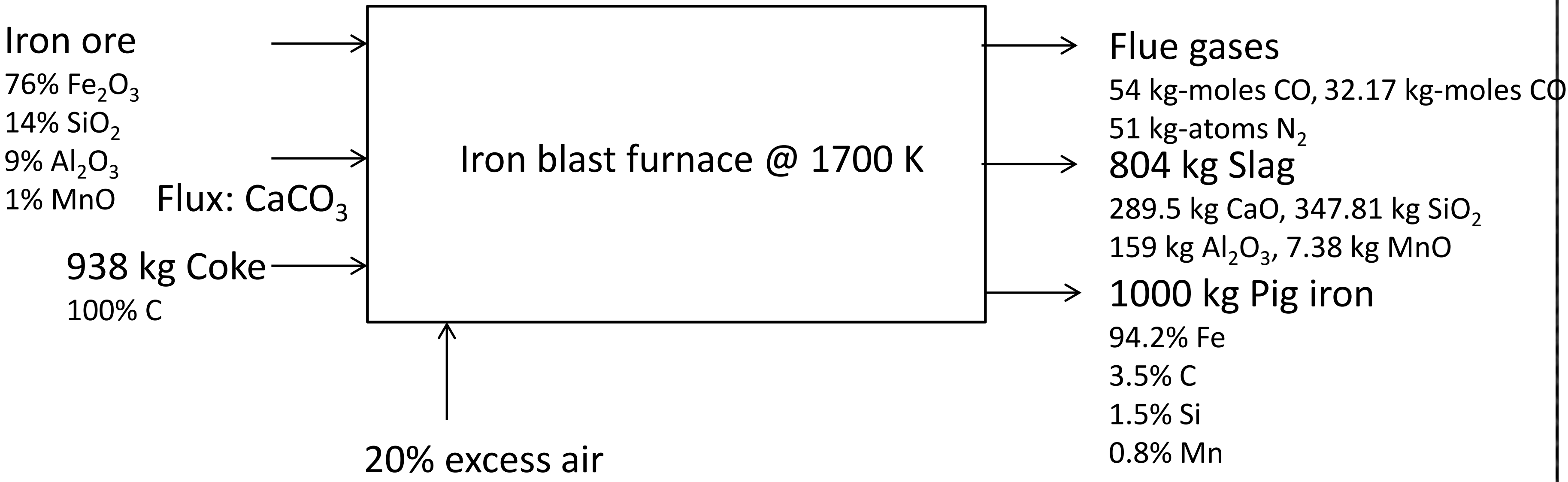
Materials and Energy Balance

Energy Saving

An ironmaking process



Iron ore
76% Fe_2O_3
14% SiO_2
9% Al_2O_3
1% MnO

Flux: $CaCO_3$

938 kg Coke
100% C

Iron blast furnace @ 1700 K

20% excess air

Flue gases
54 kg-moles CO, 32.17 kg-moles CO_2,
51 kg-atoms N_2

804 kg Slag
289.5 kg CaO, 347.81 kg SiO_2
159 kg Al_2O_3, 7.38 kg MnO

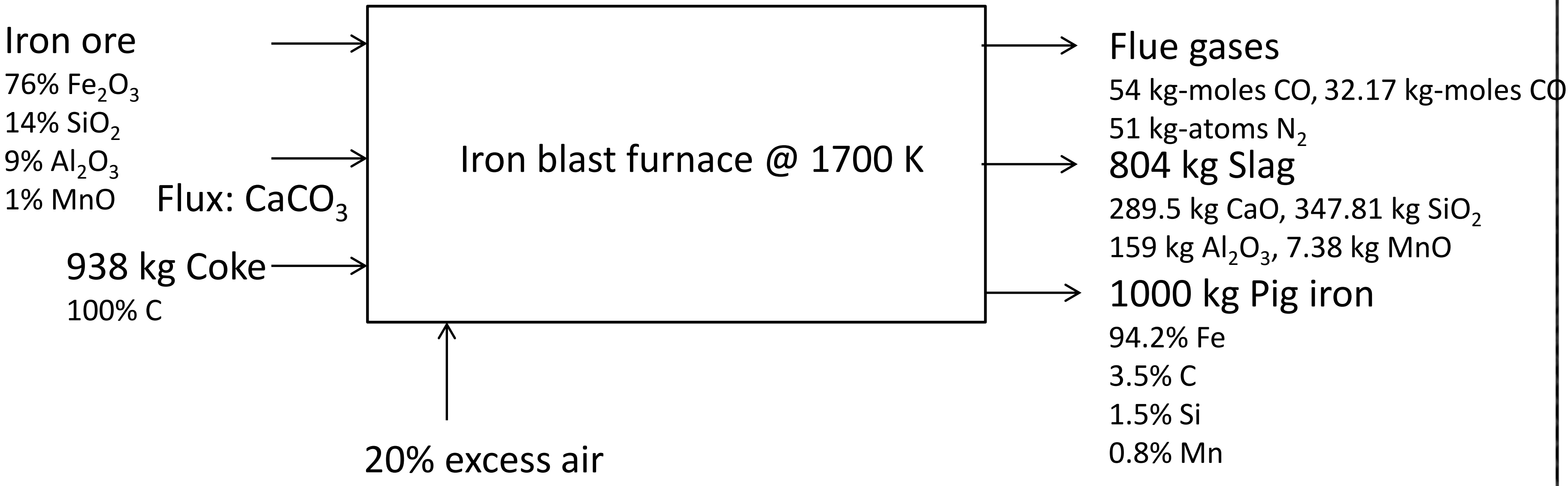
1000 kg Pig iron
94.2% Fe
3.5% C
1.5% Si
0.8% Mn

The hourly or daily averages of the inputs and outputs are recorded so that it is possible to make adjustments on the amounts of the fuel and air to increase the efficiency of the process

The operating temperature and the amounts of the main outputs of the process are the goal and they are strictly non-variable

The efficiency of the furnace can be improved by decreasing the fuel consumption and heat recycling

First thing to do before the heat balance is to obtain the fuel consumption rate so the total heat requirement of the furnace and the net available heat by combustion of the fuel are required



