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ANALYSIS OF OXYGEN ENRICHMENT IN THE MELTING PROCESS WITH SIDE SUBMERGED NOZZLE USING HSC SOFTWARE

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Abstract: The smelting of copper concentrate with a side submerged nozzle was modeled and simulated using the HSC SIM Chemistry Software version 6.12. To capture the physical-chemical behavior of the problem, the model is fed with industrial chemical analyzes corresponding to chalcopyrite concentrate used to determine the mineralogy. Heat losses were estimated at 12.05 GJ/h (3.35 MW). The model was based on simultaneous mass and heat balances using the progress of chemical reactions linked to software controllers to achieve the composition and temperature parameters of the white metal and slag.
Process analysis is performed by varying the air enrichment at different white metal grades. The most important results of the simulations are the required flows of blown air, industrial oxygen, flux and cold charge depending on the concentrate fed and its mineralogy. For a 28.74% copper concentrate that produces a 72% grade molten white metal, increasing the enrichment from 30 to 38% increases the cold charge flow from 4 to 27 t/h, increases the metal flow blank from 32 to 53 t/h, the flow of process gases decreases from 70,000 to 50,000 Nm^3/h and the SO_2 concentration increases from 22 to 29%. An operation without enrichment will require the use of fuel to balance the thermal deficit.
Finally, the oxygen coefficient and the white metal law are directly proportional.
Keywords: Modeling, simulation, fusion, concentrate, controllers.

INTRODUCTION

Pyrometallurgical processes are widely used to treat copper concentrates due to their high production capacity due to the high kinetics developed at high temperatures, energy efficiency due to their autothermicity and the production of sulfuric acid from their gases.

Autothermicity requires maintaining several operating parameters at their design values, which change due to operational variability, such as: flow of flux concentrate and circulating feed and their chemical and mineralogical compositions whose characterization is not periodic and therefore causes unforeseen events. in the operation. This makes the process unstable and must be monitored and controlled. Maintaining the temperature, composition and productivity of the final product obtained will depend on several possible operating scenarios.

The modeling and simulation of a melting furnace allows us to visualize what the optimal operating conditions will be according to the food and products to be obtained. Online, this would allow a prompt response to variations and return the process to steady state.

Oxygen enrichment directly affects the heat balance, since in the event of a thermal surplus it must decrease in such a way that the increase in the amount of nitrogen "cools the oven", and vice versa in the event of a thermal deficit. Depending on the process and also on the materials, this can reach 80%. For fusion in the bath by submerged nozzle, it does not exceed 40%.

When the limit cannot be exceeded to balance a thermal surplus, it must be controlled by adding a cold load. On the other hand, in the event of a thermal deficit, an auxiliary fuel burner, coke addition or the like must be required.

The pyrometallurgical process for obtaining copper from sulfide ores using melting in the bath [1], can be described using Figure 1.

Once the ore is released and concentrated by crushing, grinding and flotation and later thickened, filtered and dried, it is fed to the smelting furnace that melts it and produces matte that goes to conversion, slag for copper recovery and gases that go to treatment to produce sulfuric acid. The matte is converted to blister copper in Converters which is fired

