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SIMULATION-ASSISTED EVALUATION OF GRINDING CIRCUIT FLOWSHEET DESIGN ALTERNATIVES: AGHDARREH GOLD ORE PROCESSING PLANT

OCENA ALTERNATYWNYCH SCHEMATÓW TECHNOLOGICZNYCH PROCESU ROZDRABNIANIA W ZAKŁADACH PRZERÓBKI RUD ZŁOTA W AGHDARREH, Z WYKORZYSTANIEM METOD SYMULACJI

The run of mine ore from Aghdarreh gold mine must be comminuted to achieve the desired degree of liberation of gold particles. Currently, comminution circuits include a single-stage crushing using a jaw crusher and a single-stage grinding using a Semi-Autogenous Grinding (SAG) mill in closed circuit with a hydrocyclone package. The gold extraction is done by leaching process using cyanidation method through a series of stirred tanks. In this research, an optimization study of Aghdarreh plant grinding circuit performance was done to lower the product particle size (P_{80}) from 70 μm to approximately 40 μm by maintaining current throughput using modeling and simulation approach. After two sampling campaigns from grinding circuit, particle size distribution data were balanced using NorBal software. The first and second data sets obtained from the two sampling campaigns were used to calibrate necessary models and validate them prior to performing simulation trials using MODSIM software.

Computer simulations were performed to assess performance of two proposed new circuit flowsheets. The first proposed flowsheet consists of existing SAG mill circuit and a new proposed ball mill in closed circuit with a new second hydrocyclone package. The second proposed flowsheet consists of existing SAG mill circuit followed by a new proposed ball mill in closed circuit with the existing hydrocyclone package. In all simulations, SAGT, CYCL and MILL models were selected to simulate SAG mill, Hydrocyclone packages and ball mill units. SAGT and MILL models both are based on population balance model of grinding process. CYCL model is based on Plitt's empirical model of classification process in hydrocyclone units. It was shown that P_{80} can be reduced to about 40 μm and 42 μm for the first and second proposed circuits, respectively. Based on capital and operational costs, it can be concluded that the second proposed circuit is a more suitable option for plant grinding flowsheet modification.

Keywords: grinding, hydrocyclone, modeling, simulation, MODSIM

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Surowy urobek z kopalni rud złota Aghdarreh musi najpierw zostać poddany rozdrobnieniu, aby zapewnić efektywniejsze uwalnianie cząsteczek złota. W chwili obecnej obiegi rozdrabniania obejmują kruszenie jednostopniowe z wykorzystaniem kruszarek szczękowych oraz kruszenie jednostopniowe z użyciem kruszarek półautomatycznych w obiegu zamkniętym z hydrocyklonem. Odzysk złota odbywa się przy zastosowaniu procesu ługowania, z zastosowaniem metody cyjankowej w szeregu mieszalników. W pracy tej przeprowadzono optymalizację procesu rozdrabniania rud w zakładach przeróbczych Aghdarreh prowadzonego w celu zmniejszenia rozmiarów uzyskiwanych cząsteczek złota (Ps0) z 70 μm do ok. 40 μm poprzez zapewnienie ciągłości procesu, z wykorzystaniem metod modelowania i symulacji. Na podstawie dwóch zestawów próbek z ciągu technologicznego rozdrabniania, rozkłady wielkości cząstek zostały statystycznie zrównoważone z wykorzystaniem oprogramowania NorBal. Pierwszy i drugi zbiór danych otrzymanych na podstawie dwóch zestawów próbek wykorzystany został do kalibracji i walidacji modeli, przed przystąpieniem do właściwych badań symulacyjnych z użyciem oprogramowania MODSIM.

Symulacje komputerowe przeprowadzono w celu oceny wydajności dwóch proponowanych ciągów technologicznych. Pierwszy ciąg obejmuje istniejące kruszarki półautomatyczne i nowo proponowaną kruszarkę kulową pracującą w obiegu zamkniętym z hydrocyklonem. Drugi rozważany ciąg stanowi istniejąca kruszarka półautomatyczna, następnie proponowana kruszarka kulowa pracująca w obiegu zamkniętym z istniejącym hydrocyklonem. We wszystkich symulacjach bazowano na modelach SAGT, CYCL i MILL do symulacji pracy kruszarek półautomatycznych, pakietu hydrocyklonu oraz pojedynczych kruszarek. Modele SAGT i MILL oparte są na modelu zrównoważonej populacji w procesie rozdrabniania. Model CYCL opiera się na empirycznym modelu klasyfikacji Plitta zastosowanym do hydrocyklonów. Wykazano, że rozmiar cząstek zmniejszony został odpowiednio do 40 μm i 42 μm dla pierwszego i drugiego analizowanego obiegu. Uwzględniając nakłady kapitałowe oraz koszty operacyjne, wyciągnąć można więc wniosek, ze drugi proponowany układ jest korzystniejszą opcją modyfikacji istniejącego ciągu technologicznego rozdrabniania.

