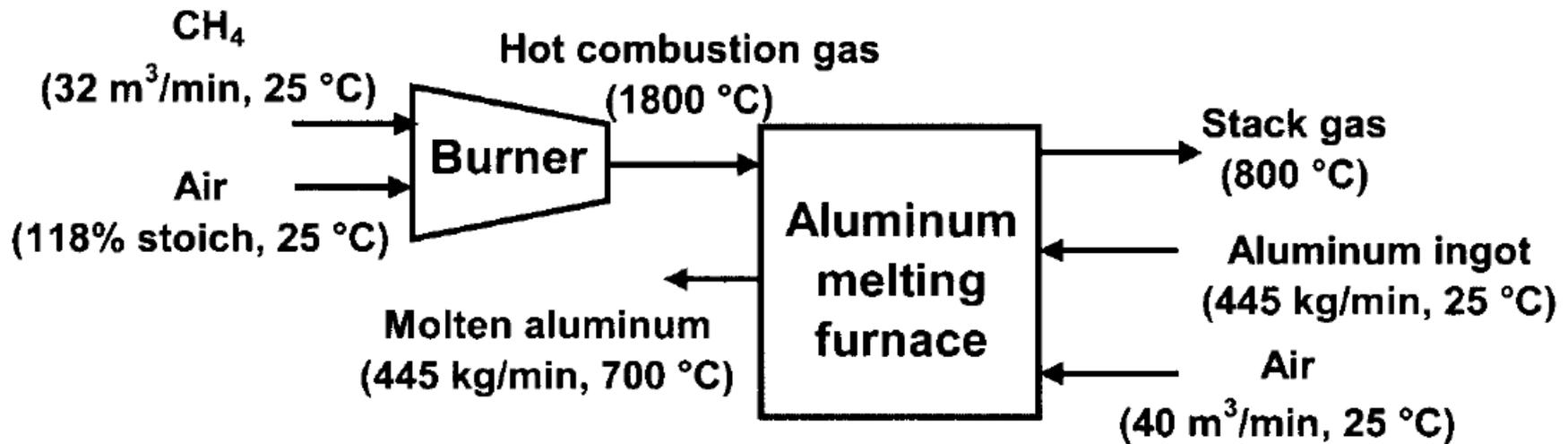
$$n_{N_2} = 11501,07 \text{ mol/min} \rightarrow V_{N_2} = 257.62 \text{ m}^3/\text{min}$$

Example: Melting Aluminum

- A continuous aluminum melting furnace receives ingots via a conveyor system and discharges molten aluminum. Volumes are STP. The furnace is heated by a natural gas burner with CH_4 as the fuel and 118 % of stoichiometric air, and produces a flame temperature of $1800\text{ }^\circ\text{C}$. The furnace design is such that the exit combustion gas goes directly to the stack at $800\text{ }^\circ\text{C}$. Make system balance for the melting furnace, and calculate the heat loss.



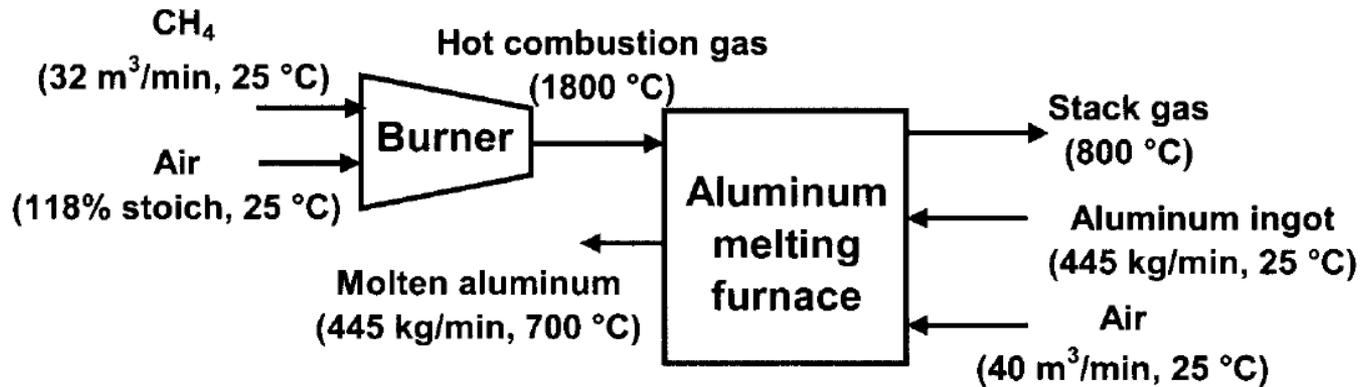
Example: Melting Aluminum



	CH ₄	CO ₂	H ₂ O	O ₂	N ₂
$H_{25^\circ\text{C}}^\circ \text{ kJ/mol}$	-74.600	-393.505	-241.826	0	0
$H_{800^\circ\text{C}}^\circ \text{ kJ/mol}$	-30.372	-356.087	-212.724	25.270	23.869
$H_{1800^\circ\text{C}}^\circ \text{ kJ/mol}$	61.314	-297.623	-164.904	61.973	58.772