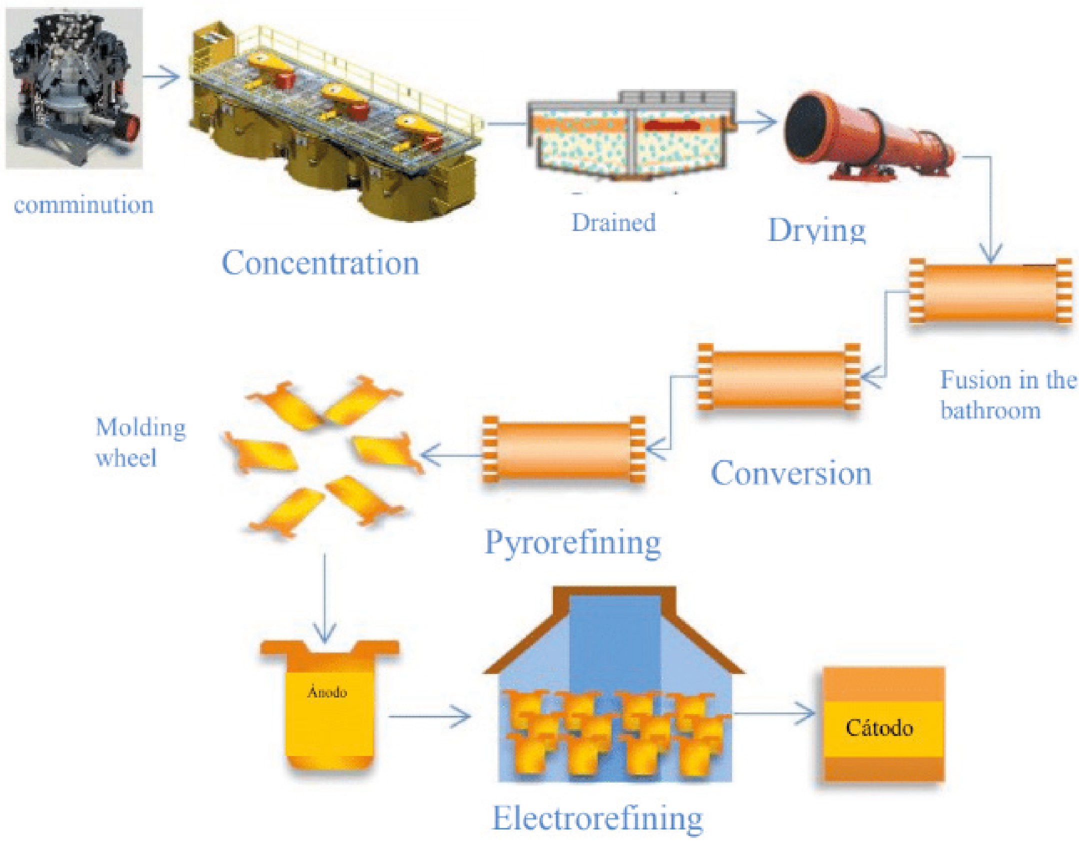

Fig. 1. Pyrometallurgical way of obtaining copper

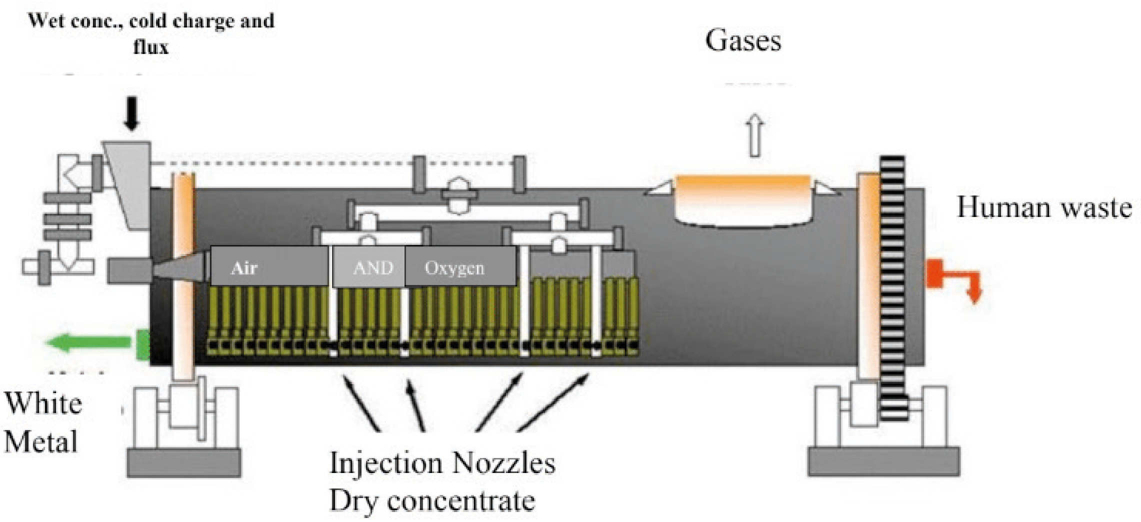

Fig. 2. Melting Furnace in the Bath by Lateral Submerged Nozzle

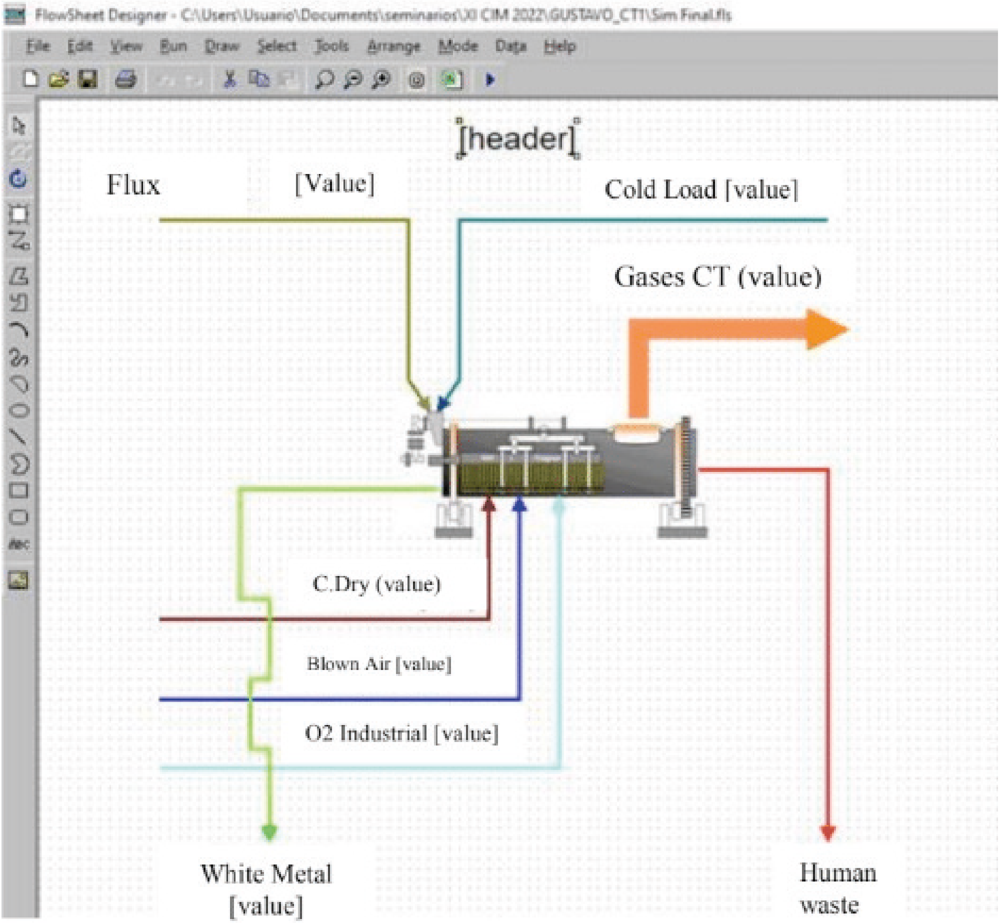

Figure 3. Furnace design and inlet and outlet flows of the process.

in anode furnaces that discharge the molten anode copper into molds to produce anodes.

In particular, the melting process in the bath [2] is described in the furnace presented in Figure 2.

Figure 2 shows that the concentrate enters mainly dry through four special nozzles located together with the enriched air injection nozzles (35 to 50) located laterally in the furnace mantle and towards the end of the cylinder head through which wet concentrate enters, cold and flux charge on the upper part of the mantle called gar-gun. This zone of concentrate/air injection presents a great turbulence where the concentrate that enters consumes heat to decompose and melt in the bath, this consumption is balanced by the generation of heat due to the oxidation of the FeS present. This produces a foamed emulsion of matte, slag and gases that are separated at the end of the furnace without nozzles and under the gas outlet. The matte sediments and settles at the bottom of the furnace from where it is discharged discontinuously through a hole and the slag, when separated, floats on the matte and is also discharged in the same way. Gases are continuously generated and emanated from the furnace mouth from where they are sent for cooling and cleaning to finally be conducted to the sulfuric acid production plant.

The operation of the Furnace consists of:

1. Continuous injection of dry concentrate and air

2. Continuous blowing of oxygen-enriched air

3. Continuous charge of flux and cold charge on the surface of the bath

4. Continuous extraction of process gases

5. Intermittent bleeding of mat and scum

6. Occasional recirculation of bushes through the mouth.

The controls applied to maintain said stability are:

1. Slag temperature (approx. 1,240°C): controlled by adjusting the flow and oxygen enrichment of the supplied air.

2. Slag Composition: controlled by the flux feed flow to maintain 35% SiO_2 in the slag. This, added to good temperature control, yields a slag with 20 ± 4% Fe_3O_4.

3. Matte Composition: it is controlled by adjusting the ratio between the total oxygen flow fed and the dry concentrate flow fed, that is, the progress of oxidation of iron and sulfur of the matte

SIMULATION MODEL

The model developed is a simultaneous balance of mass and heat. A good closure of them allows the reactor to operate in a stable manner, that is to say, that the total flow of mass fed is equal to the total flow of mass of products and that the heat contributed by the oxidation reactions is equal to that necessary to decompose the minerals from the concentrate and melt the total load fed, also considering the heat losses from the furnace.

The simulation model was developed with the "Sim Flowsheet Simulation" module of the HSC Software - Chemistry v. 6.12 and complemented with the modules "Mineralogy Iterations" to determine the mineralogical composition from the chemical composition and "Heat Loss Calculator" to estimate heat losses [3]. The model in the "Sim Flowsheet Simulation" module is presented in Figure 3.

The model requires the following information in order to be executed:

1. Mineralogy of the concéntrate

2. Composition of the cold load in percentage by mass

3. Composition of the flux in percentage

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by mass

4. Composition of industrial oxygen in percentage by volumen

5. Raw material temperatura

6. Products temperatura

7. Heat losses of the Teniente Converter

The concentrate fed is presented in the following Table 1.

Compound	$CuFeS_2$	Cu_5FeS_4	FeS_2	SiO_2	H_2O	Total
% weight	70	7	15	7.8	0.2	100

Table 1. Mineralogical composition of the concentration:

The flux is composed of 90% SiO2 and the remainder Fe_3O_4.

