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Ammoniacal Carbonate Leaching: Simulation of ammonia profile and solid concentration on a full-scale by mass balance

Lixiviación carbonato amoniacal: Simulación del perfil de amoniaco y concentración de sólidos a escala industrial por balance de masa

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ABSTRACT

Modeling and simulation are useful for testing, analysis or training a real system or concept represented by a model. This research was carried out in the ammoniacal leaching technology for nickel recovery from laterite ore, with the aim of performer a simulation algorithm of ammonia profile and solid concentration by mass balance in steady state. Flowsheet of leaching system assumed as model on a full-scale, consisted of aerated continues stirring tank reactors and thickeners tanks disposed in eight steps of leaching and washing, in countercurrent operation. As a result, the solvent flows and feed points were determined to achieve a closer approximation of operating parameters to standardized values. In future work, the residence time distribution function and kinetic modeling will be incorporated into the algorithm to simulate the efficiency of nickel leaching.

Keywords: leaching; mass balance; nickel; simulation.

RESUMEN

La modelación y simulación son útiles para evaluar, analizar o entrenar un sistema real o conceptos representados por un modelo. Esta investigación se realizó en la tecnología de lixiviación amoniacal para la recuperación de níquel del mineral laterita, con el propósito de desarrollar un algoritmo de simulación del perfil de amoniaco y la concentración de sólidos por balance de de masa en régimen estacionario. El diagrama de flujo del sistema de lixiviación asumido como modelo a escala industrial, consistió en reactores continuos aireados con agitación y sedimentadores dispuestos en ocho etapas de lixiviación y lavado, en configuración contracorriente. Como resultado, se determinaron los flujos y puntos de alimentación del solvente para alcanzar la mayor aproximación de los parámetros de operación a los valores normados. En posteriores trabajos se va a incorporar al algoritmo la función de distribución del tiempo de residencia y la modelación cinética con vistas a simular la eficiencia de lixiviación de níquel.

Palabras clave: lixiviación; balance de masa; níquel; simulación.

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Introduction

Modeling and simulation (M&S) provides virtual duplication of a system entity, process or phenomenon, and represents those in readily available and operationally valid environments. A model is a physical, mathematical or logical representation, while a simulation is the implementation of a model over time.(1,2)

M&S are useful for testing, analysis or training a real system or concept represented by a model.

Systems are modeled as having a number of inputs x_1, x_2…, x_n; outputs or responses y_1, y_2... y_n; and system parameters P_1, P_2…, P_n.

An essential stage in the development of any model is the formulation of mass and energy balance equations. In addition, kinetic reaction, rate of transfer of momentum, heat and mass, and property changes physic-chemistry and thermodynamic are considered.

Models can be static, representing a system at a particular point in time, or dynamic, representing how a system changes with time.

Several numerical or experimental works deal with M&S in the ammoniacal carbonate leaching technology have been presented, in the process steps: laterite ore beneficiation, drying (3,4,5), grinding (6), reduction-roasting(7,8) leaching of roaster product in ammoniacal solvent, precipitation of nickel as basic nickel carbonate (BNC) intermediate product in steam-stripped columns [9,10], and thermal decomposition to NiO. [11,12]

In addition, M&S of thickener tanks have been made by non-linear partial differential equations, from both mass and momentum balance equations, to attain a better knowledge of the decantation process.[13,14] Likewise, combination of Residence Time Distribution (RTD) function and kinetic modelling is used to predict the course of chemical reactions in Continuous Stirring Tank Reactors (CSTR).[15]

In this work, M&S was performed in the leaching system on a full-scale by total mass balances and component mass balances at steady-state, in order to simulate the ammonia profile and solids concentration in the system, and analyze deviations from operating parameters. Flowsheet assumed as model consisted of aerated CSTR and thickeners tanks disposed in eight steps of leaching and washing, in countercurrent operation.

