

Energy and mass balances – the main tool for sustainability analyses

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There are a number of thermodynamic analyses that are important for the students to learn as future engineers in the process industry. Two of the basic tools are energy and mass balances, which for many processes we mean enthalpy and mass balances. A sound knowledge of how mass and energy flow in and out of a process is crucial to reducing energy consumption and emissions like CO₂. It is important to incorporate energy and mass balances from an early stage and develop this competence. This paper discusses the combination of enthalpy concept and mass flows for three simplified FeMn processes treating different raw materials. Important parameters like energy consumption and CO₂ emissions are calculated for high oxygen ores and ores giving a better prereduction.

INTRODUCTION

With the transitioning to a more environmentally conscious and sustainable lifestyle (the green shift), most countries in the world have challenging goals both for 2030 and 2050, which requires radical technological changes. This requires engineers with more fundamental knowledge as new processes must be developed, and existing processes must change. It will not be enough 'to do what you did yesterday'. In this aspect advanced thermodynamic analyses of the processes are of course a part of the green shift. Typically, this type of work will be done industrially by experts, and then the process engineers must translate this knowledge into steps for improvement. There are, however, thermodynamic tools that should be used by the process engineers themselves. An example of this is energy and mass balances, over processes and their sub-processes, to optimise their process on a daily basis.

The knowledge of conservation of mass and energy for process engineers is a basic analysing tool. This should be a tool that matures through the students' education. From my experience, this is not the case. In the process engineering disciplines we, as teachers, are inclined to go more in-depth in the thermodynamic areas of equilibrium calculations, like activities, reference states and phase diagrams. Although these are important areas, the focus on more complex concepts tends to push out the simpler thermodynamic analyses of mass and energy.

Within the two areas of circular economy and reducing CO₂ emissions, the main tool is the mass balance of smaller or larger parts of the value chain. The amount of each element in each stream out of the system can be found from thermodynamic equilibrium analyses. Many processes are however not at equilibrium and hence kinetic analyses can show the streams and the element distribution. As many industrial systems have a temperature distribution, both types of analyses can be quite work intensive and in addition, as for most modelling, the answer must be known to get the correct model. A simplified way is to use experimental or industrial mass streams with experimentally determined element distribution directly. An example of this is shown in Figure 1 where the distribution of trace elements in the outstream of metal, off-gas and fume are shown, based on empirical data from an industrial FeSi process¹.

The analyses of the main elements, such as Si, Fe, O and C in a FeSi operation, determine the Si yield and CO₂ emissions. The industrial plants are, however, also obliged by national environmental authorities to control trace elements and their distribution in the outstreams as a strategy to control the elements in the emissions. For many of the trace elements the uncertainty in the analysing and sampling technique is often larger than the total content of an element, and hence the empirical data may have great uncertainties. In this paper we focus on the major elements in the process.