Słowa kluczowe: rozdrabnianie, hydrocyklon, modelowanie, symulacja, MODSIM

1. Introduction

There are some benefits for Grinding operation optimization including decreased unit operation costs, increased capacity and production of more valuable metals and improved performance of downstream processes due to improved feed size distribution. In most plants, optimization criteria are defined based on the following purposes, a) capacity maximizing while maintaining current final product specification, b) finer final product size while maintaining current capacity and c) minimizing operation costs while maintaining both current capacity and product size (Napier-Munn et al., 1996).

Nowadays, process modeling and simulation is one of the main optimization tools used in industry. The optimization using simulation consists of several stages, a) characterize operation parameters of feed in laboratory tests, b) estimate machine parameters, using plant survey, c) performing simulations to explore possible optimization solutions by changing circuit flowsheet or process equipment or operating conditions, and d) evaluation of solutions found through simulation studies by running plant tests under proposed flowsheet modifications or operating conditions (Napier-Munn et al., 1996).

Aghdarreh gold processing plant is located near Takab at north-west of Iran. Run-of-Mine (ROM) ore is processed through several stages including crushing, grinding and cyanidation leaching. In this research, grinding optimization studies were done with the objective of decreasing particle size of grinding circuit product under the same current capacity. Process modeling and simulation approach was used to find optimization solutions considering requirements of downstream leaching process.

2. Materials and Methods

2.1. Grinding circuit sampling

A sampling campaign from grinding circuit was planned to assess its performance under the current operating conditions. Presently, particles with a size greater than 90 mm enter to underflow stream and are recirculated to Semi-Autogenous Grinding (SAG) mill. The hydrocyclone overflow first passes through a trash screen to remove any oversize pieces of material and then enters to the leaching circuit (Fig. 1). In order to evaluate processing units and circuit performance, sampling from fresh feed, mill product and scats reject returning to the SAG mill, streams around hydrocyclone including feed, overflow and underflow was necessary. Two sampling campaign were scheduled so that the first sampling campaign data can be used to calibrate models and the second sampling campaign data can be used to validate simulation models.

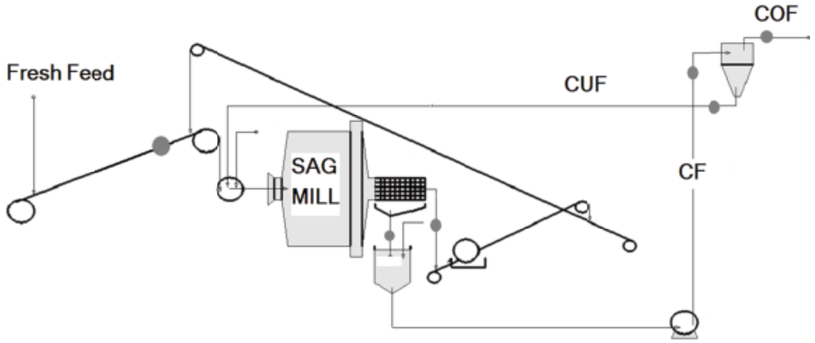

Fig. 1. Simplified grinding circuit flowsheet of Aghdarreh gold processing plant and sampling locations

The sampling was performed from various locations including trammel screen undersize, scats reject, streams around hydrocyclone simultaneously every 10 minutes and for a period of 2 hours to cover operation fluctuations. A composite sample was then obtained for every sampling point by combining collected incremental samples. To sample SAG mill fresh feed, belt conveyor was stopped and a sample was taken by removing material over a two-meter length. Operating condition during sampling was recorded. Particle Size distribution of all samples except mill fresh feed and scats reject was determined using 6730 to 38 μm screens. Solids content of all samples was also determined. Mill fresh feed particle size distribution was also determined using rod screens and laboratory screens. Weight of these samples after drying was 75 and 105 kg. Fresh feed flow rates for first and second stage sampling were 142 and 141 t/h that is almost two times of designed capacity. For mass balance of hydrocyclone streams flow rates and size distribution of hydrocyclone streams NorBal software (Spring 1996) was used. Specify gravity of fresh feed solid particles is 2.9. The circulating load ratio obtained for first sampling campaign using two methods, i. e., based on streams solids content and particle size distributions were equal to 2.68 and 2.69, respectively. For second sampling campaign, the circulating load ratio calculated using solids content and particle size distributions was equal to 2.59 and 2.66, respectively. Then specification of hydrocyclone feed, hydrocyclone overflow and hydrocyclone underflow streams calculated for two stage sampling. Then for to specify hydrocyclone current efficiency and perform necessary changes for its improvement, basis measured data, hydrocyclone tromp curve for two stage sampling provide before modification and after modification, in Excel software. Fluid (water) recovery to underflow (R_f) obtained for two sampling campaign was equal to 0.44 and 0.43 that implies a weak performance of hydrocyclone.

2.2. MODSIM software

MODSIM is a steady-state simulator that calculates the detailed mass balances for any ore dressing plant. The simulation results reported by MODSIM includes total flow rates of water and solids, the particle size distribution of the solid phase, the distribution of particle composition and the average assay of the solid phase. MODSIM is based on a modular structure which permits new models to be added for simulation of various unit operations (King, 2001).