Materials and methods

Flowsheet of leaching system on a full-scale

Roaster product is mixed with ammonia/ammonium carbonate solution in the quench tank at a liquid-to-solid ratio 5.4-6.3 kg/kg. The resulting slurry is leached in aerated CSTR. The Pregnant Liquor is separated from the undissolved solid in thickener tanks. The ammoniacal liquors (Fresh Liquor and Weak Liquor) are feed in countercurrent configuration from washing to leaching steps (figure 1).

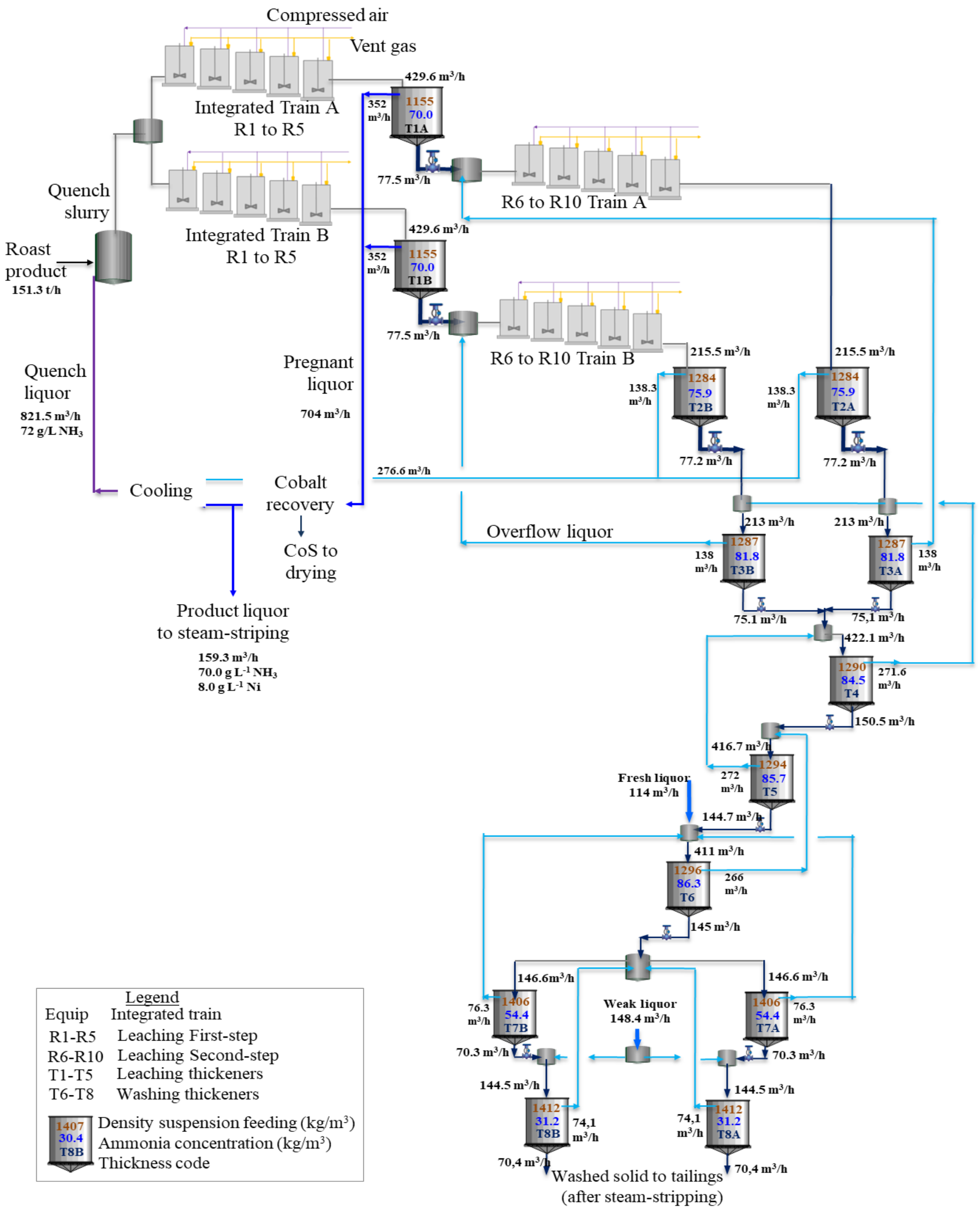

Fig. 1 - Flowsheet of leaching system on a full-scale

Product Liquor C_{Ni}: 8.0 g/L

Input parameters of simulation algorithm

Leaching conditions are based in the following independent variables: [10, 16]