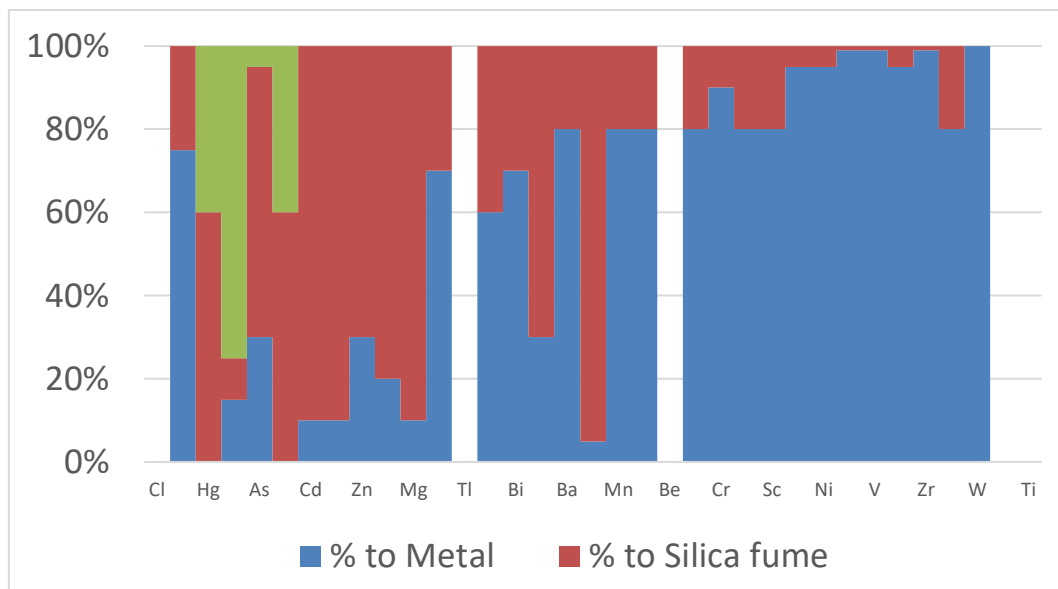


Figure 1. Distribution of elements over a FeSi furnace after Myrhaug 2003¹. Elements are ordered with increasing boiling point.

Energy is also a major part of the sustainability concept, as the production of energy or the storage of energy often has large emissions. Even for energy production with low emissions, such as renewable energy production from solar, wind and hydropower, emissions during the production of equipment must be included. It is of course also a sustainability issue when nature is disturbed during the development of these energy sources. In addition to the sustainability view, there are also many countries where electrical energy is scarce. In summary, all processes will try to minimise energy consumption per ton of material produced, with respect to sustainability and cost. Energy balances are therefore an important tool to minimise energy consumption. It has become an even larger tool when it comes to recycled energy, as heat or as electrical energy.

In this paper, some examples of mass and energy balances are shown. In Norway, after aluminium production, silicon, ferrosilicon and manganese ferroalloy production are the main metal-producing industries. The examples used here fall within FeMn production, showing how raw materials and process conditions change CO₂ emissions and electrical energy consumption. As this case study is meant as teaching examples for graduate students, simplified process conditions are used. Several examples describe more extensive industrial processes²⁻⁵, however the difference between the simplified examples and the more extensive mass balances are quite insignificant.

Mass balances: raw material receipts and CO₂ emission

Example 1: A simplified example of Mn-production with MnO₂ ore

A typical Mn-ferroalloy contains 79% Mn, 14% Fe and 7% C. It will of course also contain minor elements; however, this example excludes them. The outstreams from the process are liquid metal, liquid slag that contains the un-reducible oxides like SiO₂, CaO and unreduced MnO, and the off-gas that contains CO and CO₂ (for a closed furnace). The input raw materials are Mn-ores containing Mn-oxides, Fe-oxides such as Fe₂O₃, some SiO₂, and CaO^{6,7}. This will be mixed with carbon material that contains mainly carbon that survives high temperatures, and for simplicity, we assume that the carbon

material is 100% Fix C, that is 100% C. In this example we will use Mn-ore containing MnO₂ that is, with oxygen to manganese molar content of 2/1 (O/Mn=2/1=2).

Some assumptions about the system are made:

- One works from a reference of 1 ton of metal that is 790 kg Mn, 140 kg Fe and 70 kg C in the metal phase.
- Iron reports to the metal and none to the slag. This is a fair assumption as <0.1% FeO goes into the slag.
- A slag that contains about equal amounts of SiO₂ and CaO, about 40% MnO will stay in the slag phase.

The distribution of Mn, Fe, SiO₂ and CaO is then fixed (see Table 1), according to the assumptions made. The assumptions used in the mass balance may be based on a thermodynamic evaluation (if the system is in thermodynamic equilibrium), by kinetic evaluations, or determined by experimental results.

