17th European Symposium on Computer Aided Process Engineering – ESCAPE17
V. Plesu and P.S. Agachi (Editors)

Steady-state optimisation of the leaching process at Kwinana Nickel Refinery

Travis M. Woodward and Parisa A. Bahri

School of Electrical, Energy & Process Engineering, Murdoch University, Murdoch, WA 6150, Australia, P.Bahri@murdoch.edu.au

Abstract

A comprehensive optimisation and simulation model has been built for analysis of the Sherritt-Gordon ammoniacal pressure leaching process at Kwinana Nickel Refinery. Challenges in operating the process stem from the complex arrangement of leaching autoclaves and flows, as well as the leach chemistry. The model offers a means for considerable insight into the nature of operation of the process. The optimisation problem formulation is addressed, detailing the chief elements of construction. Optimisation results are presented for the refinery's present operational scenario, and conclusions are drawn on the state of the new, optimally operated process.

Keywords

Leaching, reactor, mathematical modelling, optimisation.

1. Introduction

Industrial leaching processes generally comprise multiple leaching autoclaves that accommodate 3-phase (solid-liquid-gas) systems that exhibit complicated chemistry and kinetics. Given that leaching processes are principally the location of hydrometallurgical refinery bottlenecks, it is essential that these processes operate optimally to ensure maximum refinery throughput. Understanding how changes in process and operating conditions influence the performance of the leach is of paramount importance in arriving at this state of operation. The present work represents the development of an analytical tool that can aid in elucidating many of these unknowns.

2. Kwinana Nickel Refinery

Kwinana Nickel Refinery is located in Perth, Western Australia, and employs the Sherritt-Gordon ammoniacal pressure leaching process [1, 2] for the extraction of nickel, copper and cobalt. The refinery feed material is a nickel matte that contains: metallic nickel (Ni^0), heazlewoodite (Ni_3S_2), chalcocite (Cu_2S), cobalt sulphide (CoS), metallic iron (Fe^0) and pyrrhotite (FeS). Nickel contributes to approximately 67% of the total particulate feed.

The process comprises six 160 m^3 capacity, compartmentalised leaching autoclaves, configured as a 2-3-1 series, 3-stage counter-current leaching operation. Each autoclave contains four mechanically agitated, equally sized compartments that are separated by weir gates. Temperature (controlled through cooling coils) and pressure conditions across the 3-stage process span 85-95˚C and 750-1000 kPa, respectively, with 2nd and 3rd stage autoclaves operating under higher temperature and pressure. Fresh air is sparged into 2nd and 3rd stage autoclaves and vent gas is fed counter-currently to the 1st stage. Anhydrous ammonia or recycled ammonia from the ammonia still are fed to each autoclave, the former being delivered to the first two compartments, whilst the latter is delivered to the 1st compartment only. Multiple re-pulp tanks and thickeners also define the process. A flow diagram of the refinery leaching process is illustrated in Fig. 1.

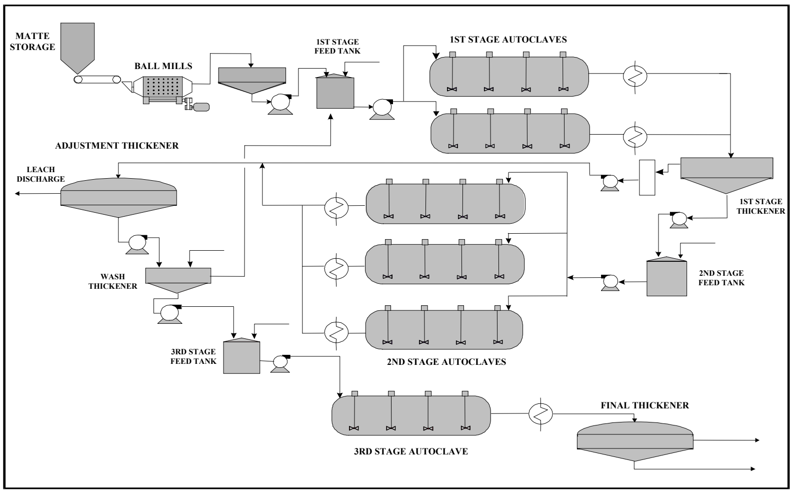

Figure 1. Kwinana Nickel Refinery Leaching Process

The principal leach chemistry is the pressure oxidation of sulphide to sulphate, where, upon oxidation, the metal ions combine with ammonia in solution to form ammine complexes, thus [3]:

$$\mathrm{MS} + 2\,\mathrm{O_2} + n\,\mathrm{NH_3} \rightarrow \mathrm{M(NH_3)}_n^{2+} + \mathrm{SO_4^{2-}} \tag{1}$$

where n is dependent on the concentration of ammonia and the type of (in this instance, divalent) metal M. The actual system considered is a much more complex series-parallel reaction network involving, among other characteristics, Cu(II) surrogate oxidation and the progressive oxidation of elemental sulphur to sulphate and sulphamate via various intermediately oxidised oxy-sulphur compounds.

3. The Optimisation Problem

The problem formulation was organised through the following elements: (1) the objective function, (2) the process model, and (3) the constraints. The objective function is the sum of the major operating costs of the leaching process at a given nickel matte feed rate. The optimisation problem takes the following form:

$$\text{Minimise:} \quad C(\boldsymbol{x}) \tag{2}$$

$$\text{Subject to:} \quad \boldsymbol{f}(\boldsymbol{x}) = \mathbf{0}, \qquad \boldsymbol{g}(\boldsymbol{x}) = \mathbf{0}, \qquad \boldsymbol{h}(\boldsymbol{x}) \geq \mathbf{0} \tag{3}$$

where $C(\boldsymbol{x})$ is the objective function, $\boldsymbol{f}(\boldsymbol{x})$ is a vector of model equations, $\boldsymbol{g}(\boldsymbol{x})$ is a vector of equality constraints, $\boldsymbol{h}(\boldsymbol{x})$ is a vector of inequality constraints, and $\boldsymbol{x}$ is a vector of n process variables ($x_1, x_2, \ldots, x_n$).

3.1. The Objective Function

The major operating costs for the process arise from anhydrous ammonia supply, steam supply and energy consumption. The requirements for anhydrous ammonia are clear-cut from discussions above. Steam, fed to the ammonia still, is considered to be central cost of providing recycled ammonia to the process. Energy consumption is due primarily to the leach air compressor, the autoclave compartment agitators, and the leach cooling water pumps.

3.2. The Process Model

The process model comprises three central unit operations: leaching reactors (autoclave compartments), tanks and thickeners. Tanks were modelled as perfect mixers, whereby the output rate is equal to the sum of the input rates. Thickeners were modelled as perfect splitters, whereby, for a fixed underflow density, the underflow rate can be calculated directly and the overflow rate is calculated by difference.

Autoclaves are described through modelling a number of leaching reactors in series that operate under the same total pressure. Leaching reactors are modelled through the coupling of three essential components: the material balance, the energy balance, and a statistical reactor model allowing the scale-up of particle kinetics; a host of supplementary equations are also required to institute the coupling. Material balances were developed for species in all three phases. An energy balance that accounts for all reactions and phase conversions was also incorporated. A total of 49 component species were considered, and the total number of reactions integrated include: 3 gas-liquid equilibria reactions, 9 heterogeneous redox reactions, 5 homogeneous redox reactions and 19 chemical equilibria reactions (i.e. metal ammine speciation). Mineral oxidation kinetics are expressed as a function of mineral conversion X, which is determined via the segregated flow model (the statistical reactor model) [4], and all other kinetics are expressed as functions of either temperature and concentration or gas partial pressure. The following equations characterise the compartment material balances, energy balance, and segregated flow model (for a single mineral), respectively:

$$F_i^{out} = F_i^{in} + \sum_k \nu_{i,k}\, r_k \tag{4}$$

$$\sum_i F_i^{out} H_i^{out} = \sum_i F_i^{in} H_i^{in} - \dot{Q} \tag{5}$$

$$1 - X = \int_0^{\infty} \int_{D_0(X_B=1)}^{D_0^{\max}} (1 - X_B)\, f(D_0)\, \mathrm{d}D_0\, E(t)\, \mathrm{d}t \tag{6}$$

where F_i is the molar flow rate of species *i*, $\nu_{i,k}$ is the stoichiometric coefficient of species *i* in reaction *k* (which takes a positive or negative value dependent on whether species *i* is a respective product or reactant), r_k is the molar rate of reaction *k*, H_i is the molar enthalpy of species *i*, $\dot{Q}$ is the net rate of heat removal, X_B is the batch reactor mineral conversion, $f(D_0)$ is the normalised, mass-weighted feed particle size distribution, D_0 is the feed particle diameter, $E(t)$ is the normalised, solids residence time distribution, and t is time.