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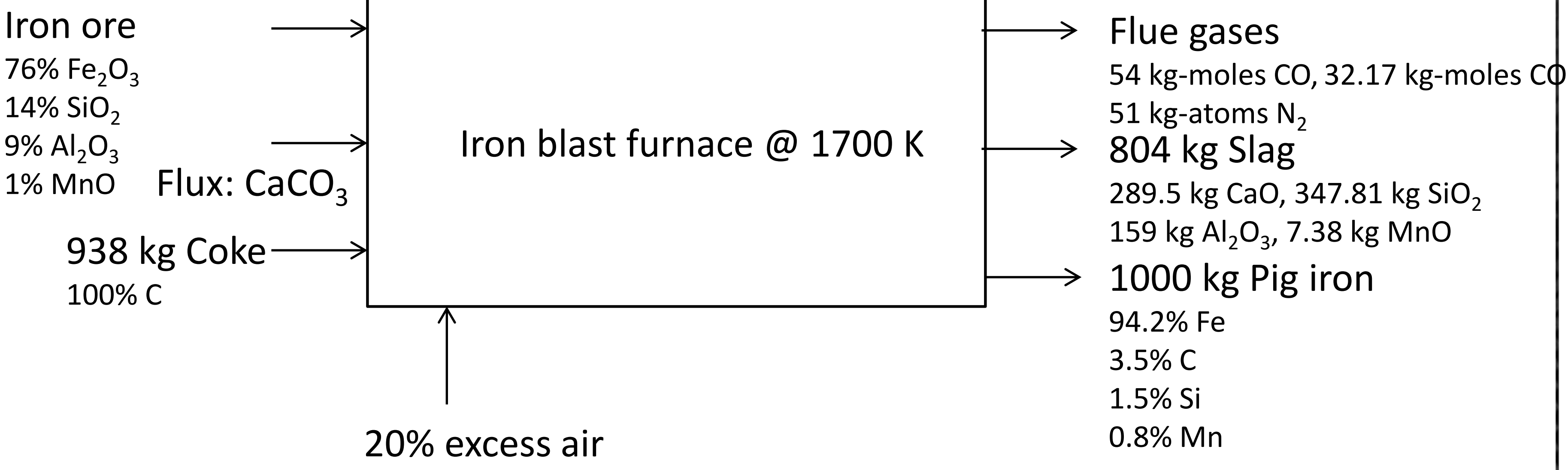
Consider these averages as the hourly production and consumption rate of the furnace
Given fuel consumption: 938 kg/hour

The products of combustion (POC) are CO_2, CO and N_2 according to the combustion reaction:
$C + 2/3O_2 + 2.5N_2 = 2/3CO + 1/3CO_2 + 2.5N_2$ $\Delta H = -49000$ kcal/kg-mole C

CO_2 coming from the decomposition of limestone = 5.17 kg-moles
Oxygen entering the reaction from the oxides = 40.43 kg-atoms
Oxygen entering the reaction from the air = 13.57 kg-atoms
Nitrogen passing through the furnace = 13.57*(79/21)= 51 kg-atoms



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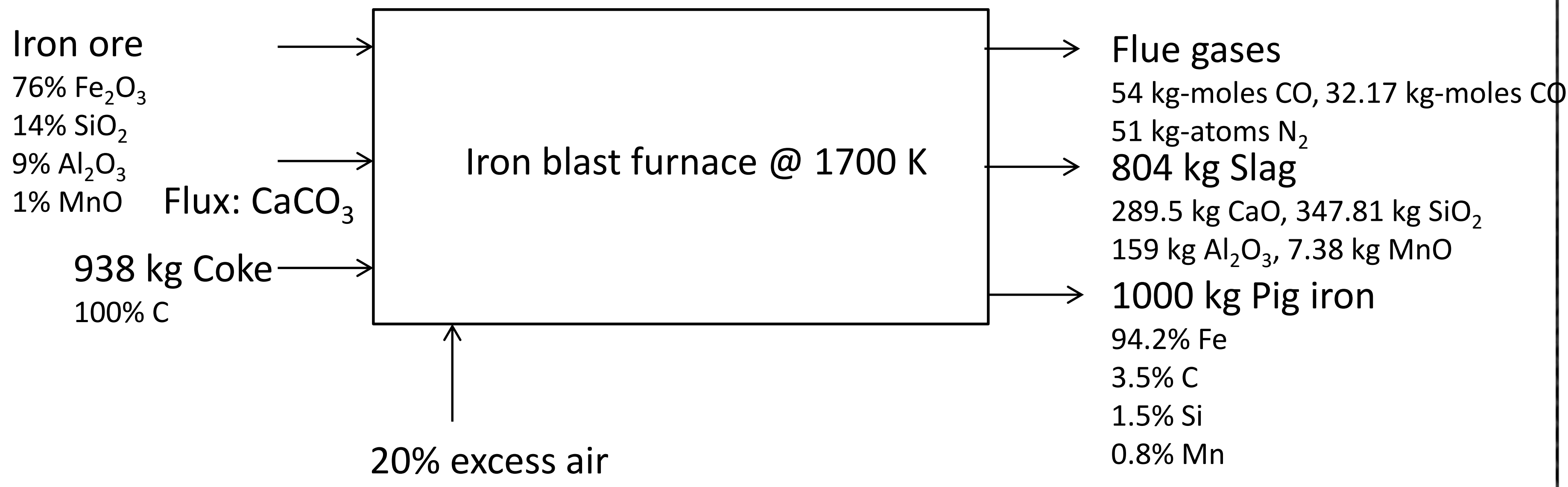
The net available heat from the fuel combustion is the difference between the total heat evolved from the combustion and the heat absorbed by the POC

Total heat evolution by 1 kg fuel= $n_C * \Delta H = (1/12) * (-49000) = 4083$ kcal/kg fuel

Heat absorption by the POC = $n_{CO} * (H_{1700}-H_{298})_{CO} + n_{CO2} * (H_{1700}-H_{298})_{CO2} + n_{N2} * (H_{1700}-H_{298})_{N2}$
$= 0.056*(17500) + 0.028*(10930) + 0.208*(10860) = 3544$ kcal/kg fuel