The cold charge is composed of 90% Cu2S and the remainder Fe_3O_4.

Air has 21% oxygen and technical oxygen has 94%. The remainder in both streams is nitrogen.

The equations that the simulator will use to generate the outputs from the input data are called rulers and must represent the physicochemistry of the process and the mechanism of decomposition, fusion and conversion. The model has 12 governing equations, which are presented in Table 2.

The above description of the governing equations and their progress is modeled in the software as presented in Figure 4 below.

To represent the process, the model, through its "distributions" tool [4], considers that 1% of the matte is trapped by the slag, distributing itself in it and that the matte contains 1% magnetite. On the other hand, it was considered that all the solids fed react completely, so the distribution of solids at the outlet is zero. Finally, the model vaporizes all the water that enters the reactor (Figure 5).

In order for the process to return to its operating parameters when faced with a system variation, the software counts as a tool the "controllers" [4] so that the mathematical model iterates the values of the specified variables until the final response converges for an operational situation. particular. Controllers can run individually or simultaneously depending on convergence [5].

The model integrates 8 controllers that determine the required flows of flux, industrial oxygen, air and cold load required to obtain a matte and slag with specified characteristics, also closing the heat balance. The following Table 3 indicates the controllers used and the action they perform.

Control	Action on
White Metal Law	FeS oxidation reaction advance$_{(l)}$
Magnetite in the Slag	FeO oxidation reaction progress$_{(l)}$
Total Silica in Slag	Flux flow fed
$FeO_{(l)}$ in the Slag	Advance reaction formation Fayalita
Total copper in the slag	Advance oxidation reaction $Cu_2S_{(l)}$
Total oxygen fed	Total Airflow Powered
Oxygen enrichment	industrial oxygen flow
Closing heat balance	cold load flow

Table 3. Controls implemented in the model.

The controllers adjust to the model parameters that correspond to values of the variables set by the user and that correspond to the operation design. The model considers the product temperatures as parameters, setting the bath temperature at 1,250°C and the gas temperature at 1,300°C. The chemical quality specifications of the matte and slag are also parameters of the model.

PROCESS ANALYSIS PLANNING

The parameters of the model and variables for analysis are presented in Table 4.

As in the melting furnaces in the bath the enrichment cannot be high [6], the autothermicity is achieved operating with high-grade mattes, which are called white

Description	Chemical reaction
Decomposition of chalcopyrite into the molten sulfides that make up the matte and the remaining sulfur oxidized with oxygen supplied to sulfur dioxide.	$2CuFeS_{2(s)} + O_{2(g)} = Cu_2S_{(l)} + 2FeS_{(l)} + SO_{2(g)}$
Decomposition of the bornite into the molten sulfides that make up the matte and the remaining sulfur oxidized with oxygen supplied to sulfur dioxide.	$2Cu_5FeS_{4(s)} + O_{2(g)} = 5Cu_2S_{(l)} + 2FeS_{(l)} + SO_{2(g)}$
Decomposition of pyrite into the molten iron sulfides that make up the matte and the remaining sulfur oxidized with oxygen supplied to sulfur dioxide.	$FeS_{2(s)} + O_{2(g)} = FeS_{(l)} + SO_{2(g)}$
Decomposition of pyrite into the molten iron sulfide that makes up the matte and the remaining sulfur oxidized with oxygen supplied to sulfur dioxide.	$FeS_{2(s)} + O_{2(g)} = FeS_{(l)} + SO_{2(g)}$
Decomposition of covelin in the molten copper sulfide that makes up the matte and the remaining sulfur oxidized with oxygen supplied to sulfur dioxide.	$2CuS_{(s)} + O_{2(g)} = Cu_2S_{(l)} + SO_{2(g)}$
Fusion of the chalcocite present in the concentrate in the molten copper sulfide that makes up the matte	$Cu_2S_{(s)} = Cu_2S_{(l)}$
Fusion of the magnetite present in the flux that goes on to compose the slag.	$Fe_3O_{4(s)} = Fe_3O_{4(l)}$
Fusion of the silica present in the concentrate and flux that goes on to compose the slag.	$SiO_{2(s)} = SiO_{2(l)}$
Vaporization of the water present in the concentrate to steam that makes up the process gases.	$H_2O_{(l)} = H_2O_{(g)}$
Oxidation of the molten FeS in the matte to FeO, which is immiscible in the matte and starts to form the slag. This exothermic reaction is the main reason why the process is autothermal and no fuel is used.	$FeS_{(l)} + {}^3/_2O_{2(g)} = FeO_{(l)} + SO_{2(g)}$
Oxidation of the FeO formed to magnetite in the slag.	$6FeO_{(l)} + O_{2(g)} = 2Fe_3O_{4(l)}$
To avoid the formation of magnetite, a siliceous flux is provided to form fayalite that makes up the slag.	$2FeO_{(l)} + SiO_{2(g)} = Fe_2SiO_{4(l)}$
Oxidation of the Cu2S that makes up the kills to Cu_2O that goes on to form the slag.	$Cu_2S_{(l)} + {}^3/_2O_{2(g)} = Cu_2O_{(l)} + SO_{2(g)}$

Table 2. Description and governing equations.

