

Supplementary material for

Energy Consumption and Greenhouse Gas Emissions of High-Carbon Ferrochrome Production

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Table S-1 Comparisons of different HC FeCr production processes [1-7]

Item	Unit	Process Technology			
		SAF	CSAF+PH	CSAF+PR	DCAF
Ore	t/t FeCr	2.4-3	2.3-2.4	1.8-1.9	1.75-2.1
Electricity	kWh/t FeCr	3800-4500	3100-3500	2600-3100	4500
(Furnace)	kWh/t FeCr	3800-4200	2800-2900	1700-2200	4000-4500
Reductant	kg/t FeCr	550-700	500-550	600	788
Fluxes	kg/t FeCr	100-400	200-300	450	385
Electrode	kg/t FeCr	8-25	7-10	20	-
Alloy	Cr %	-	-	>50	50-71
	C %	-	-	6-8	6.4-8.8
	Si%	-	-	1.5-4	0.14-5.5
Slag	t/t FeCr	1.2-1.35	1.1-1.21	1.1-1.3	0.8
	Basicity	>1	<1	>1	1.16-1.73
Cr recovery	%	70-75	83-88	88-92	88-94

Table S-2. Chemistry analysis of raw materials [1, 3, 8-10]

Unit	FeO	Fe ₂ O ₃	Cr ₂ O ₃	SiO ₂	MgO	CaO	Al ₂ O ₃	Na ₂ O	K ₂ O	CaCO ₃	C	H ₂ O (bond)	H ₂ O (free)
Ore 1	19.03	5.97	40.2	6.1	9.3	1	17.3					1.10	1
Ore 2	20.4	5.2	45.69	2.08	10.3	0.14	13.8					2.39	1
Ore 2 (lumpy)	17.66		35.68	11.17	16.1	1.2	11.6				0.77	5.82	1
Ore 3	19.03	5.97	40.2	6.1	9.3	1	17.3					1.1	1
Ore 4	11.9	2.9	51.2	6.9	19.8		6.5					0.8	1
Coke 1				9.3			4.7				85		1
Coke 2				6.27	0.1	0.33	3.03				87.3		2.97
Coke 3				10.7			5.3				83.0		1
Coke 4				8.8			4.4				85.4		1.4
Coal 3				14			10				73		3
Anthracite 3				10			3.5				81.8		4.7
Quartzite 2				95.33	0.37	0.83	0.33						3
Quartzite 1/3/4				97									3
Limestone										97			3
Bentonite 2/3		15.76		47.57	2.36	2.89	15.28	2.48	0.3				13.36

Table S-3. Charge/discharge temperature in chromite processing (Unit: °C) ^{a, b} [1, 3, 11-13]

	Case 1 SAF	Case 2 CSAF+PH	Case 3 CSAF+PR60%	Case 4 DCAF
Sintering/Prereduction				
<i>Drying zone</i>				
Incoming Gas		200	900	
Ore		150	400	
Off gas		100	100	
<i>Sintering/Prereduction zone</i>				
Incoming Gas		800	25	
Ore		150	400	
Sinter/ Pre-reduced pellets		1200	1400	
Off gas		1400	900	
<i>Primary cooling zone</i>				
Incoming Gas		25		
Sinter/ Pre-reduced pellets		1200		
Sinter/ Pre-reduced pellets (cooled)		900		
Off gas		800		
<i>Secondary cooling zone</i>				
Incoming Gas		25		
Sinter/ Pre-reduced pellets		900		
Sinter/Pre-reduced pellets (cooled)		100		
Off gas		200		
Preheating				
Sinter		25		
Dried ore		700		
Preheated auxiliary material		700		
Off gas		700		
Smelting				
Ore	25	492	400	25
Auxiliary materials	25	492	25	25
Alloy	1580	1580	1580	1800
Slag	1680	1680	1680	1828
Off gas	900	900	900	900

^a The other incoming materials not specified in the table are assumed to enter the system at 25 °C.

^b It is assumed that the chemical reaction temperature is the same as for the discharged Cr-containing materials. Typical temperatures for bond-water removal (smelting), and combustion are 400°C and 630°C, respectively

Table S-4 Mass and Energy Balance of the Case 1 SAF

<i>Smelting-Mass Balance</i>					
Input	Mass(kg)	%	Output	Mass(kg)	%
Chromite	2604	71	FeCr	1000	27
Coke	511	14	Slag	1470	40
Quartzite	105	3	Off gas	1195	33
Limestone	145	4			
Air	300	8			
Total	3665	100	Total	3665	100
<i>Smelting-Energy Balance</i>					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Electricity	15471	99	FeCr	1601	10
Carbon oxidation	203	1	Slag	3542	23
			Off gas	1277	8
			Heat loss	2821	18
			Endothermic reaction	6433	41
Total	15674	100	Total	15674	100