Net available heat = 4083– 3544 = 539 kcal/kg fuel

An ironmaking process



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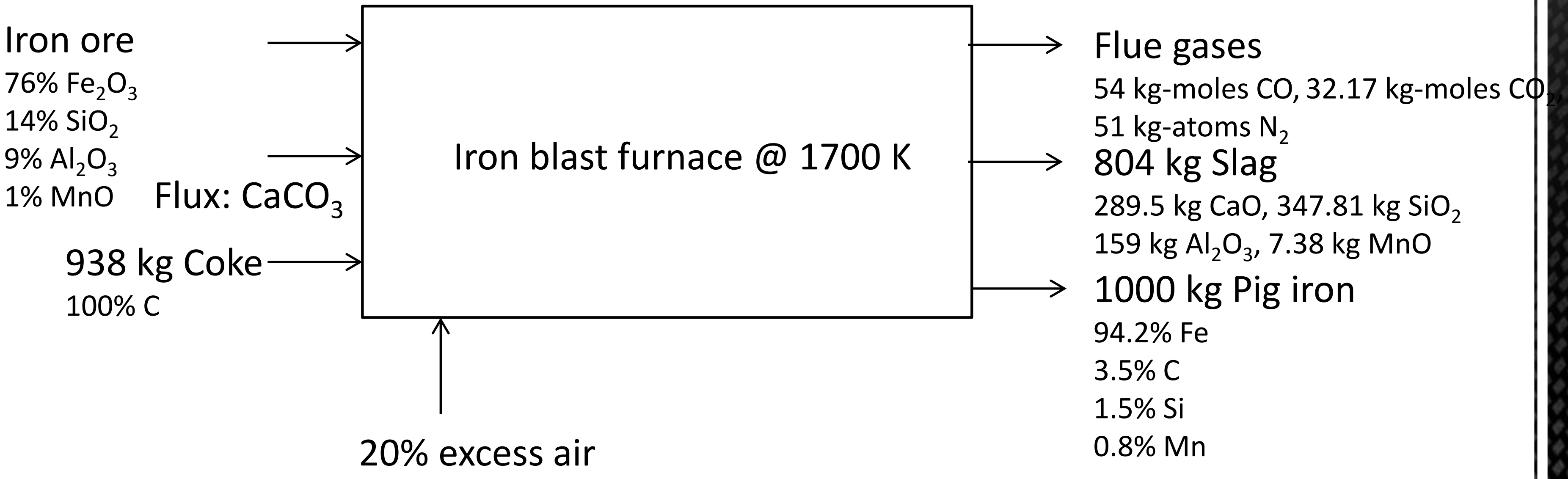
Total heat requirement is calculated by taking the products of the process – not combustion – and the endothermic reactions into account
Pig iron production = 1000 kg/hour
Slag production = 804 kg/hour

Heat requirement by the slag = $n_{CaO}*(H_{1700}-H_{298})_{CaO}+n_{SiO2}*(H_{1700}-H_{298})_{SiO2}+n_{Al2O3}*(H_{1700}-H_{298})_{Al2O3}$
$+n_{MnO}*(H_{1700}-H_{298})_{MnO}$
= 289.5/56*(17440) + 347.81/60*(22750) + 159/102*(40100) + 7.38/71*(19000) = 286520 kcal

Heat requirement by the pig iron = $n_{Fe}*(H_{1700}-H_{298})_{Fe}+n_C*(H_{1700}-H_{298})_C+n_{Si}*(H_{1700}-H_{298})_{Si}$
$+n_{Mn}*(H_{1700}-H_{298})_{Mn}$ + Heat of mixing
= 942/56*(13000) + 35/12*(6740) + 15/28*(9000) + 8/55*(12000) = 244904 + 7500 = 252404 kca

An ironmaking process



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$CaCO_3 = CaO + CO_2$ Heat requirement = 219725 kcal

$Fe_2O_3 + 3CO = 2Fe + 3CO_2$ Heat requirement = 986266 kcal

$SiO_2 + 2CO = Si + 2CO_2$ Heat requirement = 79400 kcal

Total heat requirement of the process = 286520 + 252404 + 219725 + 986266 + 79400 = 1824315 kcal/hour

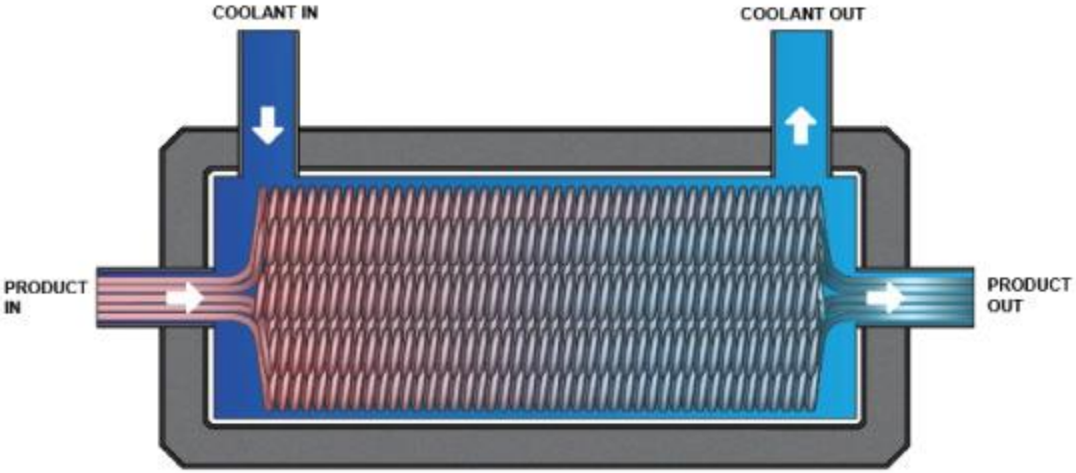
Net available heat = 1945 kcal/kg fuel

$$Theoretical\ fuel\ consumption = \frac{Total\ heat\ requirement}{Net\ heat\ given\ by\ 1\ kg\ fuel} = \frac{1824315}{1945}$$

$$= 938\ \frac{kg\ fuel}{hour}$$

How can energy be saved?