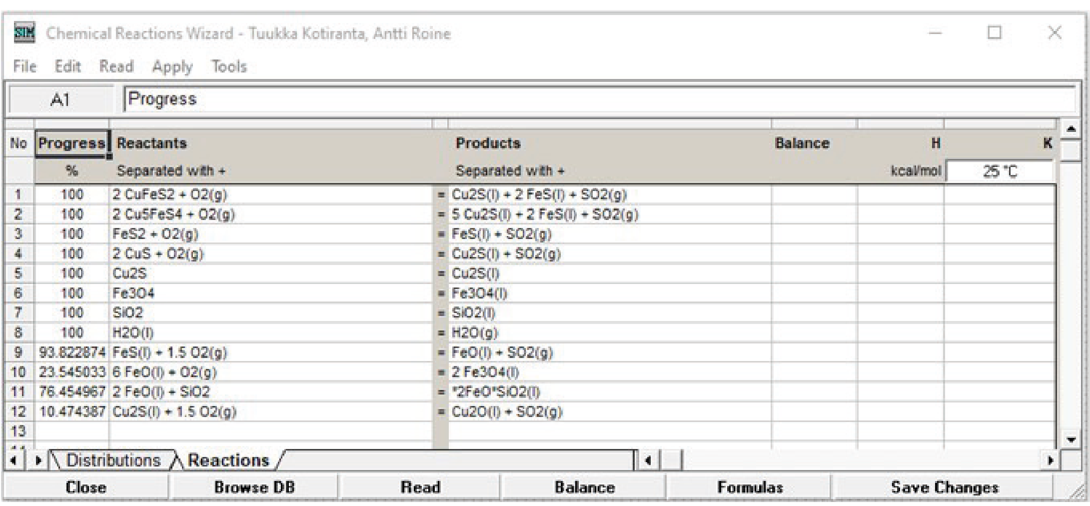

Fig. 4. Implementation of the governing equations in the model and its progress.

Chemical Reactions Wizard - Tuukka Kotiranta, Antti Roine

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	A	B	D	E	F	G	H	I
1		DISTRIBUTIONS	Total	Output Streams %				
6		Phases / Species	%	White Metal	Slag	Gases CT		
7	A	Amount	0.00					
8	T	Temperatura	0.00					
9	P	Gases	0.00					
10		O2(g)	100.00			100.00		
11		N2(g)	100.00			100.00		
12		SO2(g)	100.00			100.00		
13		H2O(g)	100.00			100.00		
14	P	Water	0.00					
15		H2O(l)	0.00					
16	P	Solids	0.00					
17		CuFeS2	0.00					
18		Cu5FeS4	0.00					
19		FeS2	0.00					
20		CuS	0.00					
21		Cu2S	0.00					
22		Fe3O4	0.00					
23		SiO2	0.00					
24	P	Molten bath	0.00					
25		Cu2S(l)	100.00	99.00	1.00			
26		FeS(l)	100.00	99.00	1.00			
27		Fe3O4(l)	100.00	1.00	99.00			
28		*2FeO*SiO2(l)	100.00		100.00			
29		SiO2(l)	100.00		100.00			
30		Cu2O(l)	100.00		100.00			
31		FeO(l)	100.00		100.00			

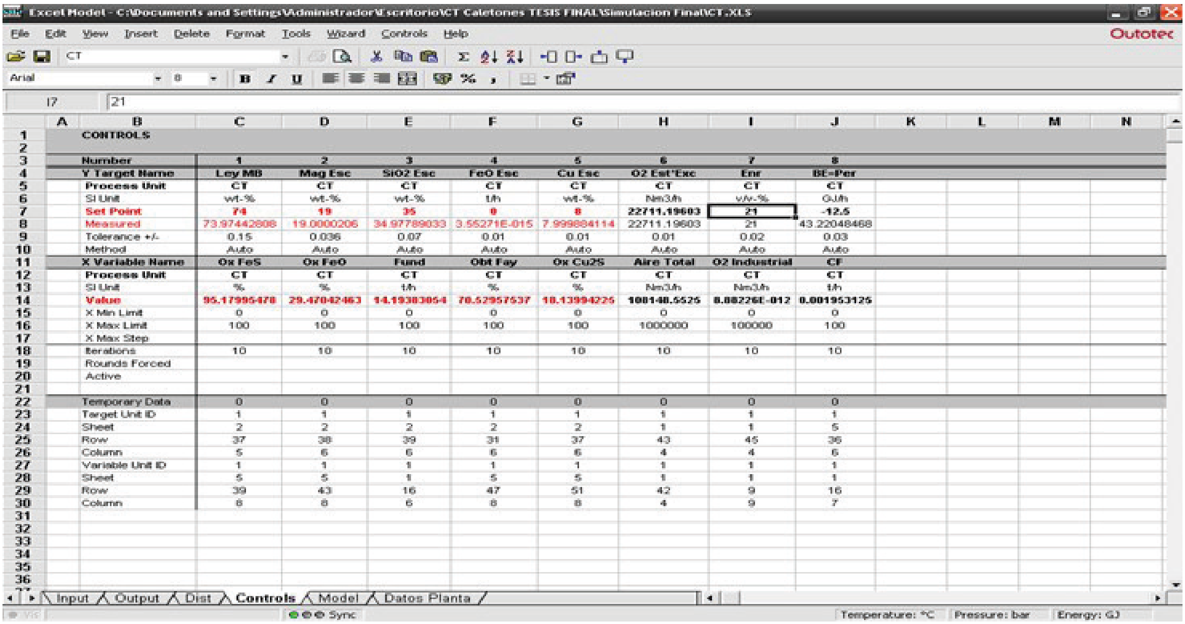
Fig. 5. Distributions of Compounds in the Flows.