- Roaster product flow (t/h) > 100 t/h
- Product Liquor: ammonia > 60 g/L, nickel > 6,5 g/L
- Feed sludge density in first leaching stage: 1142-1160 kg/m^3

- Thickened sludge density: 1700-1750 kg/m^3 for leaching-steps and 1800-1850 kg/m^3 for washing-steps
- Nickel extraction for each step (%)
- Ammonia loses in each step (g/L)
- Ammonia concentration: 120-130 g/L for Fresh Liquor, and 10-15 g/L Weak Liquor
- Density real of roaster product: 4200 kg/m^3 for leaching-steps and 4000 kg/m^3 for washing-steps
- Product Liquor density: 1024 kg/m^3 for leaching and 1000 kg/m^3 for washing-steps

Output parameters of simulation algorithm

The output parameters of simulation algorithm are:

- Fresh Liquor flow, second washing stage
- Weak Liquor flow, third washing stage
- Density profile in the feed sludge
- Ammonia concentration profile
- Flow of thickened sludge (underflow) and clear liquor (overflow)
- Ammonia losses, by the “Black box model”
- Air flow and theoretical retention time in the leaching reactors
- Makeup Fresh Liquor flow, in the second and third leaching stage and first washing stage

Equations for the mass balance

Flowsheet of thickener tanks are shown in figure 2 and the parameters: Sludge Feed (F, m^3/h), overflow or clear liquor (O, m^3/h), underflow or thickened sludge (U, m^3/h), density (ρ, kg/m^3) and solid concentration (C, kg/m^3).

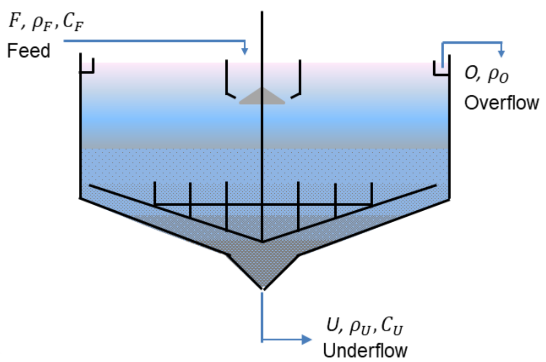

Fig. 2 – Flowsheet of thickener tanks

Mass balance for liquor and solid are represented by (1-2)

$$F\ (\rho_F - C_F) = O\ \rho_O + U\ (\rho_U - C_U) \quad (1)$$

$$F\ C_F = U\ C_U \quad (2)$$

$$F\ = \frac{O\ \rho_O}{(\rho_F - C_F) - \frac{C_F}{C_U}(\rho_U - C_U)} \quad (3)$$

Concentration of solid is determined by (4), liquid-to-solid ratio (L/S, kg/kg) (5), where sub-indexes "p, s, l" represent particle, sludge and liquor, respectively.

$$C_s = \rho_p\ \frac{(\rho_s - \rho_l)}{(\rho_p - \rho_l)} \quad (4)$$

$$\frac{L}{S} = \frac{\rho_l}{\rho_p}\ \frac{(\rho_p - \rho_s)}{(\rho_s - \rho_l)} \quad (5)$$

Feed sludge density profile in the thickener tanks was determined fallowing the algorithm from figure 3, were roasted product flow is RP (t/h). Sludge density is supposed (II) to check there is no solid accumulation (V). Then, a component mass balance was performed to determine ammonia concentration for each stage.[6] Finally, both ammonia concentration and feed density are supposed for the last step of washing (T8A and T8B); using figure 3, the solid accumulation is checked, and then ammonia concentration is tested (7).