	$H_{25^\circ\text{C,Al}}^\circ$	$H_{660.3^\circ\text{C,Al}}^\circ$	$\Delta H_{melting}^\circ$	$H_{660.3^\circ\text{C,Al(l)}}^\circ$	$H_{700^\circ\text{C,Al(l)}}^\circ$
kJ/mol	0	18.144	10.711	28.855	30.116

Example: Melting Aluminum

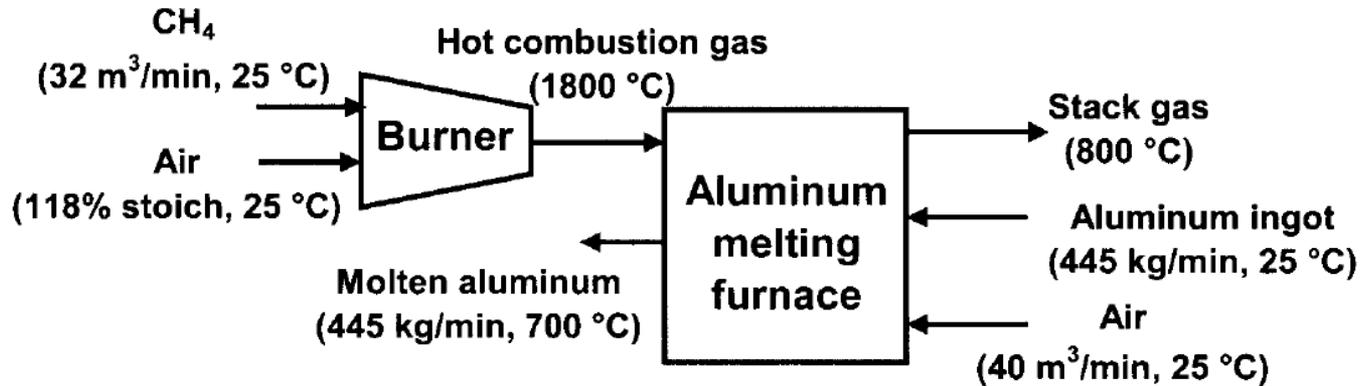


	CH ₄	CO ₂	H ₂ O	O ₂	N ₂
$H_{25^\circ\text{C}}^\circ \text{ kJ/mol}$	-74.600	-393.505	-241.826	0	0
$H_{800^\circ\text{C}}^\circ \text{ kJ/mol}$	-30.372	-356.087	-212.724	25.270	23.869
$H_{1800^\circ\text{C}}^\circ \text{ kJ/mol}$	61.314	-297.623	-164.904	61.973	58.772
$H_{1800^\circ\text{C}}^\circ - H_{25^\circ\text{C}}^\circ \text{ kJ/mol}$	135.914	95.882	76.912	61.973	58.772
$H_{800^\circ\text{C}}^\circ - H_{1800^\circ\text{C}}^\circ \text{ kJ/mol}$	-91.686	-58.464	-47.820	-36.703	-34.903
$H_{800^\circ\text{C}}^\circ - H_{25^\circ\text{C}}^\circ \text{ kJ/mol}$	44.228	37.418	29.102	25.270	23.869

#1 Burner balance

#2 Melting Furnace Balance

Example: Melting Aluminum



#1 Burner balance

$$\Delta H_{rxn,25^\circ\text{C}} = -1146508,85 \text{ kJ/min}$$

$$H_{1800^\circ\text{C}}^\circ - H_{25^\circ\text{C}}^\circ = 1134027,85 \text{ kJ/min}$$

$$\Delta H_{Loss} = 12481 \text{ kJ/min}$$

#2 Melting Furnace Balance

$$\Delta H_{gases} = [H_{800^\circ\text{C}}^\circ - H_{1800^\circ\text{C}}^\circ]_{\text{combustion gas}} + [H_{800^\circ\text{C}}^\circ - H_{25^\circ\text{C}}^\circ]_{\text{air}} = -638550,25 \text{ kJ/min}$$