3. Theory

3.1. SAG mill modeling

In MODSIM, one of the simulation models used for a SAG mill unit is SAGT (Semi-Autogenous Grinding with Trommel) model. In this model, a SAG mill with a trommel screen at mill discharge is modeled using the full population balance including particle attrition and wear (King, 2001b). In this model, three distinct breakage mechanisms have been considered, namely surface attrition, impact breakage and self-breakage. The mill is assumed to be perfectly mixed with post classification at discharge grate. The load in the mill is calculated from the mill dimensions and the average residence time is calculated as the ratio of the load to the throughput. Water can be added directly to the mill feed at a pre-specified rate or the simulator will calculate the water addition rate that is required to achieve a specified solid content in the mill discharge (King, 2001).

3.2. Grinding process modeling

The statistical modeling of comminution process based on population balance concept has been explained in Otwinowski, 2000. Impact breakage is modeled using the standard Austin breakage and selection functions. The specific rate of breakage due to self-breakage mechanism for particles smaller than 12.5 mm is significantly low and can be ignored confidently. The dominant breakage mechanism in this particle size range is impact breakage. A standard laboratory ball mill was used to determine breakage and selection functions parameters in Austin model (Hasani et al., 2009).

3.2.1. Selection function

The variation of specific rate of breakage with particle size can be fitted by the following model (Austin et al. 1984):

$$S_i = \frac{a\left(\frac{x_i}{1000}\right)^{\alpha}}{1+\left(\frac{x_i}{\mu}\right)^{\Lambda}} \tag{1}$$

where a is selection function value at 1 mm and its value changes with grinding properties variation, x_i is particle size (μm) and α is a positive value that commonly is between 0.5-1.5 depending on mineral material properties, μ is particle size at which correction coefficient $\left(Q_i = 1+\left(\frac{x_i}{\mu}\right)^{\Lambda}\right)$ is equal with 0.5 and Λ is a positive number ($\Lambda \geq 1$) which indicates how fast breakage rate will be decreased with increasing size particle depending on mineral properties, but μ changes with mill condition. To characterize impact breakage by grinding balls, laboratory standard tumbling ball mill tests were performed. The parameters of Austin model for laboratory measured selection function vs. particle size were estimated by least-square method using SOLVER tool of Excel (Fig. 2).

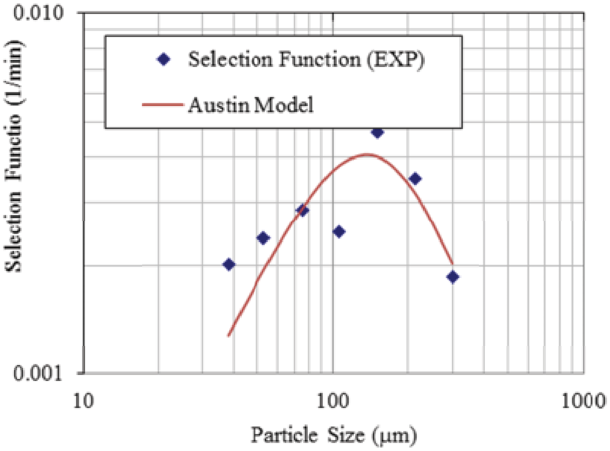

Fig. 2. Estimated selection function data points fitted with Austin model

The model fitted to measured selection function is as follows:

$$S_i = \frac{0.1\times\left(\frac{x_i}{1000}\right)^{1.33}}{1+\left(\frac{x_i}{150}\right)^{3.16}} \tag{2}$$

3.2.2. Impact breakage function

In AG/SAG mills, there are two main breakage mechanisms: impact (high energy) and abrasion (low energy). The JKMRC institute is using the concept of the percentage of broken product passing 1/10 the original particle size, t_{10}, to determine ore breakage or appearance function. Equation (3) relates t_{10} to E_{CS} which is specific energy of comminution (Napier-Munn et al., 1991):

$$t_{10} = A\left(1 - e^{-bE_{CS}}\right) \tag{3}$$

The impact breakage parameters, namely A and b, are determined using a high energy impact breakage device called JK Drop Weight Tester. Specific energy of comminution in Equation 3 can be calculated according to experimental setup data, as follows (Napier-Munn et al., 1996):

$$E_{CS} = \frac{0.0272 M_d \left(h_i - h_f\right)}{\bar{m}} \tag{4}$$

where, M_d is drop weight mass (kg), $\bar{m}$ is the medium mass of per particle size class (g), h_i is Initial height of drop weight above the anvil (cm), h_f is Final height of drop weight above the anvil (cm).

A is the maximum t_{10} value that can be achieved. This is significant for higher energy breakage. The parameter b is related to the overall slope of t_{10} versus E_{CS} curve at the lower energies. A and b are interdependent, since the value of one will directly affect the other. Parameters A and b are related and usually are reported by $A.b$ as a single value to indicate the ore hardness in terms of impact breakage. The $A.b$ parameter is the slope of the t_{10} vs E_{CS} curve at its origin and it is a measure of breakage of the ore at lower energy levels.