- Minimize heat losses by constructing a well isolated refractory wall
- Minimize heat absorptions by the products
  - Preheat the gases in combustion air that absorb sensible heat in the furnace with heat recovered from flue gases by installing heat exchanger next to the furnace



  - Reduce the nitrogen amount in the combustion gas by blowing oxygen

Minimizing heat losses by constructing a well isolated refractory wall

The heat losses from the furnace walls can be calculated in two ways:

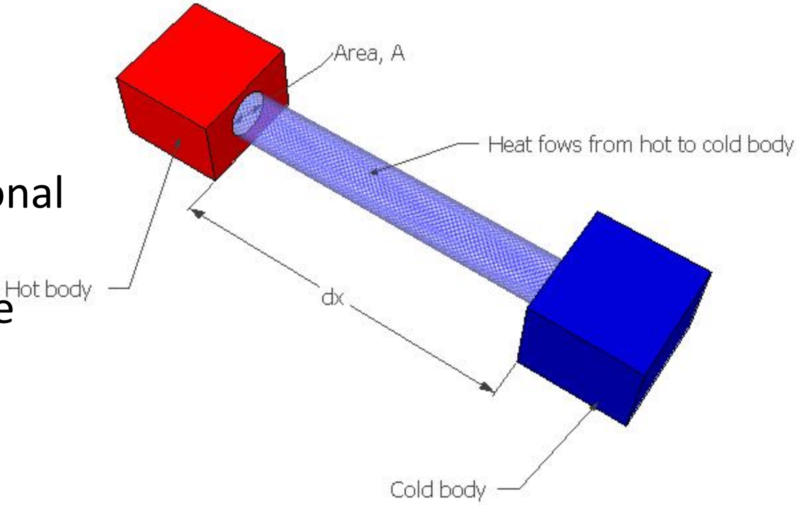
a) Energy balance

Heat loss = Heat Input – Heat Output

b) Fourier’s law

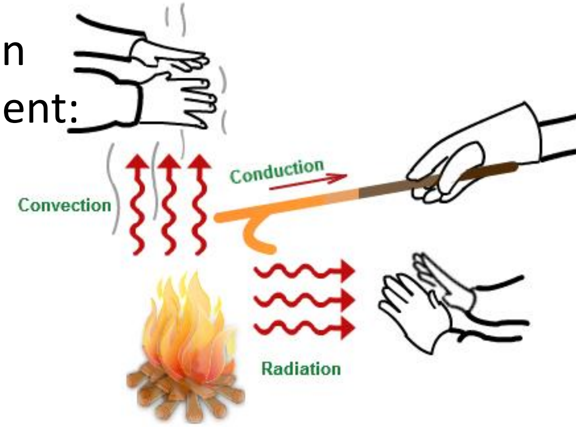
Heat flow rate for one-dimensional heat transfer between a hot and a cold body connected by a long rod made of a conducting material is proportional to the cross sectional area, temperature difference, thermal conductivity of the material and the inverse of linear distance:

$$q_x = kA\frac{dT}{dx}$$



Heat flow rate for one-dimensional heat transfer through convection is proportional to the surface area of the object, convection coefficient:

$$q = hAdT$$



The resistance of an insulating wall to the heat transfer is related to material properties:

For conduction

$$R_{cond} = \frac{T_{s1} - T_{s2}}{q_x} = \frac{L}{kA}$$

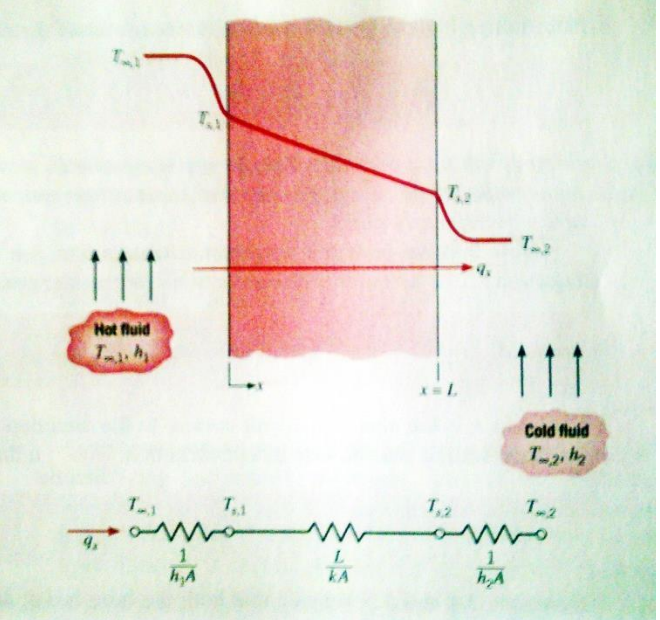
For convection

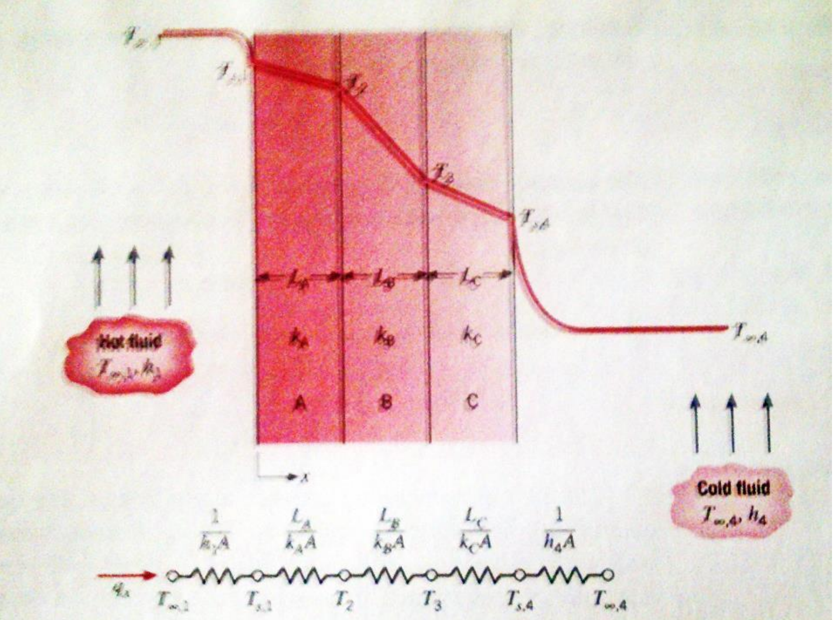
$$R_{conv} = \frac{T_s - T_\infty}{q} = \frac{1}{hA}$$

For radiation

$$R_{rad} = \frac{T_1 - T_{sur}}{q} = \frac{1}{h_r A}$$

The thermal resistances of walls for single and composite insulating walls are given as follows