Table 1. Mass balance of a simplified Mn-ferroalloy process using an MnO₂ ore (Example 1)

Raw materials in	kg	kmol	Slag	kg	kmol	Metal	kg	kmol	Off gas	kmol
MnO ₂	1593	18.33	MnO	280	3.95	Mn	790	14.38		
Fe ₂ O ₃	200	1.25				Fe	140	2.51		
SiO ₂	210	3.49	SiO ₂	210	3.49					
CaO	210	3.74	CaO	210	3.74					
C	316	26,32				C	70	5,83	CO	4,51
									CO ₂	15,98

The carbon needed for this process, and hence the CO₂ emissions from the process, must again be based on a knowledge of the system, especially at which temperatures the Mn-oxides are reduced. The reduction of Mn-oxides has three distinct areas:⁸⁻¹⁰

1. the reduction of higher Mn-oxides to Mn₃O₄ with CO gas (reaction [1]) at lower temperatures,
2. then the reduction of all, or some, of the Mn₃O₄ with C to CO gas (reaction [2]) at higher temperatures
3. and then finally the reduction of the major part of the MnO to Mn with C to CO gas according to reaction [3] at temperatures above about 1400 °C

The quantitative extent on each of these stages is shown in Table 2, from the material flows of ore in and metal and slag out. Summing up the CO produced and consumed, and the CO₂ produced, the off-gas composition can be determined as shown in Table 1. If the CO is emitted to the atmosphere, it oxidises and hence a total of 16+4.5=20.5 kmol CO₂ will be emitted, that is a total of 901 kg of CO₂ per ton of manganese.

Table 2. Extent of Mn- and Fe-reduction with produced and consumed CO and CO₂ gas using an MnO₂ ore

	kmol		Reaction
18.3 kmol Mn	6.1	$3\text{MnO}_2 + 2\text{CO} = \text{Mn}_3\text{O}_4 + 2\text{CO}_2$	[1]
18.3 kmol Mn	6.1	$\text{Mn}_3\text{O}_4 + \text{C} = 3\text{MnO} + \text{CO}$	[2]
Tot: 18.3 kmol Mn	3.9	MnO in slag	
		14.4	$\text{MnO} + \text{C} = \text{Mn} + \text{CO}$
	1.3	$\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2$	[4]

To summarise this example, we are using 2213 kg of ore and 316 kg of fixed C to produce 1 ton of metal, 700 kg of slag and an off-gas containing 4.5 kmol CO + 16 kmol CO₂, that will at the end emit 901 kg CO₂ per ton metal produced.

Example 2: A simplified example of Mn-production with Mn₂O₃ ore.

There is a tendency to believe that the more oxygen there is in the raw materials, the more the carbon is needed, and hence, the more CO₂ is emitted. The following example shows that this is not the case in Mn-production. In this example, we use an Mn₂O₃ ore, that is O/Mn=3/2=1.5. These manganese oxides have 25% less oxygen content compared to those used in Example 1. The rest of the ore has the same Mn/Fe ratio, SiO₂ and CaO, giving the same slag composition. The carbon material is 100% fixed C.

Table 3. Mass balance of a simplified Mn-ferroalloy process using an Mn₂O₃ ore (example 2)

Raw materials in	kg	kmol	Slag	kg	kmol	Metal	kg	kmol	Off-gas	kmol
Mn ₂ O ₃	1447	9.16	MnO	280	3.95	Mn	790	14.38		
Fe ₂ O ₃	200	1.25				Fe	140	2.51		
SiO ₂	210	3.49	SiO ₂	210	3.49					
CaO	210	3.74	CaO	210	3.74					
C	316	26,32				C	70	5,83	CO	13,67
									CO ₂	6,81

Table 4. Extent of the Mn- and Fe-reduction with produced and consumed CO and CO₂- gas using an Mn₂O₃ ore

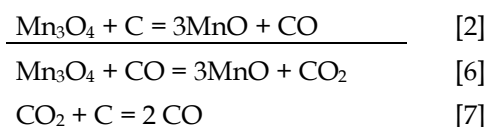
	kmol		Reaction
18.3 kmol Mn	3,1	$3\text{Mn}_2\text{O}_3 + \text{CO} = 2\text{Mn}_3\text{O}_4 + \text{CO}_2$	[5]
18.3 kmol Mn	6,1	$\text{Mn}_3\text{O}_4 + \text{C} = 3\text{MnO} + \text{CO}$	[2]
Tot: 18.3 kmol Mn	3,9	MnO in slag	
		14,4	$\text{MnO} + \text{C} = \text{Mn} + \text{CO}$
	1,3	$\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2$	[4]