3.2.3. Abrasion breakage modeling

To characterize abrasion breakage mechanism, the parameter t_a is defined as one tenth of t_{10} as follows (Napier-Munn et al., 1996):

$$t_a = t_{10}/10 \tag{5}$$

The abrasion breakage parameter, t_a, is determined by performing a tumbling test. A lower value of t_{10} (hence a lower t_a value) indicates that there is a lower percentage of material passing 1/10th the original particle size, or greater resistance to abrasion breakage. Napier-Munn et al. indicate a possible correlation between the impact ($A.b$) and abrasion (t_a) parameters and the Bond ball mill work index given by the equations (Hasani et al., 2009):

$$A \times b = -3.5W_i + 117 \tag{6}$$

$$t_a = 19.7W_i^{-1.34} \tag{7}$$

These relations are based on a large number of tests on different ore types by JKMRC institute. Table 1 shows work index and parameters of abrasion and impact breakage mechanisms of Aghdarreh mixed ore.

TABLE 1

Bond work index and parameters of abrasion and impact breakage mechanisms of Aghdarreh mixed ore

Ore type	W_i **(kWh/t)**	$A \times b$	t_a
Mixed	14.14	67.51	0.57

Accordingly, the impact breakage mechanism model for Aghdarreh mixed ore can be written as:

$$t_{10} = 67.51 \times \left(1 - e^{-1 \times Ecs}\right) \tag{8}$$

3.3. Classification process modeling

Simulation of classification process can be done based on Tromp curve (also known as partition curve) model. The recovery of feed solids to underflow in i^{th} size class (R_i) is calculated based on Tromp curve described by the following equation:

$$R_i = R_f + \left(1 - R_f\right) \times \left(1 - e^{-0.693\left(\frac{d_i}{d_{50c}}\right)^m}\right) \tag{9}$$

where d_i is the particle size i^{th} size class and R_f is the recovery of feed water to underflow. Plitt's model has various applications such as process analysis and diagnosis by looking at the values of d_{50c}, m and R_f parameters estimated based on plant data. Plitt's model also can be used in circuit design to find the appropriate hydrocyclone geometry and the required number of the hydrocyclones. Otwinowski, 2013, has also discussed Tromp curve in detail and proposed a matrix model for classification.

One of the best empirical models of hydrocyclone units is Plitt's model that was originally introduced in 1976. In MODSIM software, Plitt's model can be selected by user to simulate hydrocyclone units. The set of four equations which are collectivity referred as Plitt's model are as follows (Plitt, 1976):

$$d_{50c} = CF_1 \frac{39.7 D_C^{0.46} D_i^{0.6} D_O^{1.21} \eta^{0.5} \exp^{0.063\varnothing}}{D_u^{0.71} h^{0.38} Q^{0.45} \left(\rho_S - \rho\right)^{0.5}} \tag{10}$$

$$S = CF_2 \frac{1.9\left(D_u \middle/ D_0\right)^{3.31} h^{0.54} \left(D_u^2 + D_o^2\right)^{0.36} \exp^{0.0054\varnothing}}{D_c^{1.11} H^{0.24}} \tag{11}$$

$$m = CF_3 \times 1.94 \left(\frac{D_c^2 h}{Q}\right)^{0.15} \exp\left(-1.58 \frac{S}{1+S}\right) \tag{12}$$

$$p = CF_4 \frac{1.88 Q^{1.78} e^{0.0055\varnothing}}{D_c^{0.37} D_i^{0.94} h^{0.28} \left(D_u^{2} + D_o^{2}\right)^{0.87}} \tag{13}$$

The Plitt's model includes two sets of variables; dependent variables are as follows: corrected cut point (d_{50c}), pressure (P), stream volume splitting ratio (S) and separation sharpness (m). Independent variables are hydrocyclone diameter (D_C), vortex diameter (D_O), spigot diameter (D_u), inlet diameter (D_i), composition of those (D_u/D_O, $D_O^2 + D_u^2$) and also vortex free height (h). η is slurry viscosity, $\varnothing$ is volume solid percentage of hydrocyclone feed, Q is volume flow rate of hydrocyclone feed, ρ_s is solid density and CF_1 to CF_4 are Plitt's model calibration coefficients. The Influence of feed size particle on Plitt's model is not obvious from main specification of Plitt's model. Solids content, solids flow rate, solids density and slurry density are feed parameters that are used in model structure (Plitt 1976).

4. Results and Discussion

4.1. Aghdarreh SAG mill

The specification of Aghdarreh SAG mill unit and operating condition recorded at sampling times are shown in Table 2.

TABLE 2

Dimensions and operating parameters of Aghdarreh SAG mill

Parameters	Value
Diameter (m)	5
Center line length (m)	8.27
Belly length (m)	6.36
Trunnion diameter (m)	1.2
Load volume (%)	21
Ball volume (%)	10
Ball size (mm)	90
Mill speed (%)	75
Grate aperture (mm)	23
Trommel mesh size (mm)	16

Starkey (2007) has considered that Aghdarreh mill (D/L ratio < 1) can be operated at mill loads equal to 20%, 26% and 30%. Mill load (volumetric) parameter for the Aghdarreh mill can be increased to 35%. The maximum suitable ball charge is 12%. The weight of mill load for 12% ball charge and 26% volumetric mill load is 105 t.