Table S-5 Mass and Energy Balance of the Case 2 CSAF+PH

<i>Pelletizing-Mass Balance</i>					
Input	Mass(kg)	%	Output	Mass(kg)	%
Chromite ore	1450	89	Pellet	1633	100
Coke	8	0.5			
Bentonite	15	1			
Water	161	10			
Total	1633	100	Total	1633	100
<i>Sintering (drying zone)-Mass balance</i>					
Input	Mass(kg)	%	Output	Mass(kg)	%
Pellets	1633	26	Dried pellets	1609	26
Recycled hot gas	4575	74	Off gas	4600	74
Total	6208	100	Total	6208	100
<i>Sintering (drying zone)-Heat balance</i>					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot gas (secondary cooling)	1072	100	Dried pellets	231	22
			Off gas	459	43
			Heat loss	1	0
			Vaporizing	382	36
Total	1072	100	Total	1072	100
<i>Sintering (sintering zone)-Mass balance</i>					
Input	Mass(kg)	%	Output	Mass(kg)	%
Dried pellets	1609	55	Sintered pellets	1449	49
Recycled hot gas	994	34	Off gas	1492	51
Furnace gas fuel	339	12			
Total	2941	100	Total	2941	100
<i>Sintering (sintering zone)-Heat balance</i>					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot gas (primary cooling)	469	11	Dried pellets	1155	27
Dried pellets	158	4	Off gas	2267	53.5
Combustion	3611	85	Oxidation	522	12.3
			Vaporizing	293	7
Total	4238	100	Total	4238	100
<i>Sintering (primary cooling zone)-Heat balance</i>					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot sinter	1624	100	Hot sinter	1155	71
			Off gas	469	29
Total	1624	100	Total	1624	100
<i>Sintering (Secondary cooling zone)-Heat balance</i>					
Input	Heat (MJ)	%	Output	Heat (MJ)	%

Hot sinter	1155	100	Sinter pellets	83	7
			Off gas	1072	93
Total	1155	100	Total	1155	100
Smelting-Mass Balance					
Input	Mass(kg)	%	Output	Mass(kg)	%
Sinter	1449	36	FeCr	1000	25
Lumpy ore	815	20.1	Slag	1173	29.0
Coke	441	10.9	Off gas (smelting)	798	19.7
Quartzite	299	7	Off gas (pre-heating)	1076	27
Off gas fuel	311	8			
Air (preheating combustion)	711	18			
Air (smelting)	20	0			
Total	4046	100	Total	4046	100
Smelting (preheating zone)-Energy Balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Combustion	2930	100	Hot feed	2014	69
			Off gas	829	28
			Vaporizing	87	3
Total	2930	100	Total	2930	100
Smelting (smelting zone)-Energy Balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot feed	1331	11	FeCr	1520	12
Electricity	11167	89	Slag	2279	18
Carbon oxidation	57	0	Off gas	811	6
			Heat loss	1883	15
			Endothermic reaction	6062	48
Total	12556	100	Total	12556	100

Table S-6 Mass and Energy Balance of the Case 3 CSAF+PR60%

Pelletizing-Mass Balance					
Input	Mass(kg)	%	Output	Mass(kg)	%
Chromite ore	2155	79	Pellet	2745	100
Anthracite	292	11			
Bentonite	43	2			
Water	255	9			
Total	2745	100	Total	2745	100
Prereduction-Mass balance					
Input	Mass(kg)	%	Output	Mass(kg)	%
Pellets	2745	70	Pre-reduced pellets	1999	51
Oxygen gas	540	14	Off gas	1908	49
Recycled off gas (smelting)	458	12			
Coal	164	4			
Total	3907	100	Total	3907	100
Prereduction (drying zone)-Heat balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot off gas	1598	100	Dried pellets	815	51
			Off gas	162	10
			Heat loss	143	9
			Vaporizing	478	30
Total	1598	100	Total	1598	100
Prereduction (prereduction zone)-Heat balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Combustion	7850	91	Pre-reduced pellets	4438	51
Dried pellets	815	9	Off gas	1598	18
			Reduction	2630	30
Total	8666	100	Total	8666	100
Smelting-Mass Balance					
Input	Mass(kg)	%	Output	Mass(kg)	%
Pre-reduced pellets	1999	71	FeCr	1000	35
Coke	294	10	Slag	1314	47
Quartzite	206	7	Off gas	505	18
Limestone	300	11			
Air	20	1			
Total	2819	100	Total	2819	100
Smelting-Energy Balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Hot pre-reduced pellets	775	8	FeCr	1237	13
Electricity	8410	91	Slag	2536	27
Carbon oxidation	52	1	Off gas	470	5
			Heat loss	1386	15
			Endothermic reaction	3609	39
Total	9237	100	Total	9237	100

Table S-7 Mass and Energy Balance of Case 4 DCAF

Smelting-Mass Balance					
Input	Mass(kg)	%	Output	Mass(kg)	%
Chromite ore	2225	79	FeCr	1000	36
Coke	475	17	Slag	1026	36
Quartzite	93	3	Off gas	787	28
Air	20	1			
Total	2813	100	Total	2813	100
Smelting-Energy Balance					
Input	Heat (MJ)	%	Output	Heat (MJ)	%
Electricity	15710	100	FeCr	1496	9
Carbon oxidation	53	0	Slag	3157	20
			Off gas	833	5
			Heat loss	4414	28
			Endothermic reaction	5864	37
Total	15763	100	Total	15763	100

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