Slag parameters	Variable	White Metal Parameter (Cu Law)
19% Magnetite	Oxygen enrichment	72 %
35% Total Silica		74 %
8% total copper		76 %

Table 4. Parameters of the model and variables for analysis

Required Flows	Generated flows	Indexes
Blowing air flow, Nm^3/h	White Metal, t/h	Oxygen Coefficient
Industrial O_2 flow (94%), Nm^3/h.	Slag, t/h	% $SO_{2(g)}$ in process gas flow
Flux flow, t/h	Process gases, Nm^3/h	
Cold cargo flow, t/h		

Table 5. Results of model parameters and variables for análisis



	B	C	D	E	F	G	H	I	J
1	CONTROLS								
2									
3	Number	1	2	3	4	5	6	7	8
4	Y Target Name	Ley MB	Mag Esc	SiO2 Esc	FeO Esc	Cu Esc	O2 Est'Exc	Enr	BE=Per
5	Process Unit	CT	CT	CT	CT	CT	CT	CT	CT
6	SI Unit	wt-%	wt-%	wt-%	t/h	wt-%	Nm3/h	v/v-%	GJ/h
7	Set Point	74	19	35	0	8	22711.19603	21	-12.5
8	Measured	73.97442808	19.0000206	34.97789033	3.55271E-015	7.999884114	22711.19603	21	43.22048468
9	Tolerance +/-	0.15	0.036	0.07	0.01	0.01	0.01	0.02	0.03
10	Method	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto
11	X Variable Name	Ox FeS	Ox FeO	Fund	Obt Fay	Ox Cu2S	Aire Total	O2 Industrial	CF
12	Process Unit	CT	CT	CT	CT	CT	CT	CT	CT
13	SI Unit	%	%	t/h	%	%	Nm3/h	Nm3/h	t/h
14	Value	95.17995478	29.47042463	14.19383054	70.52957537	10.13994225	108148.5525	8.88226E-012	0.001953125
15	X Min Limit	0	0	0	0	0	0	0	0
16	X Max Limit	100	100	100	100	100	1000000	100000	100
17	X Max Step								
18	Iterations	10	10	10	10	10	10	10	10
19	Rounds Forced								
20	Active								
21									
22	Temporary Data	0	0	0	0	0	0	0	0
23	Target Unit ID	1	1	1	1	1	1	1	1
24	Sheet	2	2	2	2	2	1	1	5
25	Row	37	38	39	31	37	43	45	36
26	Column	5	6	6	6	6	4	4	6
27	Variable Unit ID	1	1	1	1	1	1	1	1
28	Sheet	5	5	1	5	5	1	1	1
29	Row	39	43	16	47	51	42	9	16
30	Column	8	8	6	8	8	4	9	7

Input / Output / Dist / Controls / Model / Datos Planta

Fig. 10. Results in the heat balance when operating without enrichment (white metal grade 72%).

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metal, however, the above, its value varies from 72 to 76 % that is what will be analyzed through simulations, which must yield the following results.

The operation of the smelting furnace in the bath bases its enrichment on the increase in the flow of technical oxygen, which leads to a greater oxidation of FeS, and this, in turn, generates greater heat. This and other variables impact the operating parameters, therefore, the simulation through the "controllers" tool must return the process to its steady state, delivering new results such as the flow of white metal, slag and process gases.

RESULTS AND DISCUSSIONS

The effect on the industrial air/oxygen mixture required to produce a high-grade matte of 72% is shown below, given the increase in enrichment from 29 to 39%.