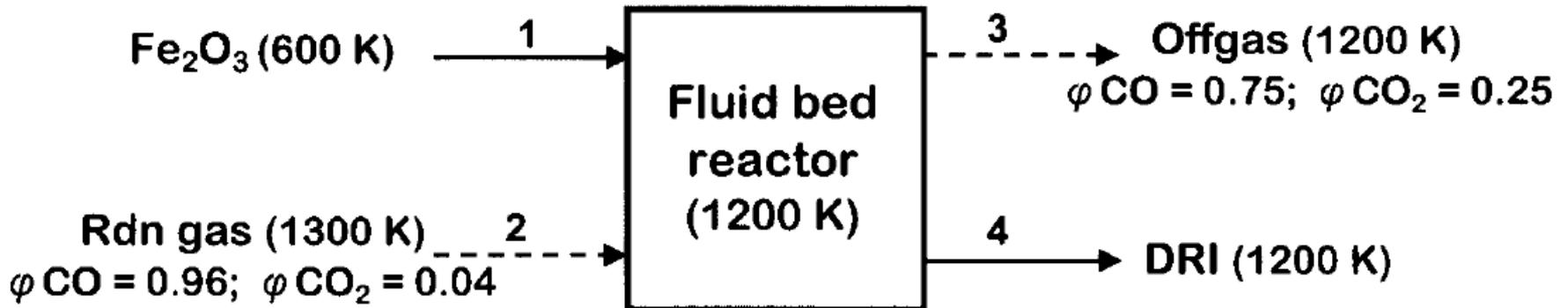
$$\Delta H_{Al} = [H_{660,3^\circ\text{C}}^\circ - H_{25^\circ\text{C}}^\circ]_{\text{Solid Al}} + [\Delta H_{melting}^\circ]_{660,3^\circ\text{C}} + [H_{700^\circ\text{C}}^\circ - H_{660,3^\circ\text{C}}^\circ]_{\text{Liq. Al}} =$$

$$\Delta H_{Al} = 496724,27 \text{ kJ/min}$$

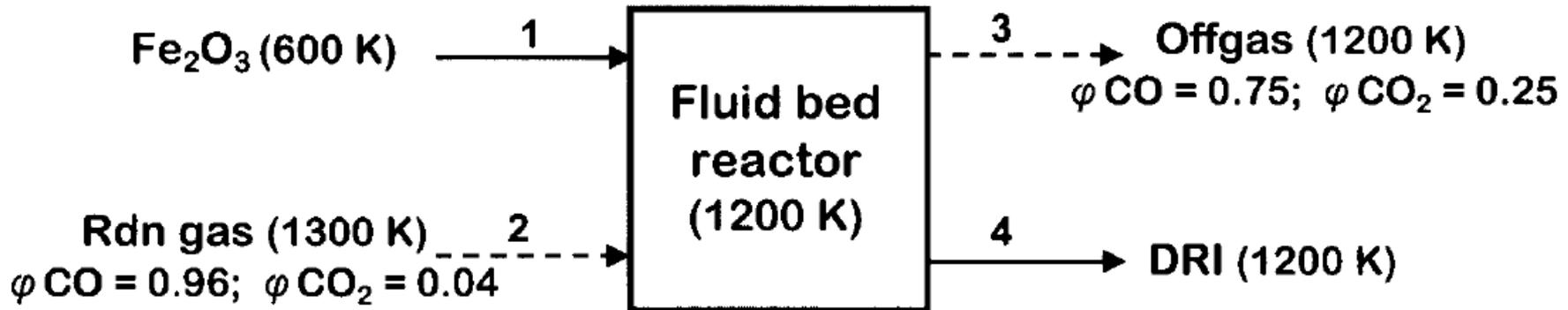
$$\Delta H_{Loss} = 141825,98 \text{ kJ/min}$$

Example: DRI process

- a DRI producer that uses a CO-rich gas to reduce Fe_2O_3 to iron in a fluidized bed reactor at 1200 K. Figure shows a sketch of the process. In order to assure complete reduction of the Fe_2O_3 , the minimum amount of CO in the offgas at 1200 K is 75%. The heat loss is 11 kJ/mol of Fe_2O_3 reduced. Calculate the amount of reduced gases and complete the heat balance.



Example: DRI process



$$H_{\text{CO}_2,1200\text{K}}^\circ = -349.006 \text{ kJ/mol}$$

$$H_{\text{CO}_2,1300\text{K}}^\circ = -343.328 \text{ kJ/mol}$$

$$H_{\text{CO},1200\text{K}}^\circ = -78.612 \text{ kJ/mol}$$

$$H_{\text{CO},1300\text{K}}^\circ = -82.108 \text{ kJ/mol}$$

$$H_{\text{Fe}_2\text{O}_3,600\text{K}}^\circ = -785.357 \text{ kJ/mol}$$

$$H_{\text{Fe}_2\text{O}_3,1200\text{K}}^\circ = -694.881 \text{ kJ/mol}$$

$$H_{\text{Fe},1200\text{K}}^\circ = 35.119 \text{ kJ/mol}$$

- #1 Heating of Fe_2O_3 from 600K to 1200K
- #2 Cooling of Rdn gas from 1300K to 1200K
- #3 Chemical Reaction at 1200K
- #4 Heat Loss

$$\Delta H_{\#1} = 90.476 \text{ kJ}$$

$$\Delta H_{\#2} = -50.057 \text{ kJ}$$

$$\Delta H_{\#3,rxn} = -35.575 \text{ kJ}$$

$$\Delta H_{\#4,loss} = 11.000 \text{ kJ}$$

$$\sum H = 15.844 \text{ kJ/molFe}_2\text{O}_3$$

Next Week

- **Mid-Term II**
- **Group HWs Deadline Apr. 28th, 2016**