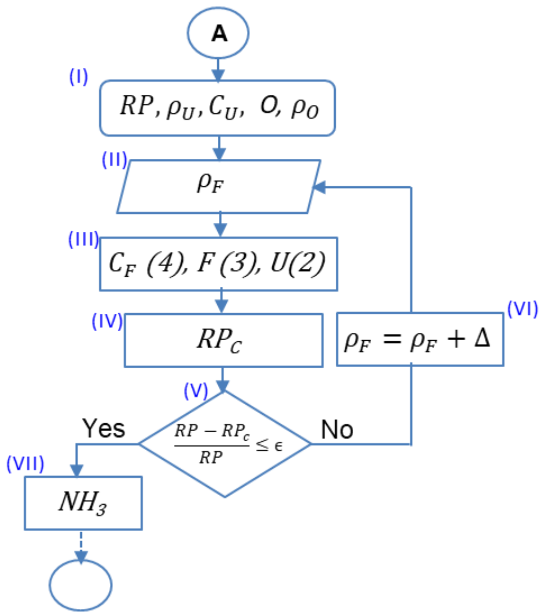

Fig. 3 – Algorithm for density profile in the thickeners feed

$$C_{NH3}^{T6} = \frac{\left[\frac{F}{\rho_l}(\rho_F - C_F)\, C_{NH_3}\right]^{T5} - \left[\frac{U}{\rho_l}(\rho_U - C_U)\, C_{NH_3}\right]^{T4}}{O^{T6}} \tag{6}$$

$$C_{NH3}^{T8A} = \frac{\left[\frac{U}{\rho_l}(\rho_U - C_U)\, C_{NH_3}\right]^{T7A} + \frac{1}{2}\, WL\ C_{NH_3}^{WL}}{\left[\frac{F}{\rho_l}(\rho_F - C_F)\, C_{NH_3}\right]^{T8A}} \tag{7}$$

Restrictions and validation of simulation algorithm

Mass balance was performed in steady state. The ammonia concentration in the third washing step is approximately 30 g/L.(16) Sludge density in the thickeners feed should as following: First-step of leaching 1142-1160 kg/m^3, second-step of leaching 1200-1250 kg/m^3, from third to fifth step of leaching 1300-1350 kg/m^3, and from first to third step of washing: 1350-1450 kg/m^3.

The simulation algorithm was validated by the “Black-box model” for the flows of sludge (8), solid and the component ammonia, the interpretation of simulation results and industrial operation.

$$WL + FL + U^{T1} = O^{T2} + U^{T8} \tag{8}$$

Results and discussion

Mass balance was performed at the operating parameters showed in table 1, simulating different ammonia gradient (∇_{NH3}) in the reactors of first leaching step.

Table 1- Input/output parameter of simulation algorithm (C_{Ni} 8.0 g/L)

	Code	unit	Value		
Input parameter					
Roasted product	RP	t/d		153.3	
Nickel extractions in reactors of leaching	-	%		76.0	
Nickel extractions in thickness tanks	-	%		3.0	
Nickel in Product Liquor	C_{Ni}	g/L		8.0	
Ammonia in Product Liquor	C_{NH3}	g/L		70.0	
Ammonia gradient, second-step	∇_{NH3}	g/L		2.0	
Ammonia gradient, first-step	∇_{NH3}	g/L	1.5	3.5	5.5
Output parameter					
Product Liquor	PL	m^3/h		159.3	
Weak Liquor (T8A+T8B)	WL	m^3/h	148.4	131.8	118.8
Fresh Liquor (T7A+T7B)	FL	m^3/h	0.4	0.3	0.5
Makeup Fresh Liquor (T6)	-	m^3/h	113.6	60.9	41.7
Makeup Fresh Liquor (T3A+T3B)	-	m^3/h	0	34.6	102.0

From table 1, the higher the ammonia gradient in first-step leach reactors is, the lower Weak Liquor flow and the higher the makeup Fresh Liquor flow are. No Fresh Liquor was fed to thickener tanks T7A and T7B because an ammonia concentration is obtained in the third washing step (T8A, T8B) much higher than the recommended value (30 g/L). This avoids greater energy consumption in the steam stripping column for the ammonia recovery from washed solid residue (figure 4).