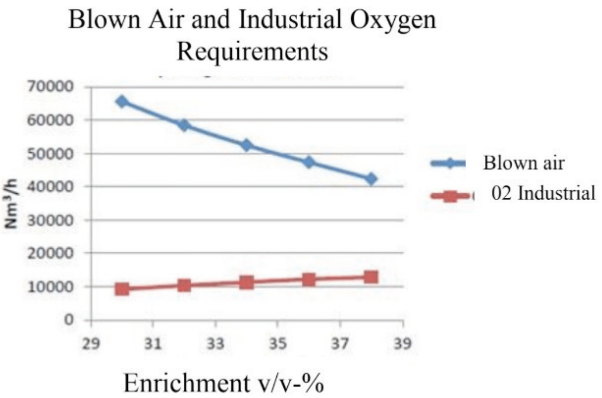

Fig. 6. Blowing air and industrial oxygen requirements versus % enrichment (white metal grade 72%).

From Figure 6 it can be inferred that as the enrichment increases from 30 to 38% the air flow decreases from 65,000 to 42,000 Nm^3 while industrial oxygen increases from 9,000 to 12,000 Nm^3. Correct situation since industrial oxygen is composed almost exclusively of oxygen. For example, for a volume of 100 Nm^3 of air there are 21 Nm^3 of oxygen and for 100 Nm^3 of industrial oxygen there are 94 Nm^3 of oxygen, therefore, a mixture with a greater flow of industrial oxygen than air flow will deliver a further enrichment.

The effect on flux feed and cold charge supply required to produce a 72% high grade matte is shown below, given the increase in enrichment from 29 to 39%.

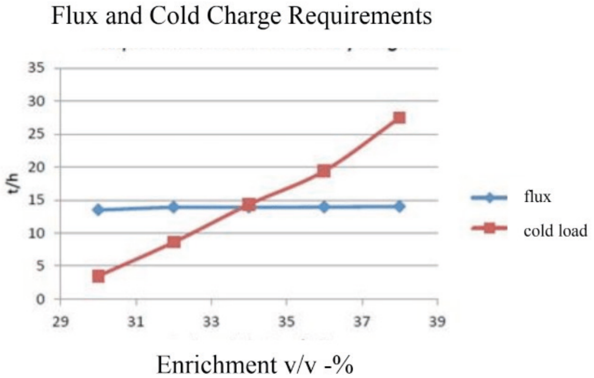

Fig. 7. Flux and cold charge requirements versus % enrichment (72% white metal grade).

The behavior shown in figure 7 indicates that as the enrichment increases from 30 to 38%, the flux demand remains practically constant at 14 t/h, this is due to the fact that the flux has effects on the silica content in the slag and its value is not appreciably related to the heat balance, however the cold load increases from 4 t/h to 27 t/h, which is coherent given that by increasing the enrichment less nitrogen is being blown into the reactor which it does not react and it simply takes sensible heat from the system, that is, it acts as a refrigerant, therefore, an increase in enrichment implies a greater quantity of oxygen and less nitrogen, therefore, the system presents a thermal surplus, part of it is released to the environment according to the losses of the equipment but the thermal surplus that still resides in the reactor must be balanced and this is achieved by consuming heat through low-temperature materials that consume sensible heat to reach the process temperature and reactions that are endothermic, as is the case of the components of the cold load.

Below is the effect on white metal production and slag generation when a 72% white metal is produced, given the increase in enrichment from 29 to 39%.

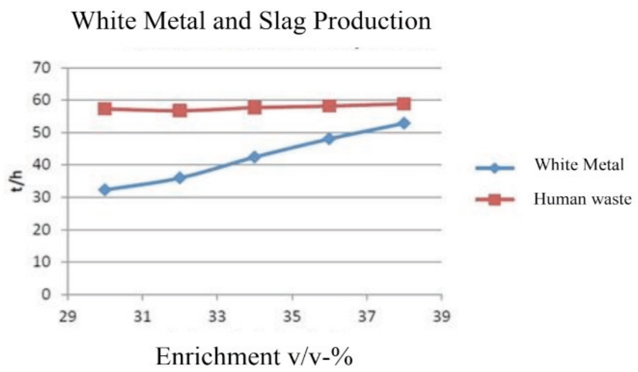

Fig. 8. Production of white metal and slag versus % enrichment (white metal grade 72%).

The behavior shown in figure 8 shows that as the enrichment increases from 30 to 38%, the slag production remains practically constant at 58 t/h but increasing and that of white metal increases significantly from 32 t/h to 53 t /h, this is due to the fact that as the enrichment increases, the cold load increases from 4 t/h to 27 t/h, which is made up of 90% Cu2S and 10% Fe3O4, the amounts of which become part of the matte and slag, respectively. Therefore, the increase in white metal is due to the high percentage of Cu2S in the cold charge used in the model.

Next, the effect on the volumetric flow of process gases and their concentration of sulfur dioxide in percentage is shown when a white metal of 72% is produced, given the increase in enrichment from 29 to 39%.