4.2. Aghdarreh hydrocyclone modeling

The goal of Aghdarreh hydrocyclone performance optimization was to achieve a product with a d_{80} size smaller than 50 mm. through changing hydrocyclone parameters. Simulation was used for testing possible solutions for hydrocyclone optimization. The CYCL model available in MODSIM, based on Plitt's model, was selected as hydrocyclone classifier model (King, 2001). Table 3 shows hydrocyclone geometry of Aghdarreh plant.

TABLE 3

Aghdarreh hydrocyclone geometry

Parameter	Value
Inlet diameter (cm)	6
Hydrocyclone diameter (cm)	25
Free height of hydrocyclone (cm)	105
Vortex diameter (cm)	8.7
Spigot diameter (cm)	7

For both sampling campaigns, d_{50c} was obtained by plotting hydrocyclone classification curve based on measured flow rates and particle size distributions. The hydrocyclone pressure, P, measured value was equal to 175 kPa. The values of R_f and S are obtained using the adjusted flow rates of hydrocyclone streams. However, parameters d_{50c} and R_f as well as m can be calculated more accurately by fitting Equation (13) to measured R_i values in Excel spreadsheet software with least squared method and SOLVER non-linear optimization tool.

4.3. MODSIM predictions

After the breakage different mechanisms of semi-autogenous mill and selection of Plitt's model for hydrocyclone, the performance of Aghdarreh grinding circuit is predicted for the two sampling campaign using MODSIM software. The predicted and measured properties for various streams around mill and hydrocyclone units are shown in Tables 4 and 5. Also particle size distributions of various streams can be seen in Figures 3 to 6.

TABLE 4

Predicted and measured values of streams specification around SAG mill using MODSIM

Stream		**First sampling campaign**				**Second sampling campaign**			
		Solids (t/h)	**d_{80} (µm)**	**Solids content (%)**	**Water (m^3/h)**	**Solids (t/h)**	**d_{80} (µm)**	**Solids content (%)**	**Water (m^3/h)**
Trommel undersize	Measured	462.5	702.5	68	363.4	433.7	338.1	68	204.1
	Predicted	465.1	188	66.2	237.2	432	187	65.8	225
Fresh feed		125.5	104000	88.4	16.5	120.8	112000	85.7	20.2
Scats reject	Measured	6	20000	95	0.32	6	21000	95	0.32
	Predicted	0.01	20900	95	0.0005	0.01	20300	95	0.0003

TABLE 5

Predicted and measured values of streams specification around hydrocyclone package using MODSIM

Stream		First sampling campaign				Second sampling campaign			
		Solids (t/h)	d_{80} (µm)	Solids content (%)	Water (m^3/h)	Solids (t/h)	d_{80} (µm)	Solids content (%)	Water (m^3/h)
CF	Measured	462.5	306	56	363.4	433.7	320.9	58	314.1
	Predicted	465.1	188	56.6	357.2	432	187	56.7	330
COF	Measured	125.5	69.4	38	205	120.8	72.7	40.2	180
	Predicted	125.5	69.1	39.6	191.5	120.8	72.3	40.8	175.2
CUF	Measured	336.9	444.9	68	158.6	312.9	508.8	70	134.1
	Predicted	339.5	226	67.2	165.7	311.1	225	66.8	154.8