Furthermore, when ammonia gradient increases the slurry density feed to thickeners tanks also tend to increase. For ∇_{NH3} = 5.5 g/L the density is higher than the target values. Therefore, operation of the leaching system at these flow and concentration conditions could result in a higher concentration of suspended solids in the overflows and a lower settling velocity, which is determined experimentally. Dirty thickener overflows affect the efficiency of the ammoniacal liquor cooling system, by increasing deposits accumulation onto the internal surfaces of the heat exchangers. [17] The higher the temperature in the leaching system the greater the evaporation of ammonia, thus generating a chain of disturbances that tend to reduce leaching efficiency (figure 5).

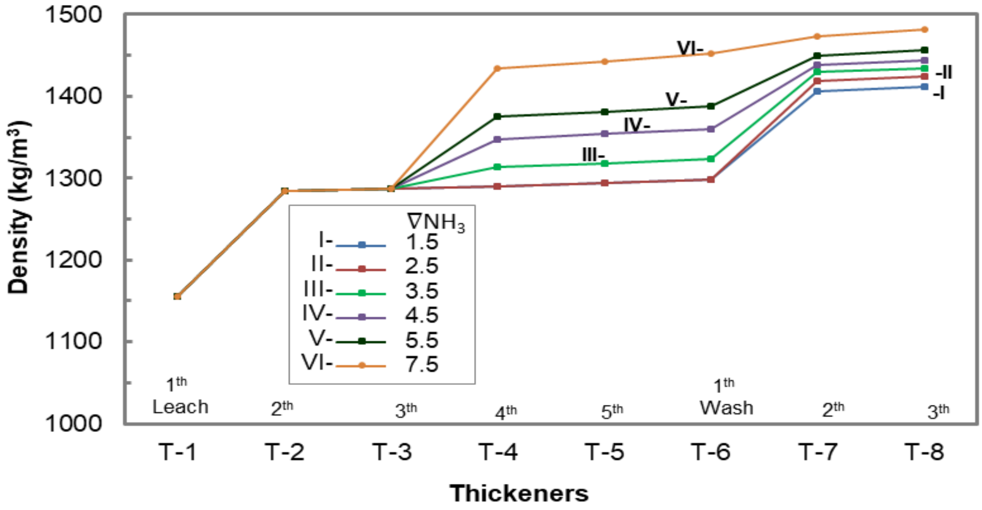

Fig. 4- Simulation of density profile of leaching process on a full-scale at different ammonia gradients in the reactors of leaching first-step, C_{Ni} 8 g/L (table 1)