The main difference between examples 1 and 2 is reaction 1 and reaction 5, where the manganese oxides are reduced to Mn₃O₄ from either MnO₂ in example 1 or Mn₂O₃ in example 2. These two reactions do

not however consume any carbon, only CO gas, which means that the total C consumption is still 316 kg fixed C per ton of metal, and the CO₂ emissions are still 20.5 kmol, that is 901 kg CO₂ per ton of metal. The main difference now is that the off-gas contains 67% CO compared to 22% CO in example 1. Hence, if one used this gas for combustion and electricity production, this ore would give a richer off-gas and hence one could produce more electrical energy. The mass of ore will be a bit lower as it contains less oxygen; that is 2067 kg of ore per ton of metal.

Example 3: A simplified example of Mn-production with better prereduction

In the two former examples we assumed that all Mn₃O₄ is reduced with solid carbon to MnO. This reaction is the sum of the two reactions 6 and 7, where Mn₃O₄ is really being reduced with CO gas, and then the produced CO₂ will react with carbon according to the Boudouard reaction, reaction 7.



In iron production one would differentiate between ore reduced with C or CO, and use the terms direct or indirect reduction. In Mn-production one typically refers to the terms high and low degree of prereduction. A high prereduction is that Mn₃O₄ is reduced by CO gas at temperatures before the Boudouard reaction is active. A consequence is that the CO₂ produced does not react with solid C, as the temperature is too low. In Mn-production we therefore talk about good prereduction degrees, that is a high extent of the gas reaction 6, or low degree of prereduction, which means that the reduction of Mn₃O₄ will happen with solid carbon. It has previously been seen industrially over a five-year period that typically amount of Mn₃O₄ that will react with CO gas is between 10 and 60%⁸. One can hence estimate CO₂ emissions for 50% of Mn₃O₄ reacting with CO and 50% with C as per example 3. The total streams in and out are then shown in Table 5 and the extent of the Mn- and Fe-reduction reactions are shown in Table 6.

The table summarises the in and out streams, and again, the CO₂ emissions are of importance. When the CO is oxidised as it meets the surrounding atmosphere, a total of 7.5+9.9=17.4kmol, that is 767 kg CO₂ per ton of metal produced. This is a 15% reduction of CO₂ emission, compared to examples 1 and 2. The CO content will now drop to 43% in the off-gas, as the amount of fixed C in the raw materials has decreased to 279 kg.

Table 5. Mass balance of a simplified Mn-ferroalloy process using an Mn₂O₃ ore with 50% prereduction of the Mn₃O₄

Raw materials in	kg	kmol	Slag	kg	kmol	Metal	kg	kmol	Off gas	kmol
Mn ₂ O ₃	1447	9,16	MnO	280	3,95	Mn	790	14,38		
Fe ₂ O ₃	200	1,25				Fe	140	2,51		
SiO ₂	210	3,49	SiO ₂	210	3,49					
CaO	210	3,74	CaO	210	3,74					
C	279	23,27				C	70	5,83	CO	7,56
									CO ₂	9,87

Table 6. Extent of Mn- and Fe-reduction with produced and consumed CO and CO₂- gas using an Mn₂O₃ ore with 50% better prereduction of Mn₃O₄

	kmol		Reaction
18.3 kmol Mn	3,1	$3\text{Mn}_2\text{O}_3 + \text{CO} = 2\text{Mn}_3\text{O}_4 + \text{CO}_2$	[5]
Tot: 18.3 kmol Mn	3,1	$\text{Mn}_3\text{O}_4 + \text{CO} = 3\text{MnO} + \text{CO}_2$	[6]
	3,1	$\text{Mn}_3\text{O}_4 + \text{C} = 3\text{MnO} + \text{CO}$	[2]
Tot: 18.3 kmol Mn	3,9	MnO in slag	
	14,4	$\text{MnO} + \text{C} = \text{Mn} + \text{CO}$	[3]
	1,3	$\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2$	[4]