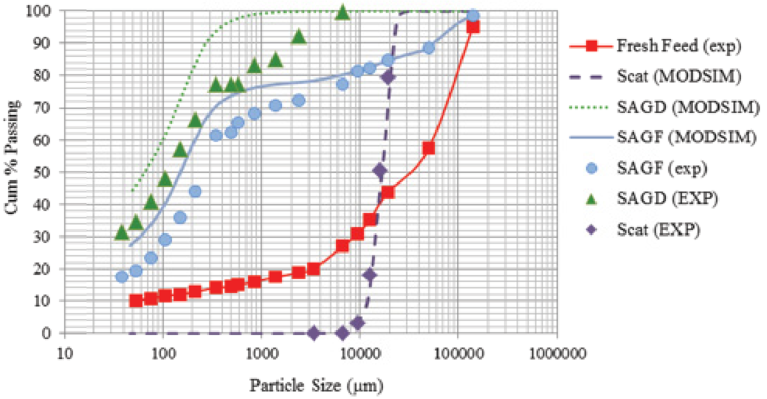

Fig. 3. PSD of various streams around SAG mill unit in first sampling campaign

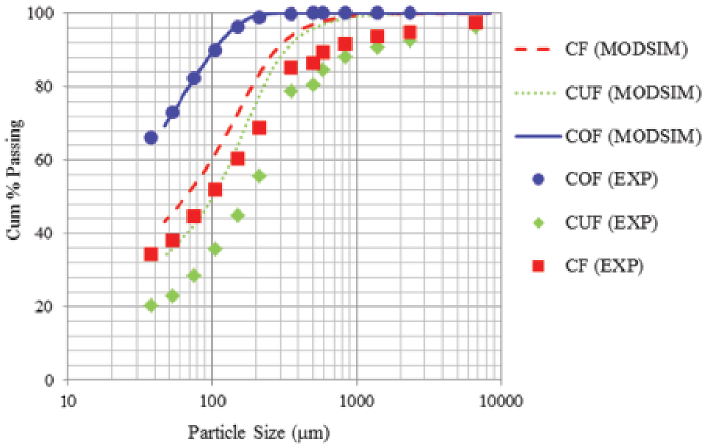

Fig. 4. PSD of streams around hydrocyclone unit in first sampling campaign

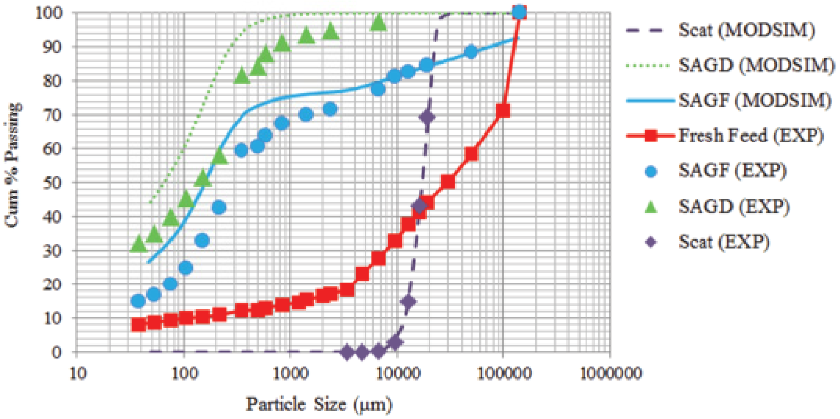

Fig. 5. PSD of various streams around SAG mill unit in second sampling campaign

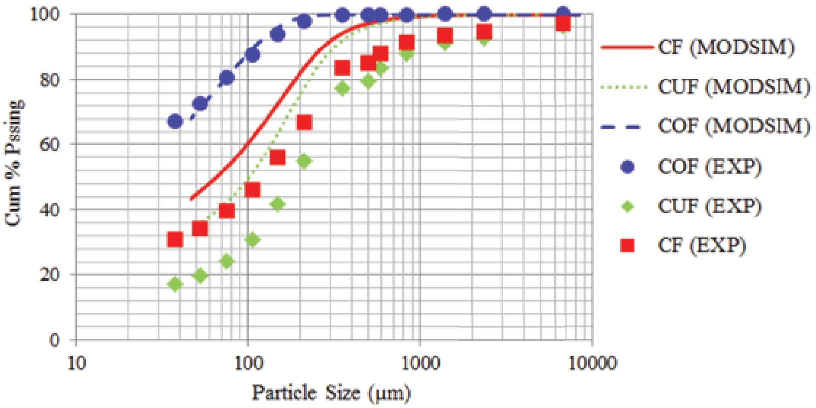

Fig. 6. PSD of various streams around hydrocyclone unit in second sampling campaign (MODSIM predictions are based on non-calibrated Plitt's model)

The mill power draws were 1754.1 and 1814 kW for two sampling campaigns, respectively. The average residence time of solid particles inside the mill during both sampling campaigns was estimated to be around 5.9 min. Also mill load weight excluding grinding balls was estimated to be equal to 46.1 and 42.6 t, respectively.

4.4. Plitt's model calibration

The Plitt's model parameters determined based on the model predictions and measured data are usually different due to inherent empirical nature of the Plitt's model. Therefore, Plitt's model must be adjusted to measured hydrocyclone device condition using a set of calibration coefficients. In this research, for calculation of these coefficients the measured and predicted values of d_{50c}, m and R_f parameters (Table 6) were used in Equation (14).

TABLE 6

Plitt's model parameters for the first sampling campaign

Parameter	Measured	Predicted
d_{50c}, (μm)	89.1	85.53
S	1.11	1.201
m	1.10	0.348

$$Calibration\,Factor\left(CF\right) = \frac{measured\,values}{predicted\,values} \tag{14}$$

Table 7 is showing the calibration coefficients of Aghdarreh hydrocyclone Plitt's model. In MODSIM, hydrocyclone pressure, P, must be given as a known parameter data, thus a calibration coefficient for this parameter was not calculated.

TABLE 7

Calibration coefficients of Plitt's model adjusted to Aghdarreh hydrocyclone

CF_i	Parameter	Value
CF_1	d_{50c}, (μm)	1.04
CF_2	S	0.92
CF_3	m	3.1

4.5. Models validation and simulations

In order to validate the calibrated Plitt's model, data set obtained from second sampling campaign was used which is independent from the first data set used to build the model. MODSIM predictions for all streams with applying CF_i are shown in Table 8.