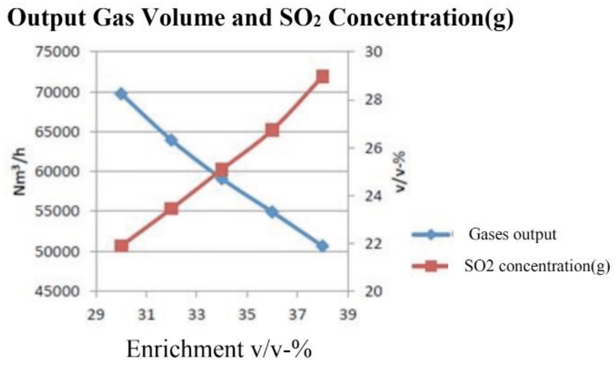

Fig. 9. Flue gas volumetric flow and % SO_2 versus % enrichment (72% white metal grade).

The behavior shown in figure 9 shows that as the enrichment increases from 30 to 38%, a lower volumetric flow of exhaust gases is generated and a higher concentration of sulfur dioxide in them, this is due to the fact that when enriching the volumetric flow of nitrogen, which is inert, is decreased and therefore its output value is equal to the input value. On the other hand, the volumetric flow of oxygen does not increase significantly before enrichment, therefore, the exhaust gases decrease from 70,000 Nm3/h to 50,000 Nm3/h, whose difference is attributable to the decrease in the volumetric flow of nitrogen, and as, the volumetric flow of sulfur dioxide is maintained, then the concentration of sulfur dioxide increases from 22% to 29% SO_2.

Next, the effect of operating without enrichment is shown, that is, the oxygen required to carry out the oxidation of the impurities is in a concentration of 21%, with the remaining 79% being nitrogen.

It can be seen that the heat balance does not close (Cell “J8”), and that the system presents a thermal deficit or is endothermic ($\Delta H > 0$), that is, the reactor requires heat to operate within the thermal parameters. This can be balanced by burning fossil fuel, preheating the feed streams, delivering sensible heat to the system, or another alternative would be to feed low grade molten matte from another smelter.

The results for higher grade bushes (74 and 76%) are similar to the previous ones and their quantification is given by the execution of the simulation. For the oxygen coefficient index, it increases linearly from 266 to 281 Nm^3 of O_2/ton of concentrate as the white metal grade increases from 72 to 76%, operating with an enrichment of 36%.

CONCLUSIONS

To produce a 72% matte, as the enrichment increases from 29 to 39%, the air flow decreases from 65,000 to 42,000 Nm^3 while the industrial oxygen increases from 9,000 to 12,000 Nm^3.

To produce a 72% matte as enrichment increases from 29 to 39%, the flux feed is a constant 14 t/h, and the cold charge increases from 4 t/h to 27 t/h.

To produce a 72% matte as enrichment increases from 29 to 39%, slag generation is 58 t/h, and white metal increases from 32 t/h to 53 t/h.

To produce a 72% matte as enrichment increases from 29 to 39%, the volumetric flow of process gases decreases from 70,000 Nm3/h to 50,000 Nm3/h and the sulfur dioxide concentration increases from 22% to 29% of SO2.

Without enrichment extra heat supply is required to close the balance.

Keeping the enrichment fixed at 36%, the oxygen coefficient increases linearly from 266 to 281 Nm^3 O_2/ton of concentrate as the white metal grade increases from 72 to 76%.

REFERENCES

1. ADRIAZOLA, G. **Modelación y Simulación de una fundición de cobre usando software comercial HSC-Chemistry.** Universidad de Santiago de Chile, Facultad de Ingeniería, Departamento de Ingeniería Química, 2009.

2. MANRÍQUEZ, J; NAVARRO, P; GUTIERREZ, A; CABELLO, G. **Oxygen enrichment analysis in Smelting Process by lateral submerged tuyere using HSC software.** XI CIM 2022.

3. CUBILLOS, F; VEGA, R. **Uso de herramientas de balances pirometalúrgicos usando HSC 6.1,** Universidad de Santiago de Chile, Facultad de Ingeniería, Departamento de Ingeniería Química, 2012.

4. ROINE, A; KOTIRANTE, T. **HSC Chemistry® 6.0 User´s Guide, Volume 2/2,** Outotec, Finlandia, 2006.

5. DONOSO, G. **Análisis del tratamiento de escorias provenientes de un horno de fusión y un horno de conversión mediante simulación de balance de masa y energía en HSC.** Universidad de Santiago de Chile, Facultad de Ingeniería, Departamento de Ingeniería Metalúrgica, 2022.

6. PARRA, I. **Modelamiento y análisis del proceso de fusión en un horno SKS con tecnología china de fusión soplado inferior BBS (Bottom Blowing Smelting).** Universidad de Santiago de Chile, Facultad de Ingeniería, Departamento de Ingeniería Metalúrgica", 2019.