3.3. The Constraints

The constraints are described through both equalities and inequalities. The equality constraints are defined for the following variables: compartment temperature, autoclave feed pulp density, stage feed tank repulp liquor flow rate, total autoclave anhydrous ammonia flow rate and 1st and 2nd compartment apportionment, autoclave recycled ammonia flow rate, autoclave feed gas compartment apportionment, and 2nd stage discharge conditions (i.e. nickel, ammonium sulphate and total intermediately oxidised oxy-sulphur compound concentrations). The inequality constraints define the limits for the following variables: 1st stage, 3rd stage and total leach discharge conditions, and 1st stage, 2nd stage and 3rd stage nickel extraction.

4. Simulation Results and Discussion

The model was constructed in Aspen Custom Modeler® [5], and can operate under "Optimization" and "Steady State" simulation modes; the latter executing only the process model code.

Under each mode, the effect the following key performance-determining reactor variables have on operation can be explored: component species' solution concentration, temperature, gas partial pressure, mean residence time, pulp density, agitation, and feed gas and ammonia compartment apportionment. The effects of other variables such as the following can also be established: leach feed matte flow rate, mineralogical composition and particle size distribution of the feed matte, total leach air supply rate and apportionment to 2nd and 3rd stage autoclaves, and stage feed tank repulp liquor flow rates and concentration profiles.

The Aspen Custom Modeler® reduced space, feasible path successive quadratic programming optimiser, termed *FEASOPT*, was selected for optimisation simulation [6]. The decision variables considered were: total leach air supply rate and apportionment for each of the 2nd and 3rd stage autoclaves. The power draw for each of the compartment agitators and cooling water pumps are set equal to their installed power ratings, and thus the associative energy consumption also remains a fixed quantity.

The nickel matte feed rate was specified at 320 tpd, with a mineralogical composition of: 7.5% Ni^0, 81.2% Ni_3S_2, 3.8% Cu_2S, 1.7% CoS, 0.7% Fe^0 and 5.1% FeS. This feed rate conforms to the 67,000 tpa target refinery nickel production at 86% process availability. Optimisation results are summarised in Table 1.

Table 1. Leach Performance Improvements at the Optimum

Optimised Variable	Improvement Factor (%)	Optimised Variable	Improvement Factor (%)
Major Operating Costs	9.7	Total Anhydrous NH_3	12.0
Total O_2 Utilisation	-4.8	Total Recycled NH_3	3.3
Total NH_3 Utilisation	0.7	Total Process Air	4.1

The results signify that under the conditions specified at the optimum, improved performance can be realised. The major operating costs are reduced, as is total ammonia usage and air supply. At the specified total leach air supply rate, however, alterations in air apportionment amongst 2nd and 3rd stage autoclaves and autoclave compartments doesn't lead to improvements in oxygen utilisation.

5. Conclusions and Future Work

A detailed analytical tool for analysis of the Kwinana Nickel Refinery leaching process has been developed. Optimisation results for the present target refinery nickel production have been presented. Future optimisation work will include: (1) a sensitivity analysis to determine the extent to which changes in process variables, such as matte mineralogy, affect the optimum, and (2) investigation of how changes in process structure, such as autoclave configuration and gas flow arrangement, influence overall leach performance.

Acknowledgements

Thanks are conveyed to the Australian Research Council and Kwinana Nickel Refinery for financial support, and to BHP Billiton Ltd for permission to publish the paper.

References

1. F.A. Forward, Canadian Institute Mining Transactions, 56 (1953) 373.
2. F.A. Forward and V.N. Mackiw, Journal of Metals, 7 (1955) 457.
3. B.F. Wishaw, The Chemistry of the Sherritt-Gordon Nickel Extraction Process, Internal Report, BHP Billiton Ltd, 1996.
4. O. Levenspiel, Chemical Reaction Engineering, 2nd Ed., John Wiley & Sons, New York, 1972, Ch. 9 & 12.
5. AspenTech, Aspen Custom Modeler® 12.1: User Guide, Cambridge, MA (2003).
6. AspenTech, Aspen Custom Modeler® 12.1: Aspen Modeler Reference Guide, Cambridge, MA (2003).