Consider the refractory wall around a furnace operating at 1500 K
Calculate the heat lost by conduction through an alumina wall with surface area of 10 m^2 and refractory thickness of 0.1 m

$$q_x = kA\frac{\Delta T}{\Delta x}$$

$$q_x = 40 * 10 * \frac{1500 - 300}{0.1} = 4800\ kJ/s$$

Calculate the heat lost by conduction through a composite alumina-magnesia wall with surface area of 10 m^2 and thickness of 0.1 m for each refractory material

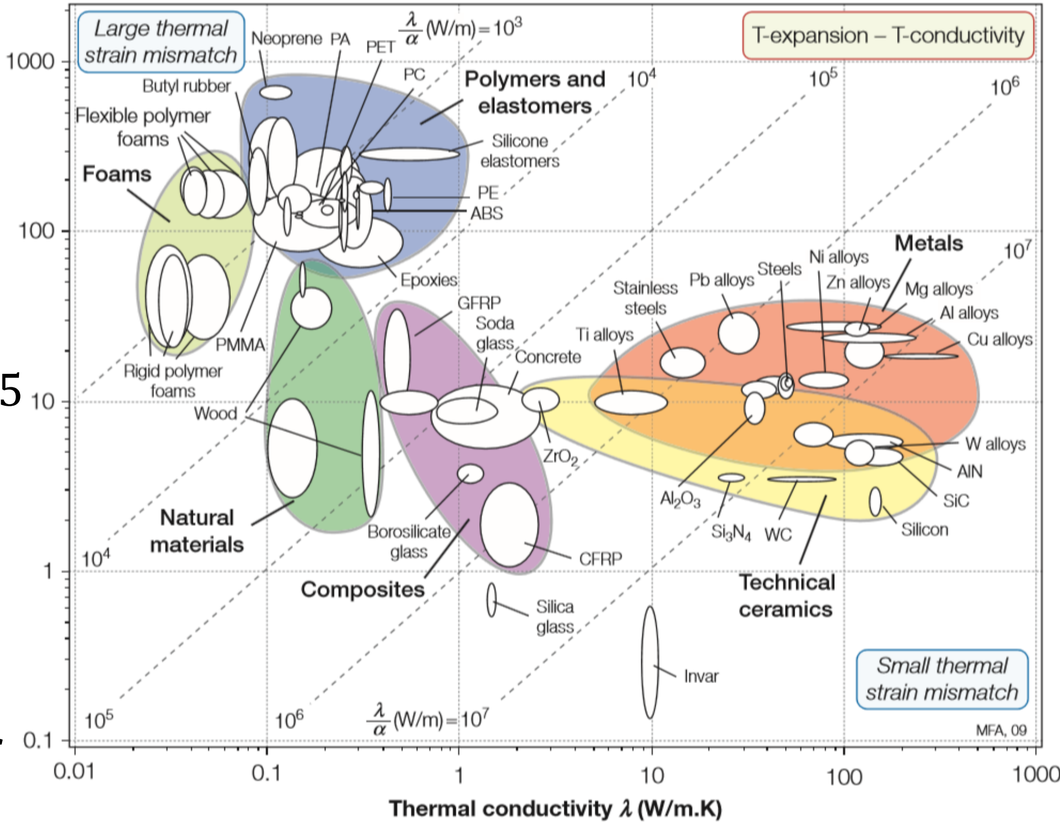
$$R_{cond} = \frac{\Delta x}{kA}$$

$$R_{tot} = \frac{L_{Al}}{k_{Al}A} + \frac{L_{Zr}}{k_{Zr}A}$$

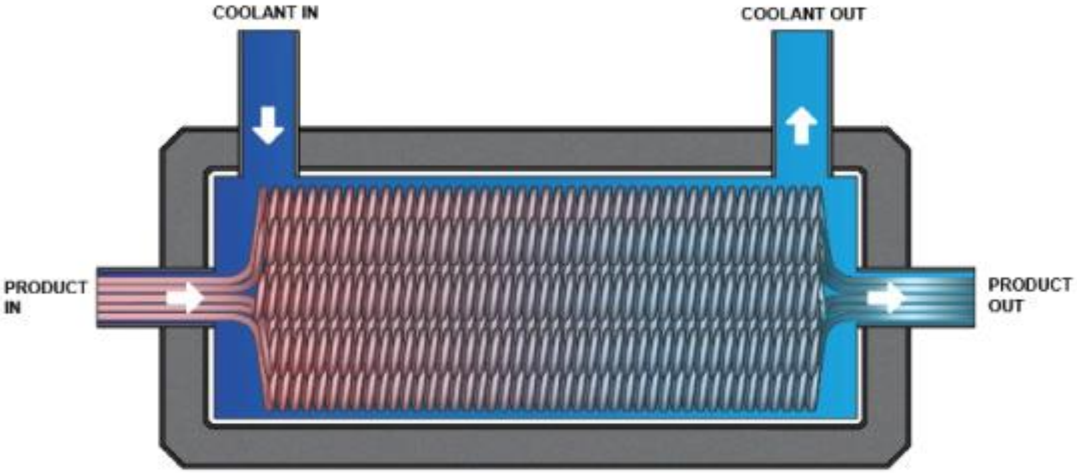
$$R_{tot} = \frac{0.1}{40 * 10} + \frac{0.1}{2 * 10} = 0.00525$$

$$q_x = \frac{\Delta T}{R_{tot}}$$

$$q_x = \frac{1500 - 300}{0.00525} = 228.5\ kJ/s$$



Heat exchangers



Heat exchangers are tanks containing two currents of fluids flowing in thermal equilibrium with each other in order to transfer the sensible heat in the hot fluid to the cold fluid which is utilized in the primary process

Thermal efficiency of the heat exchanger depends on

- The flow rates of the currents
- The heat conductivity and surface area of the separating material
- The difference in the heat capacities of the fluids

$$\text{Thermal efficiency} = \frac{Sensible\ heat\ in\ heated\ air}{Sensible\ heat\ in\ the\ hot\ flue\ gases} * 100$$

$$\text{Efficiency limit} = \frac{Sensible\ heat\ in\ air\ heated\ to\ hot\ flue\ gas\ temperature}{Sensible\ heat\ in\ the\ hot\ flue\ gases} * 100$$

$$= \frac{(n_{O2} * Cp_{O2} + n_{N2} * Cp_{N2}) * \Delta T}{(n_{CO} * Cp_{CO} + n_{N2} * Cp_{N2} + \sum n_i * Cp_i) * \Delta T} * 100$$