Summary: The effect of raw materials and operation on CO₂ emissions in the FeMn production

Table 7. Summary of how Mn-oxide and degree of prereduction affect the CO₂ emissions in the FeMn process

	Example 1	Example 2	Example 3
Degree of prereduction	0 %	0 %	50 %
Ore base	MnO ₂	Mn ₂ O ₃	Mn ₂ O ₃
kg ore	2213	2067	2067
kg Fix C	316	316	279
%CO in off-gas	22 %	67 %	43 %
kg CO ₂ emissions	901	901	767

Mass balances of a simplified FeMn process have been made to show how CO₂ emissions per ton of metal change with the O/Mn ratio and the degree of prereduction. It has been shown that the O/Mn ratio does not affect the carbon in, and hence the CO₂ emissions out. With the exception of the carbon dissolved in the metal, the rest of the carbon added correlates linearly with CO₂ emissions, assuming that there is no accumulation of carbon in the furnace. Note that MnO₂ ores will be typically mixed with Mn-sources of lower oxygen content industrially, because of safety risks, especially in closed furnace. However, the argument can be used for Mn₂O₃- versus Mn₃O₄-sinter blends as well, that the change in total oxygen content will not change the total carbon consumption, and hence the CO₂ emissions if the extent of prereduction is the same.

In an industrial FeMn process, the CO₂ emissions are affected by the degree of prereduction, as described above, but emissions may rise if carbonates are introduced with the raw material blend. The CO₂ in the carbonates will be released and emitted as CO₂. Calcium carbonates may release the CO₂ at high enough temperatures that it will react with C according to the Boudouard reaction (Reaction 7), emitting even more CO₂.

Electric energy consumption vs exergy analyses vs Sankey diagrams

From a sustainability point of view the use of electrical energy per ton of metal is important. Energy production emits CO₂ when fossil fuels are combusted. Even for renewable energy production, materials and equipment are produced with CO₂ emissions. In addition, the production of renewable

energy has other sustainability liabilities such as use of land area, which may cause significant challenges for the population in the vicinity of a plant. Electrical energy will therefore be responsible from minor to major CO₂ emissions. All producers, independent on energy source, will need to make an effort in producing the product with the least electrical energy. Examples of this are the Norwegian Si and FeSi plants which have installed energy-recovery plants, to recover energy from the off-gas, despite levelled prices, stable accessibility, and low CO₂ emissions due to use of hydropower. In countries that do not have renewable energy sources it will be even more important with low energy consumption and additionally recover the energy from the process.

Students who have been taught basic thermodynamics and are familiar with the concepts of heat capacity, reaction enthalpies and phase transformation enthalpies, and typically have access to basic thermodynamic software such as HSC Chemistry, can calculate the electrical energy consumption quite easily from the conservation of enthalpy:

Enthalpy in raw materials + electrical energy = enthalpy in products

This is done for examples 1-3 and is shown in Table 8. There are two major differences that affect the electrical energy consumption, calculated as the difference in enthalpy in and out. The first is the oxygen content in the ore. All the reduction of higher manganese oxides with CO gas are exothermic reactions, that is reaction 1, 5 and 6. As you have more oxygen, the total reduction with CO gas will be more exothermic, and hence the Mn₂O₃ ore will in theory have 500 kWh/ton higher energy consumption than the MnO₂ ore—that is 30% higher energy consumption. The second part that affects the energy consumption will be the degree of prereduction, that is the difference between example 2 and 3. Prereduction of 50% will decrease the energy consumption from 2114 kWh/ton to 1962 kWh/ton—that is a reduction of 7%.