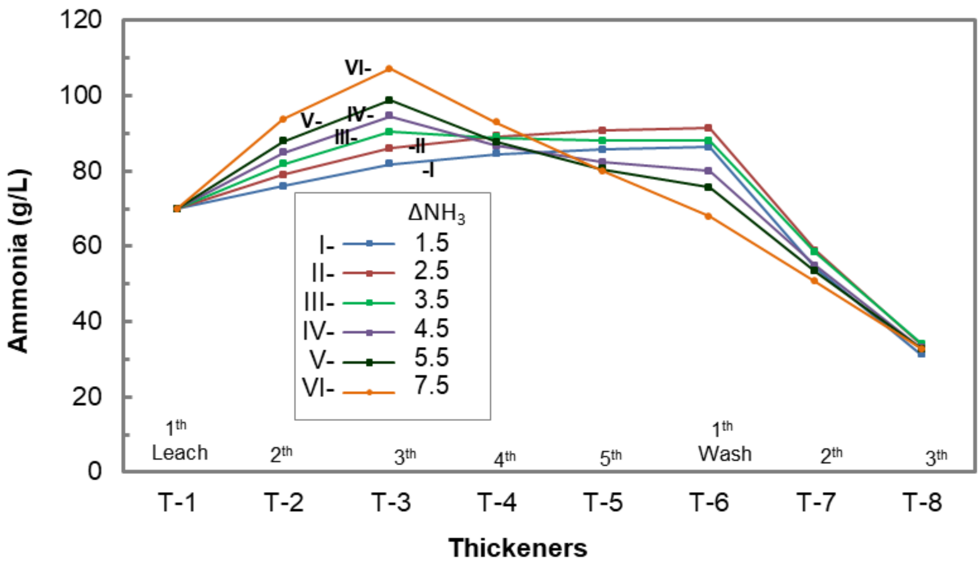

Fig. 5- Simulation of ammonia profile of leaching process on a full-scale at different ammonia gradients in the reactors of leaching first-step, C_{Ni} 8 g/L (table 1)

In addition, a mass balance was performed at a nickel concentration of 6,5 g/L in the Product Liquor (PL), at the same input parameters (table 2) (figure 6).

Table 2- Input/output parameter of simulation algorithm (C_{Ni} 6.5 g/L)

	Code	unit	Value		
Input parameter					
Ammonia gradient, second-step	∇NH_3	g/L		2.0	
Ammonia gradient, first-step	∇NH_3	g/L	1.5	3.5	5.5
Output parameter					
Product Liquor	PL	m^3/h		196.0	
Weak Liquor (T8A+T8B)	WL	m^3/h	170.6	151.9	137.3
Fresh Liquor (T7A+T7B)	FL	m^3/h	0.2	0.2	0.1
Makeup Fresh Liquor (T6)	-	m^3/h	129.8	147.4	88.1
Makeup Fresh Liquor (T3A+T3B)	-	m^3/h	0	0	73.8

As shown in table 2, the lower the concentration of nickel in the Product Liquor, the flow of Product Liquor, Weak Liquor, Fresh Liquor, and the second stage overflow liquor flow (313 m^3/h) tend to increase. Then, an increase in the liquor velocity can be expected, with a greater possibility of entraining fine particles.

Density profile of fed sludge to the thickener tanks decreased, thus achieving a density closer to operating standards (figure 7).

Ammonia profile was approximately the same compared to the simulation at C_{Ni} 8,0 g/L, for the same NH_3 concentration gradient (figure 8).

The algorithm was tested using the "Black Box Model", and as a result the flows of sludge, solids and ammonia in the inlet and outlet streams of the system presented an absolute error in the estimate of less than 0,5 %.

The results contribute to decision-making regarding the feeding point of ammoniacal solvent (Fresh Liquor and Weak Liquor) to achieve a lower deviation of operating parameters with respect to standardized values in the leaching process. Future work will incorporate the residence time distribution function and kinetic modeling into the algorithm to simulate nickel leaching efficiency.[18] Furthermore, it is necessary to perform an experimental evaluation of the simulation results.