Example – A heat exchanger receives hot flue gas at 1600 K and cold air at 298 K. The heated air leaves the exchanger at 1400 K and flue gas leaves at 298 K. The flue gas contains 45.87 kg-moles CO, 28.1 kg-moles CO_2, and 20.58 kg-atoms N_2. Air contains 18 kg-atoms O_2 and 67.8 kg-atoms N_2. 10% of the heat in flue gases is lost to the surrounding.
$Cp_{CO} \approx 6.79$ cal/mol.K, $Cp_{CO2} \approx 10.56$ cal/mol.K, $Cp_{O2} \approx 7.16$ cal/mol.K, $Cp_{N2} \approx 6.66$ cal/mol.K

$$\text{Efficiency limit} = \frac{(n_{O2} * Cp_{O2} + n_{N2} * Cp_{N2})}{(n_{CO} * Cp_{CO} + n_{CO2} * Cp_{CO2} + n_{N2} * Cp_{N2})}$$

$$\text{Thermal efficiency} = \frac{(n_{O2} * Cp_{O2} + n_{N2} * Cp_{N2}) * (1400 - 298)}{(n_{CO} * Cp_{CO} + n_{CO2} * Cp_{CO2} + n_{N2} * Cp_{N2}) * (1600 - 298)}$$

Capturing and reusing the sensible heat in the products of combustion

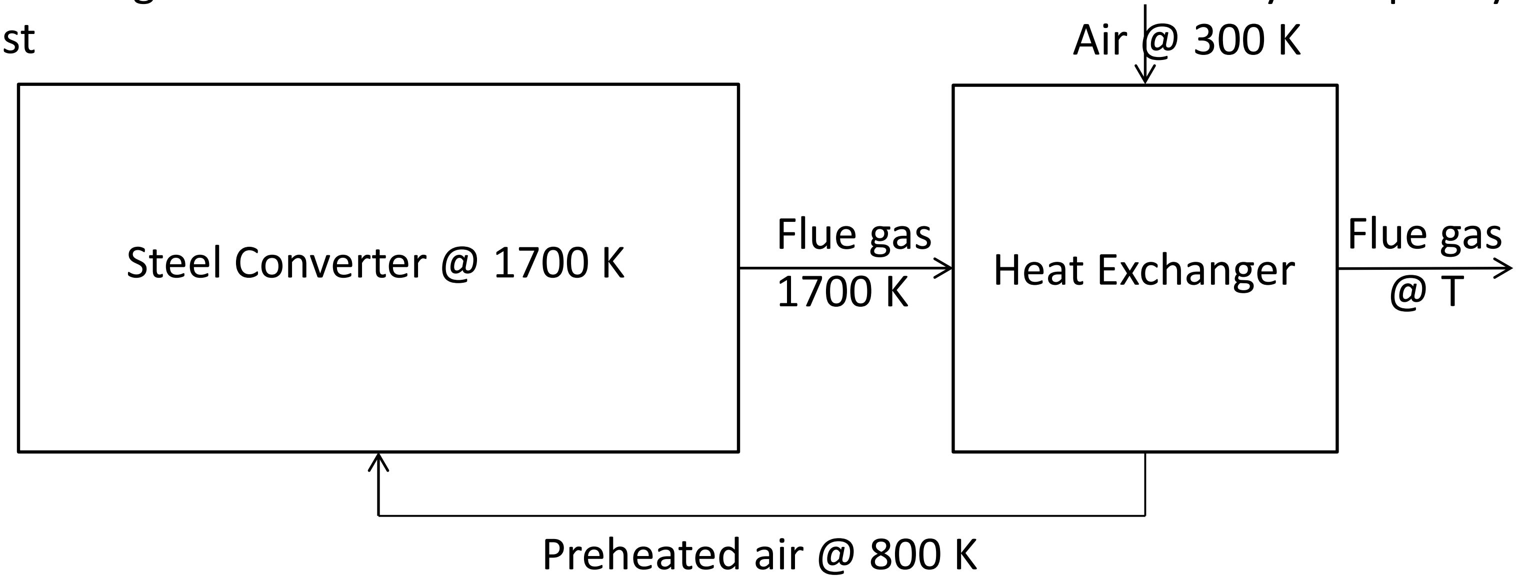
In integrated steel foundries where liquid steel is produced from pig iron, rolled and shaped into products, the heat given to the steel in the furnace is subsequently utilized in shaping mills

Molten slag also produces glassy phases which are utilized in cement and ceramic industries

Only the heat lost to the hot flue gases is not commonly utilized in steel foundries

Efficiency of steel production processes are increased by coupling the furnace with a heat exchanger so that the heat lost to the flue gases are reused by blowing back the heated air

The heat exchanger costs an initial investment but the increase in efficiency will quickly pay for the cost