Table 8. Energy (ΔH°) and exergy input and output of the three examples chosen (calculated with HSC Chemistry 10)

Example 1: MnO ₂ ore					Example 2: Mn ₂ O ₃ ore					Example 3: Mn ₂ O ₃ ore with 50% prereduction				
INPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh	INPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh	INPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh
Ore	25	2213	-4477	274	Ore	25	2065	-4269	394	Ore	25	2065	-4269	394
MnO ₂		1594			Mn ₂ O ₃		1446			Mn ₂ O ₃		1446		
Fe ₂ O ₃		200			Fe ₂ O ₃		200			Fe ₂ O ₃		200		
SiO ₂		210			SiO ₂		210			SiO ₂		210		
CaO		210			CaO		210			CaO		210		
Carbon	25		0	3000	Carbon	25	316	0	3000	Carbon	25	279	0	2652
C		316	0		C		316			C		279		
OUTPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh	OUTPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh	OUTPUT SPECIES	Temp. °C	Amount kg	Total H kWh	EXERGY kWh
Slag	1400	700	-1625	516	Slag	1400	700	-1625	516	Slag	1400	700	-1625	516
MnO(l)		280			MnO(l)		280			MnO(l)		280		
SiO ₂ (l)		210			SiO ₂ (l)		210			SiO ₂ (l)		210		
CaO(l)		210			CaO(l)		210			CaO(l)		210		
Metal	1400	1000	560	3306	Metal	1400	1000	560	3306	Metal	1400	1000	560	3306
Mn(l)		790			Mn(l)		790			Mn(l)		790		
Fe(l)		140			Fe(l)		140			Fe(l)		140		
C(l)		70			C(l)		70			C(l)		70		
Off gas	400	830	-1798	464	Off gas	400	683	-1090	1108	Off gas	400	646	-1242	657
CO(g)		126			CO(g)		383			CO(g)		212		
CO ₂ (g)		703			CO ₂ (g)		300			CO ₂ (g)		434		
Total energy consumption			1614 kWh/ton		Total energy consumption			2114 kWh/ton		Total energy consumption			1962 kWh/ton	
Total Exergy consumption			1012 kWh/ton		Total Exergy consumption			1537 kWh/ton		Total Exergy consumption			1433 kWh/ton	

Exergy is a measure of energy quality, stating the maximum work that can be extracted from a system, only interacting with its environment. Exergy analyses can be used to determine the process that loses the least amount of exergy, and it might be an important measure regarding usable energy in the output streams for recycling purposes. If we compare the energy balance with the exergy balance for the three processes above, we see that both analyses give the same conclusion, that higher oxygen content in the ore and better prereduction gives lower energy consumption and lower exergy losses. Figure 2 compares the energy and exergy balances. The exergy consumption is 530–600 kWh/ton metal less than the energy (enthalpy) consumption. For these types of processes, we see that the optimisation of energy

consumption in the process can be done with enthalpy analyses as it gives the same overall conclusions as the exergy analyses. The advantage is of course that for most engineers as well as students, the enthalpy balance is a more mature concept. The correlation between the energy and exergy analyses, and that both tools obtain the same conclusion regarding the process, has also been shown by Larssen et.al., (2018)⁴.

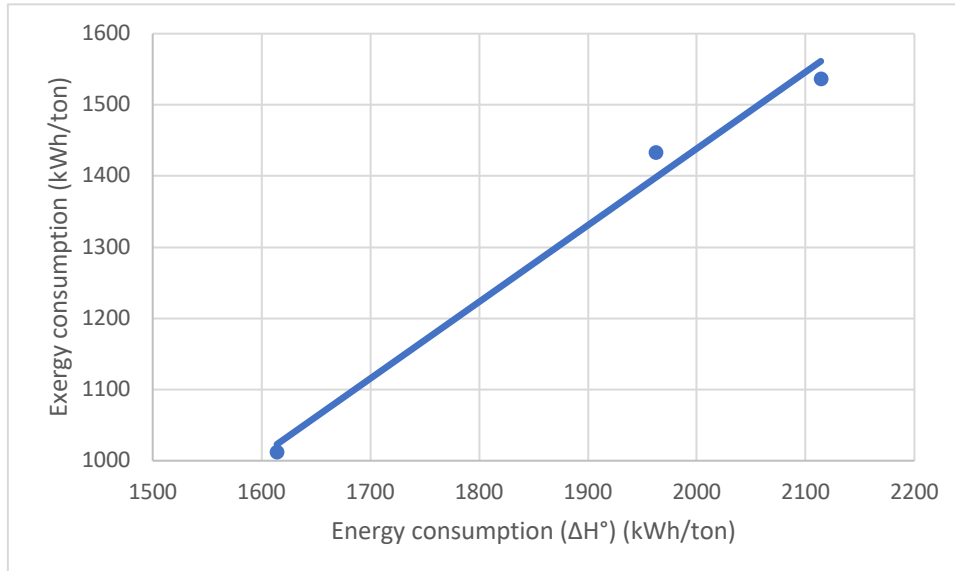
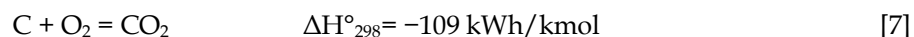