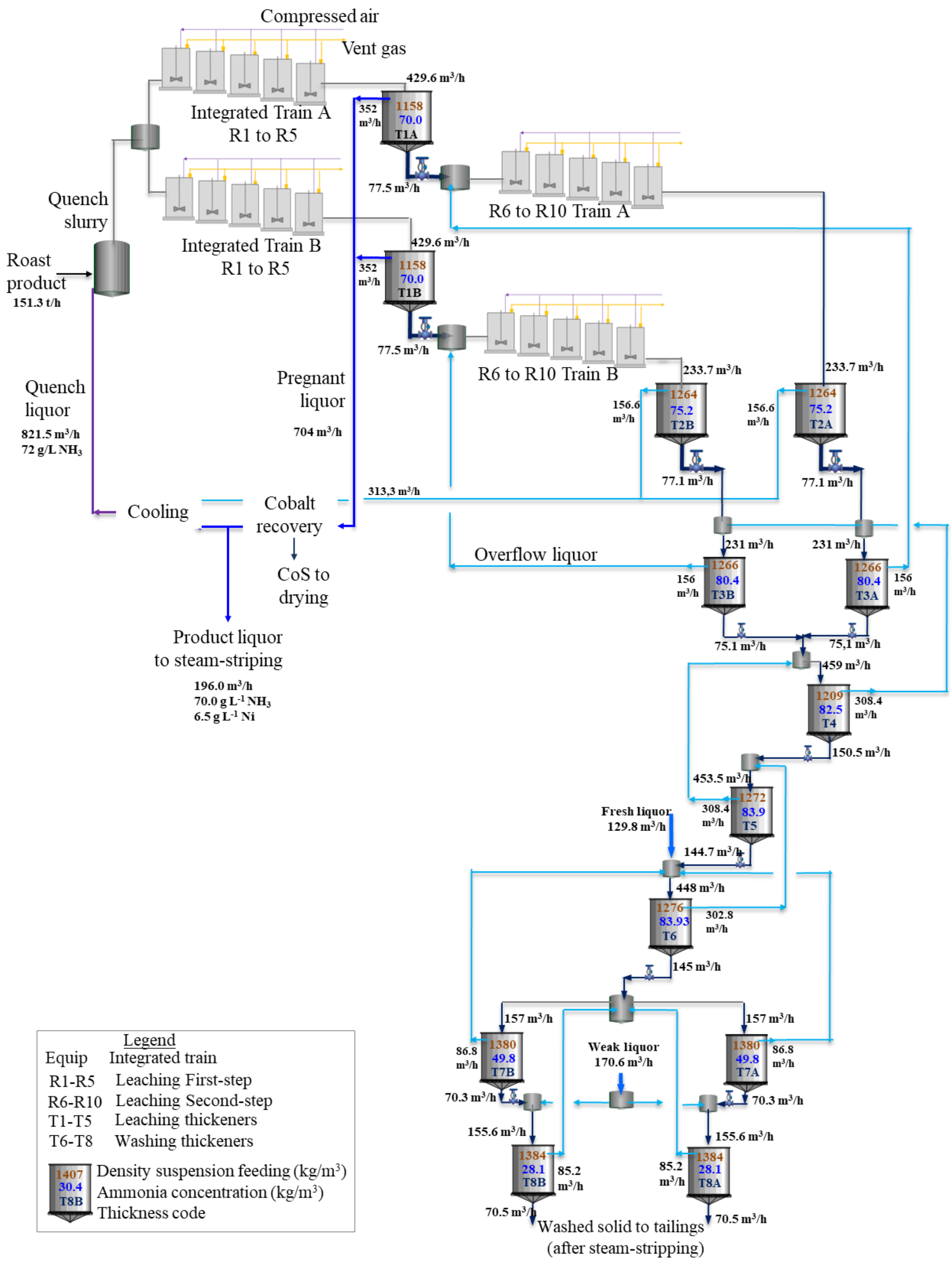

Fig. 6 - Flowsheet of leaching system on a full-scale

Product Liquor C_{Ni}: 6,5 g/L

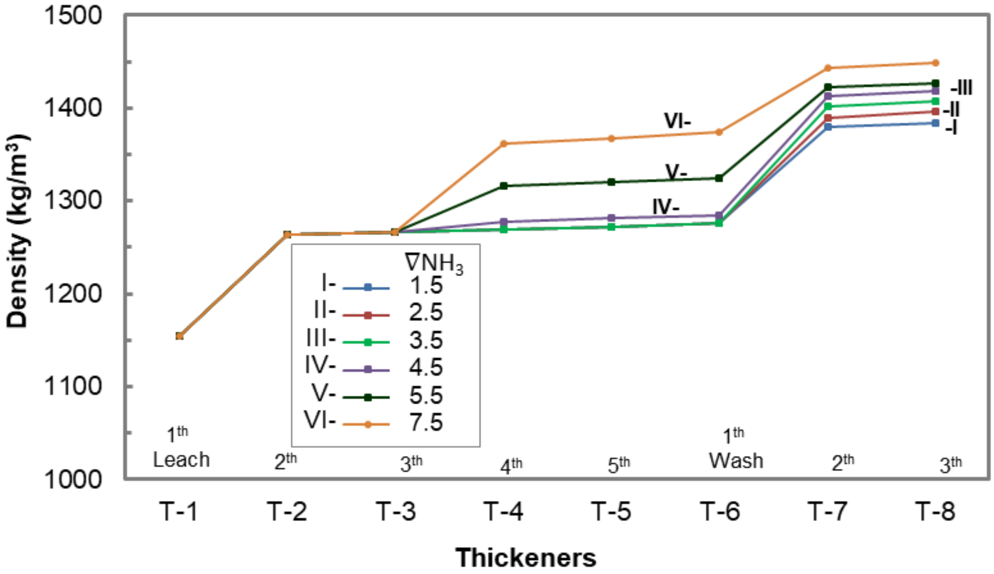

Fig. 7- Simulation of density profile of leaching process on a full-scale at different ammonia gradients in the reactors of leaching first-step, C_{Ni} 6,5 g/L (table 2)

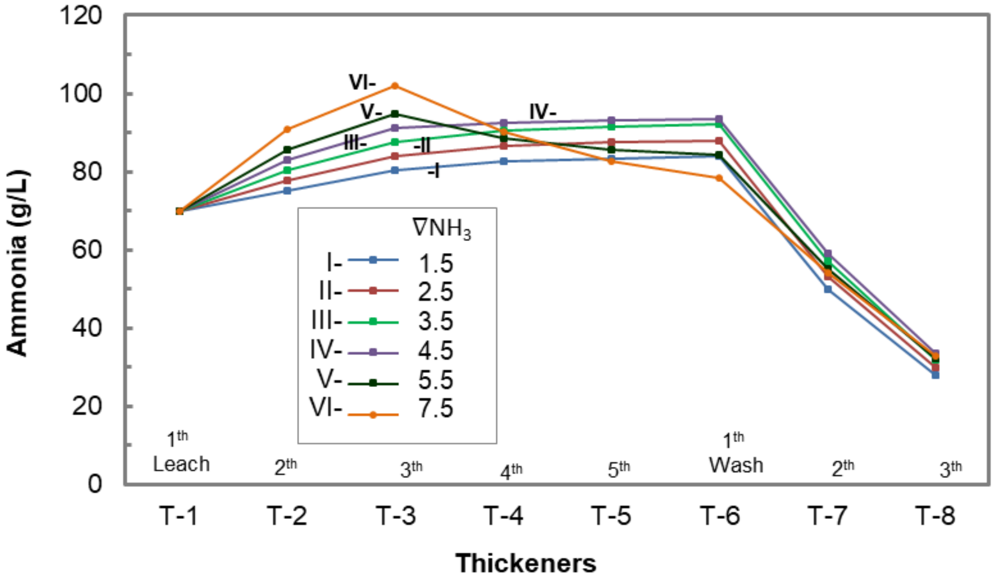

Fig. 8- Simulation of ammonia profile of leaching process on a full-scale at different ammonia gradients in the reactors of leaching first-step, C_{Ni} 6,5 g/L (table 2)

Conclusions

1. A numeric algorithm was performed by mass balance in steady state to model ammonia profile and solid concentration in the nickel leaching process on a full-scale, which was validated by the "Black Box model", the interpretation of simulation results and the industrial operation.

2. Simulation of operating parameters was carried out at different ammonia gradients in the leaching reactors, then the nickel concentration in the Product Liquor must be considered to determine solvent flows and feed points to achieve a closer approximation to standardized values.

Nomenclature

C, kg/m^3, solid concentration
F, m^3/h, sludge Feed
L, kg, liquid
O, m^3/h, overflow or clear liquor
RP, t/h, roasted product flow
S, kg, solid
U, m^3/h, underflow or thickened sludge
ρ, kg/m^3, density
"p, s, l" Indexes, represent particle, sludge and liquor, respectively.

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Declaration of interest

The author declares that he has not competing interest that could have appeared to influence the work reported in this paper.

Authorship contribution

Armando Rojas Vargas: conceptualization, ethodology, Investigation, Writing - Reviewing and Editing.