Air @ 300 K

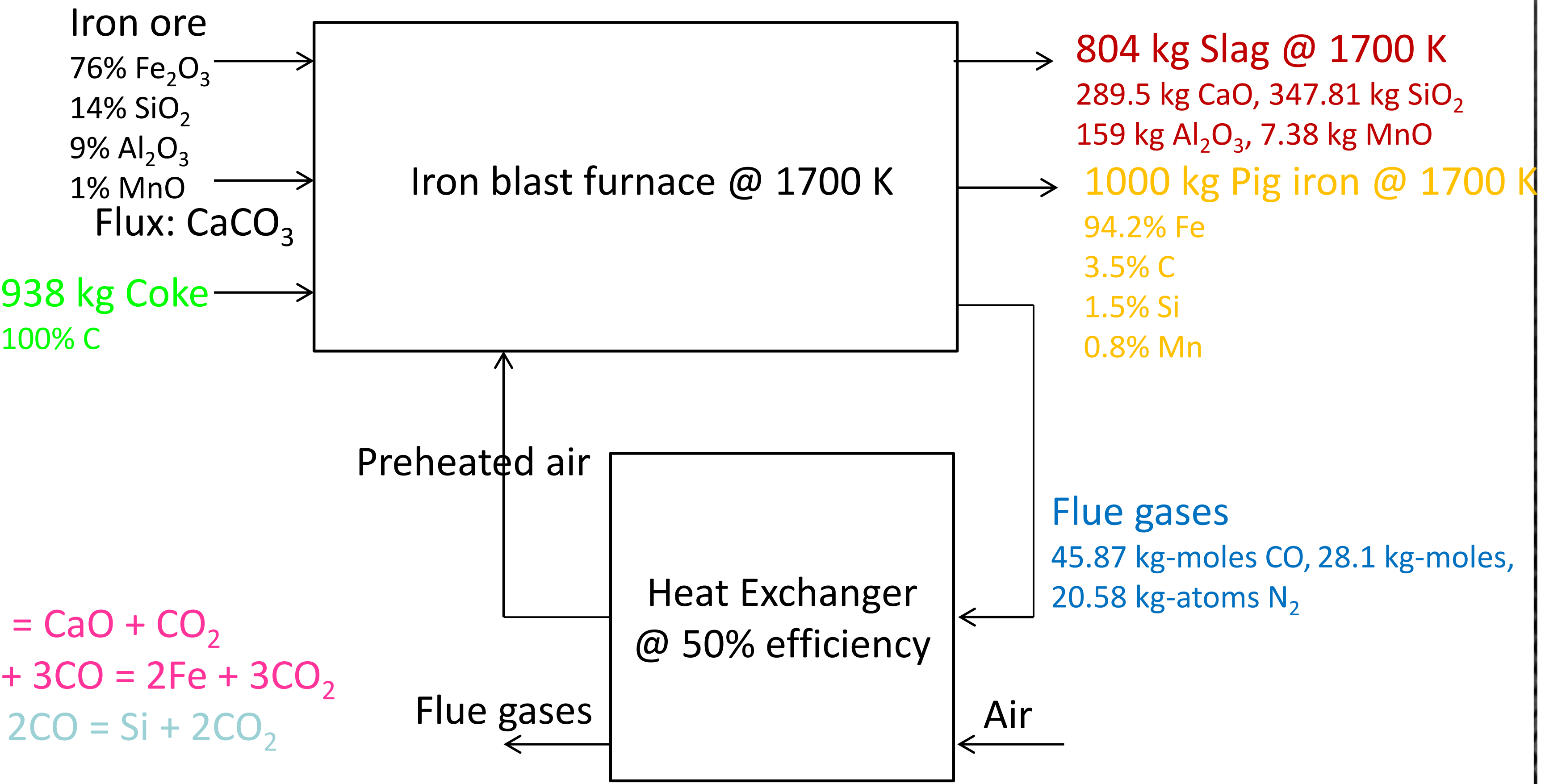
Steel Converter @ 1700 K

Flue gas
1700 K

Heat Exchanger

Flue gas
@ T

Preheated air @ 800 K



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938 kg Coke
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1000 kg Pig iron @ 1700 K
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0.8% Mn

Preheated air

Heat Exchanger
@ 50% efficiency

Flue gases
45.87 kg-moles CO, 28.1 kg-moles,
20.58 kg-atoms N_2

Flue gases

Air

$CaCO_3 = CaO + CO_2$
$Fe_2O_3 + 3CO = 2Fe + 3CO_2$
$SiO_2 + 2CO = Si + 2CO_2$

Total heat requirement of the process = 286520 + 252404 + 219725 + 986266 + 79400 = 1824315 kcal/hour

Net available heat = 3593– 1648 = 1945 kcal/kg fuel

Heat Input per hour
Heat from combustion = 3593 * F
Heat from heat recycling = 0.5 * 1648 * F
2769 * F = 1824315
F = 659 kg fuel

Heat Output per hour
Heat to iron + slag + reactions = 1824315 kcal
Heat to POC = 1648 * F

Amount of fuel saved = 938-659 = 279 kg

The heat exchanger operating at 50% efficiency takes about half of the sensible heat in the flue gases and transfers it to air that is blown into the furnace

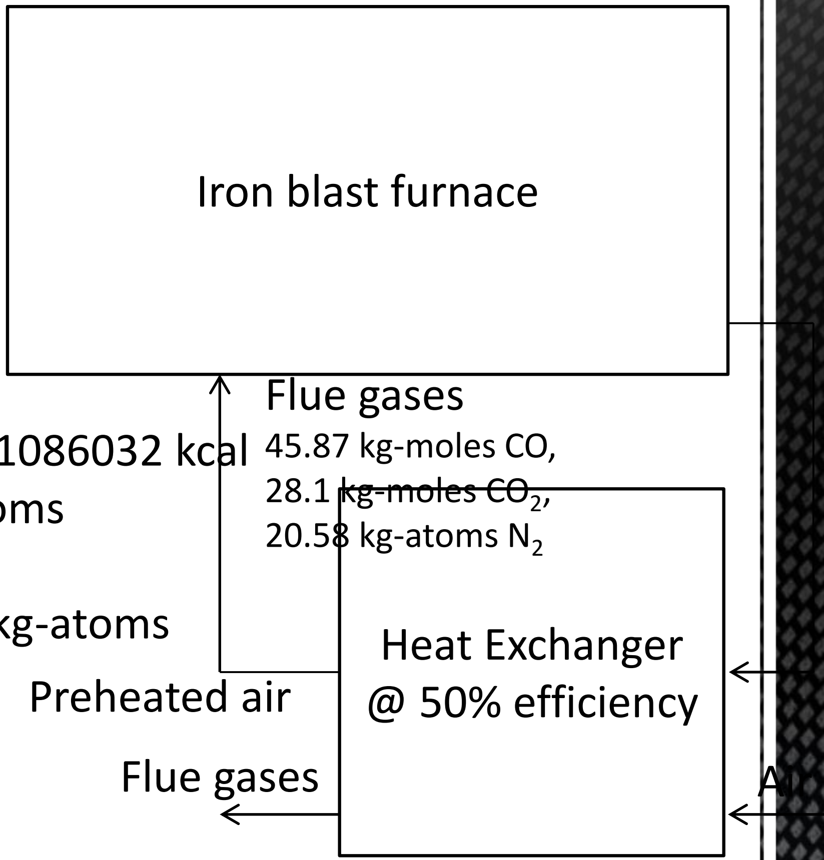
The temperature of the preheated air depends on the sensible heat in the flue gases and the efficiency

Example – Sensible heat in the flue gases = 1648 * F = 1086032 kcal
Carbon in the coke = 938*0.88 = 825.4 kg = 68.8 kg-atoms
Oxygen needed = 2/3*68.8 = 45.9 kg-atoms
Oxygen entering the reaction from the oxides = 40.43 kg-atoms