Figure 2. Comparison between the energy consumption (kWh/ton), given by enthalpy balance, and the exergy consumption (kWh/ton)

The energy analyses of processes are often shown using Sankey diagrams. They are useful when examining the energy in the outstreams, especially in the context of energy recycling. The reference state will now be changed: In thermodynamic analyses, we typically choose pure elements at 25 °C to have zero energy, as HSC Chemistry do. When we however discuss the recovery or production of energy, we want to know how much energy we can produce by combustion with oxygen, and hence we choose the most oxidative state as reference and the energy of the most oxidative state will hence be zero. An example is carbon, which from a chemical point of view contains zero energy at 25 °C. From an energy production point of view, one wants to know how much energy carbon develops when it combusts to CO₂ according to reaction [7]:



If this were to occur at 25 °C, the reaction would produce 109 kWh/kmol carbon, that is 9 kWh/kg of carbon. In a similar manner CO can be oxidised to CO₂, Fe to Fe₂O₃ and Mn to MnO (as chosen here). One can also use MnO₂ as the stable phase, as MnO may be oxidised to MnO₂. When MnO is chosen as the reference state, the slag will then have no chemical energy. To understand the Sankey diagram, one needs to be aware of the difference in the reference states between chemical thermodynamics and energy production. Though trained as a metallurgist, and hence in a school where the reference state is the elemental state, I do recognise that the Sankey diagram may be more intuitive for the students to understand.