TABLE 8

Post-calibration predicted specification of grinding circuit streams by MODSIM

Stream	Solid (t/h)	d_{80} (μm)	Solids content %	Water (m^3/h)
Trommel undersize	456.5	225	69.6	199.5
Scats reject	0.0022	19900	95	0.00012
CF	456.5	225	60	304.5
COF	120.8	73	40.8	175.2
CUF	335.6	255	72.2	129.3

For the second sampling campaign after calibration, the mill power is calculated 1830 kW, residence time of solid particles in mill is calculated 5.8 min and also the weight of mill load without ball is calculated 44.3 t. The particle size distribution of circuit predicted streams after calibration is shown in Figure 7.

As a rough observation, if one compare predicted and measured PSDs in Figures 7 and 8, obviously, predicted PSDs of streams around hydrocyclone are closer to measured PSDs after

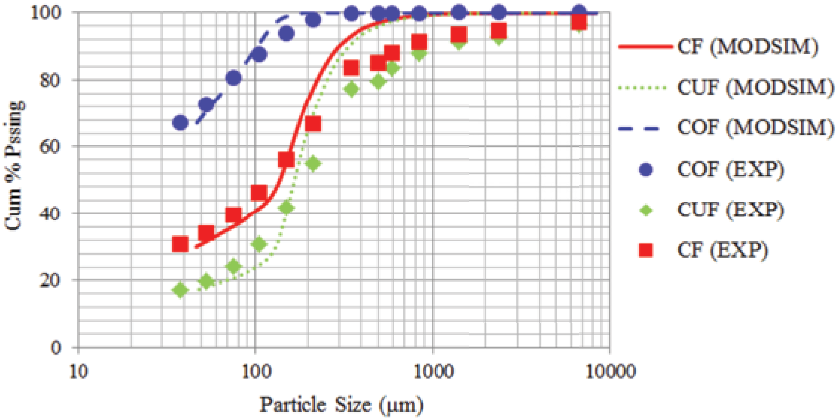

Fig. 7. PSD of various streams around hydrocyclone unit in second sampling campaign (MODSIM predictions are based on calibrated Plitt's model)

calibration of Plitt's model. The product size, P_{80}, was obtained 73 mm which is very closed to measured value. To compare, the pre-calibration and post-calibration values of Plitt's model parameters have been shown in Table 9.

TABLE 9

Plitt's model parameters for second sampling campaign

Parameter	Measured	Pre-calibration	Post-calibration
d_{50c}, (µm)	88	91.65	116.9
S	1.09	1.21	1.13
m	1.18	0.35	0.72

In a previous study (Hoseinzadeh Gharehgheshlagh, 2007) it was found that circulating load, hydrocyclone feed solids content, mill load and F_{80} are the four most important parameters that affect P_{80} of product particle size distribution. It was very difficult to study the effect of F_{80} on P_{80} because fresh feed had relatively large variations and also was not under control. Also, the effect of circulating load on P_{80} could not be studied as circulating load is not an independent variable that can be changed directly. Therefore, only the effects of mill load (volumetric) and solids content of hydrocyclone feed of P_{80} were studied and necessary data was collected for a period of 8 weeks. The results are shown in Figures 8 and 9 (data are the average of per week and is collected in 8 week).

As Figures 8 and 9 show, product size, P_{80}, is increased by an increase in mill load and is decreased with an increase in solids content of hydrocyclone feed. Simulation trials of grinding circuit performance to achieve a P_{80} less than 70 µm have shown that volumetric mill load (26%, 30% and 35%) has maximum impact on P_{80}. In addition, hydrocyclone geometrical variables in Plitt's model, number of operating hydrocyclones and solids content of hydrocyclone feed affect product size significantly. Table 10 is showing simulated grinding circuit performance with 6 hydrocyclones in operation, vortex diameter equal to 82 mm and spigot diameter equal to 70 mm.