Air needed in one hour = 20.58 kg-atoms N_2
5.47 kg-atoms O_2

Sensible heat in the preheated air = η * 1648 * F
= 0.5 * 1648 * 938 = 772912 kcal
= $n_{N2} * H_T\text{-}H_{298}(N_2) + n_{O2} * H_T\text{-}H_{298}(O_2)$

Sensible heat in the cooled gases = (1-η) * 1648 * F
= 0.5 * 1648 * 938 = 772912 kcal
= $n_{CO} * H_T\text{-}H_{298}(CO) + n_{CO2} * H_T\text{-}H_{298}(CO_2)$
$+ n_{N2} * H_T\text{-}H_{298}(N_2)$



Iron blast furnace

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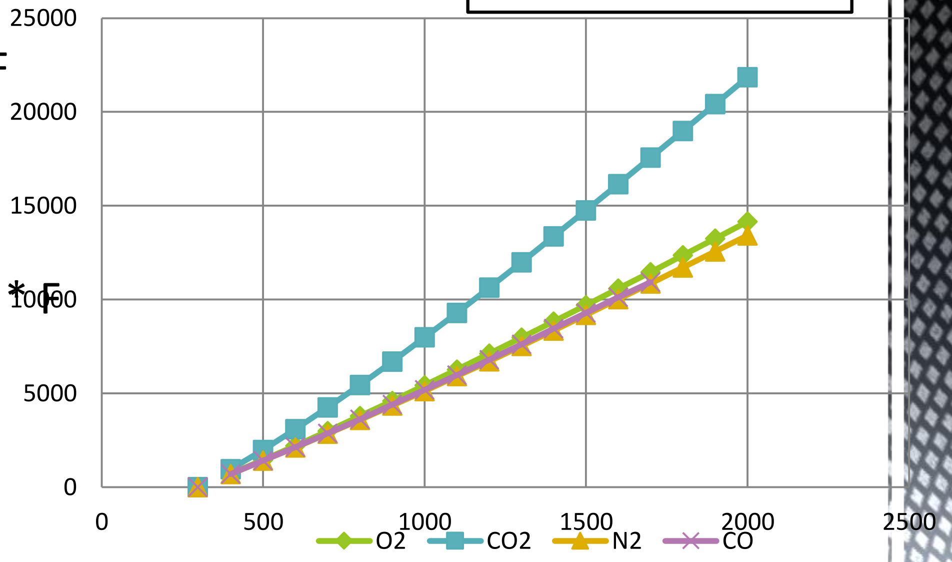
Heat Exchanger
@ 50% efficiency

Preheated air

Flue gases

Ai



Blowing pure oxygen into the furnace

Alternative to installing a heat exchanger and reusing the sensible heat in the flue gas is to cut the heat absorption by the flue gases by removing some of the N_2 that takes away heat

Excess oxygen amount is added in pure state in this case to the theoretically consumed air

Example – What is the amount of Oxygen in kg per hour to obtain same fuel consumption as in the previous example with heat exchanger:

Heat Input per hour	Heat Output per hour
Heat from combustion = 3593 * F	Heat to iron + slag + reactions = 1824315 kcal
Heat from heat recycling = 0.5 * 1648 * F	Heat to POC = 1648 * F

Total heat evolution by 1 kg fuel= n_C * ΔH = 1*0.88*(1/12) * (-49000) = 3593 kcal/kg fuel
Heat absorption by the POC = 1648 kcal/kg fuel
Modified heat absorption by the POC = 1648/2 = 824 kcal/kg fuel
$824 = 3.76 n_{O2} * 11465$
n_{O2} = 0.019 kg-atoms/kg fuel
0.019 * 938 = 17.82 kg-atoms pure O_2 is added, removing 3.76 * 17.82 = 67 kg-atoms N_2

There were 20.58 kg-atoms N_2 in the furnace so all of the air is replaced by oxygen added in the ratio of 20.58(21/79) = 5.47 kg-atoms

Initial flue gas composition: 45.87 kg-moles CO, 28.1 kg-moles CO_2, 20.58 kg-atoms N_2

Initial reaction:
$C + 2/3O_2 + 2.5N_2 = 2/3CO + 1/3CO_2 + 2.5N_2$

Heat absorption by the POC = $n_{CO} * (H_{1700}-H_{298})_{CO} + n_{CO2} * (H_{1700}-H_{298})_{CO2} + n_{N2} * (H_{1700}-H_{298})_{N2}$
= 0.05*(17500) + 0.025*(10930) + 0.046*(10860) = 1648 kcal/kg fuel

Modified flue gas composition with pure oxygen blowing: 45.87 kg-moles CO, 28.1 kg-moles CO_2

Modified reaction:
$C + 2/3O_2 = 2/3CO + 1/3CO_2$
Modified heat absorption by the POC = $n_{CO} * (H_{1700}-H_{298})_{CO} + n_{CO2} * (H_{1700}-H_{298})_{CO2} + n_{N2} * (H_{1700}-H_{298})_{N2}$
= 0.05*(17500) + 0.025*(10930) = 1148.25 kcal/kg fuel

The modified reaction is an incomplete combustion

Additional amount of oxygen should completely combust all carbon

Fully combusting the fuel

Previous modified reaction:
$C + 2/3O_2 = 2/3CO + 1/3CO_2$ ΔH= -49000 kcal/kg-atom C
Heat evolution by partial combustion:
ΔH= 68.8*(-49000) = -3371200 kcal

The additional O_2 combusts the remaining CO in the furnace
$CO + ½ O_2 = CO_2$ ΔH= -67760 kcal/kg-atom CO
CO remaining in the furnace = 45.87 kg-moles
Heat evolution from complete combustion with the additional O_2:
ΔH= 45.87*(-67760) = -3108151 kcal

Total combustion reaction:
$C + O_2 = CO_2$ ΔH= -94000 kcal/kg-atom C
Carbon in the coke = 938*0.88 = 825.44 kg = 68.8 kg-atoms
Oxygen entering the reaction from the oxides = 40.43 kg-atoms
Oxygen required for full combustion = 68.8 – 40.43 = 28.4 kg-atoms
Total O_2 blown = 5.47 + 22.94 = 28.41 kg-atoms
Total heat evolution by combustion:
ΔH= 68.8*(-94000)= -6467200 kcal

Converting 2/3 of carbon to CO produces about half the heat compared to converting all to CO_2