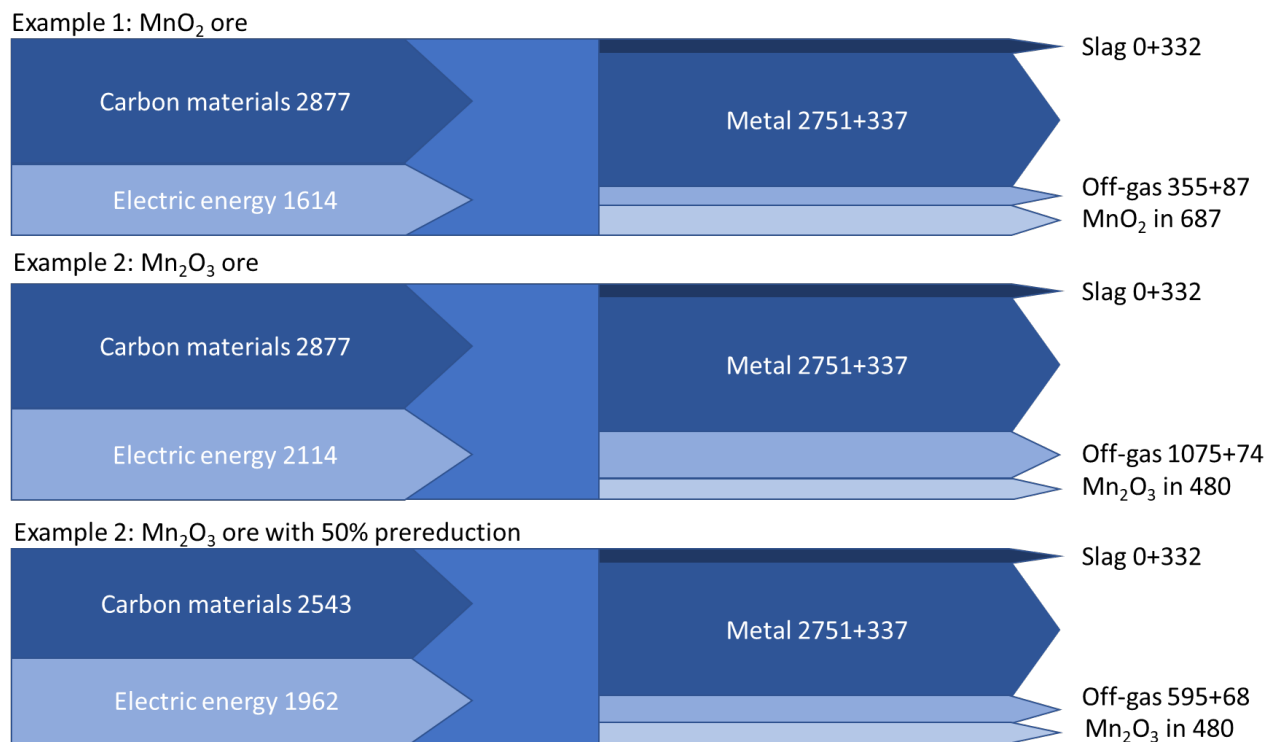


Figure 3. Sankey diagrams, showing the energy flow (enthalpy) in simplified FeMn process illustrating the three examples. In the exit streams the energy is given by chemical energy + heat. (As the reference state is MnO for the manganese oxide, the difference between MnO₂/Mn₂O₃ and MnO is given as energy in the output streams. Heat losses are not included.)

Figure 3 shows a Sankey diagram of a simplified FeMn process illustrated by the three examples discussed previously. The energy from electrical energy and the carbon goes mainly to the metal, where the main part is chemical energy (2751 kWh/ton metal) and heat (337 kWh/ton metal). As we are producing the same metal at the same temperature, the energy content will of course be the same in the three different process conditions. Metal is also what we sell, and hence adding most of the energy into the product gives an efficient process. The slag will have zero chemical energy content, but as it is tapped at 1400 °C, the heat in the slag will be 332 kWh/ton metal, for this tapping temperature and this slag/metal ratio. At higher slag/metal ratios more heat will be in the slag, and more electric energy will be needed.

The off-gas is maybe the stream that one is mostly concerned with, as the off-gas can either be sold due to the CO content or oxidised to produce energy. The heat in the off gas is not very high, as it is in the order of 70 kWh/ton metal at 400°C. Typically one would like to operate the furnace with off gas temperature at around 200°C, which again would half the heat content. The chemical energy content in the off gas, given by the amount of CO gas, may however be significant. Reducing the oxygen content in the raw materials from MnO₂ to Mn₂O₃ ore increases the CO content and the chemical energy content increases from 355 to 1075 kWh/ton metal. The latter is more than 20% of the total energy in and 50% of the electrical energy in. This is of course paid for by a high carbon consumption, and again if the carbon consumption decreases (example 3) the CO content in the off-gas and thus the energy content in the off-gas decreases accordingly. As a rule of thumb for recycling, it is better not to consume (carbon and energy) than to recycle it after it is consumed. For the producer and the environment, it is better to use less electrical energy and carbon, and consequently have a low recycling potential in the off-gas.

SUMMARY

Calculating mass and energy balances is part of the important skillset engineers need to investigate sustainability issues in their metallurgical processes. Based on the conservation of mass and enthalpy for processes one can investigate different scenarios with different raw materials and different operating conditions. Simplified mass and energy balances are used as examples to show how one can change the CO₂ emission and electrical energy consumption. In FeMn introduction we find that despite more oxygen needing to be removed, carbon consumption does not necessarily increase, for both C and CO are reductants. Higher oxygen content does however reduce electrical energy consumption due to more exothermic reactions. One also finds that higher degrees of prereduction lower both CO₂ emission and the energy consumption. For processes like this, one also finds that exergy analyses do not add to the knowledge about potential savings compared to enthalpy analyses. Lastly, showing Sankey diagrams for the energy streams in and out of a process may be valuable when it comes to emphasizing the possibility of recovering energy from output streams.

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