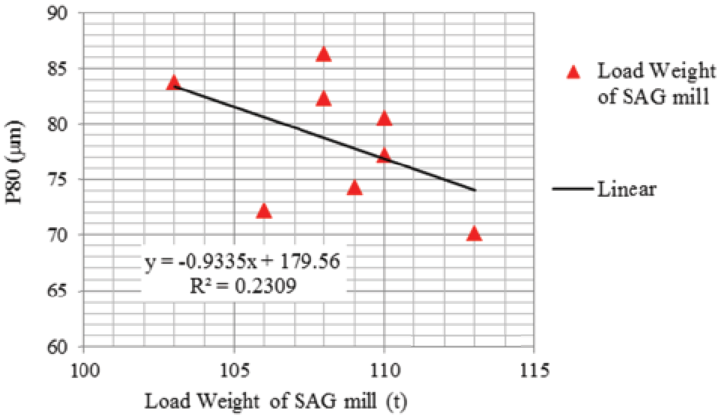

Fig. 8. The effect of mill load on P_{80}

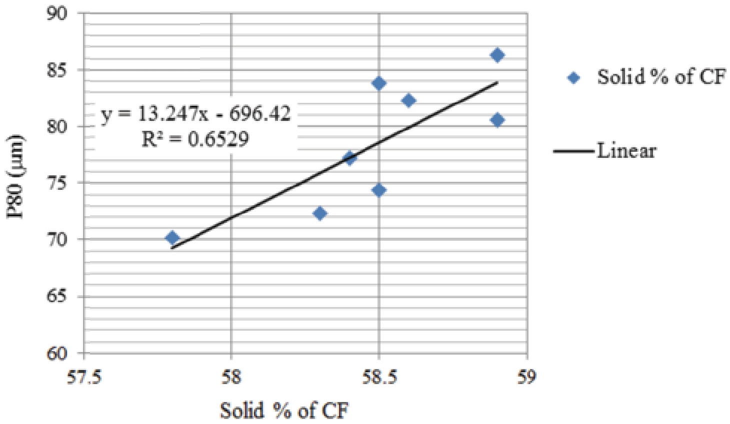

Fig. 9. The effect of solids content of hydrocyclone feed on P_{80}

TABLE 10

Results of grinding circuit performance simulation for various mill loads

Parameter	**Mill load (volumetric)**		
	26%	**30%**	**35%**
d_{50c} (µm)	94.2	87.2	81.35
S	1.34	1.33	1.32
Mill load without ball (t)	61.1	74.3	91
Mill power, (kW)	1944.3	2011	2067.1
Solids residence time, (min)	7.4	9.4	12
m	0.7	0.7	0.7
R_f	0.48	0.49	0.49
P_{80}, (µm)	61.7	56.1	50.9

Simulations showed that mill load and solids content of hydrocyclone feed have the greatest impact on P_{80} of grinding circuit product. By decreasing solids content from 58.3% to 57.2% (by increasing water addition rate to hydrocyclone sump from 105 m^3/h to 130 m^3/h), P_{80} was reduced around 2 µm (from 72.4 to 70.4 µm). The flow rate of water addition to hydrocyclone sump could not be increased over 130 m^3/h, as solids content of hydrocyclone overflow which feeds leaching process had to be within a limited range of 37-38%.

4.6. Proposed grinding circuit flowsheets

The simulation of current grinding circuit flowsheet under the best operating condition showed that product size, P_{80}, can be reduced maximum to 51 µm. However, based on mineralogical studies (AMTEL 2008) finer grinding (less than 51 µm) is needed in order to increase plant current recovery from 90% to 95%. For this reason, simulations were performed assuming two proposed grinding circuit flowsheet by adding a ball mill unit after SAG circuit. The proposed ball mill was designed to process 130 t/h of feed produced by SAG circuit. The specification of proposed ball mill is shown in Table 11 (Starkey, 2007).

TABLE 11

Proposed ball mill specification

Mill type	**Diameter (m)**	**Length (m)**	**Rotational speed (rpm)**	**Critical speed (%)**	**P_{80} (µm)**	**Calculated power (kW)**	**Installed power (kW)**	**Load volume (%)**
Overflow	3.66	5.24	16.9	75	30-40	939	950	40

4.6.1. Ball mill modeling

The "MILL" model of MODSIM was selected for the ball mill simulation. In this model, the mill is assumed to be a single perfectly mixed region (King, 2001b). A standard Austin model was considered as selection function which includes a maximum that defines the onset of abnormal breakage as size gets larger. For Austin model parameters, values provided by the MODSIM software were used to define selection function of the proposed ball mill as follows:

$$S_i = \frac{0.4 \times \left(\frac{x_i}{1000} \right)^{0.5}}{1 + \left(\frac{x_i}{10} \right)^{2.513}} \tag{15}$$

The ore breakage distribution function in MILL model is defined by Broadbent and Callcott (1956) as given in Equation (16):

$$B_{i1} = \varphi \left(\frac{d_i}{d_1} \right)^{\gamma} + (1 - \varphi) \left(\frac{d_i}{d_1} \right)^{\beta} \tag{16}$$

where d_i and d_1 are the i^{th} screen size and the first screen size (300 micron), respectively. φ, γ and β are model parameters where γ and β define impact and cleavage breakage mechanisms, respectively. The breakage distribution function of Aghdarreh gold ore was determined by performing laboratory grinding tests and using BFDS software to process test data based on Herbst and Fuerstenau method (Hoseinzadeh Gharehgheshlagh, 2007):

$$B_{i1} = 0.673\left(\frac{d_i}{d_1}\right)^{1.043} + (1 - 0.673)\left(\frac{d_i}{d_1}\right)^{6} \tag{17}$$

The mean residence time of the solids must be given (5 min). The model does not need any details of the mill geometry. Water can be added directly to the mill feed at a pre-specified rate or the simulator will calculate the water addition rate that is required to achieve a given solids content in the mill discharge (King, 2001).

4.7. First grinding flowsheet design

In this flowsheet, the overflow of first hydrocyclone package enters the proposed ball mill which is in closed circuit with a second hydrocyclone package (Fig. 10). The CYCL model with similar parameters was selected to simulate the second hydrocyclone package.

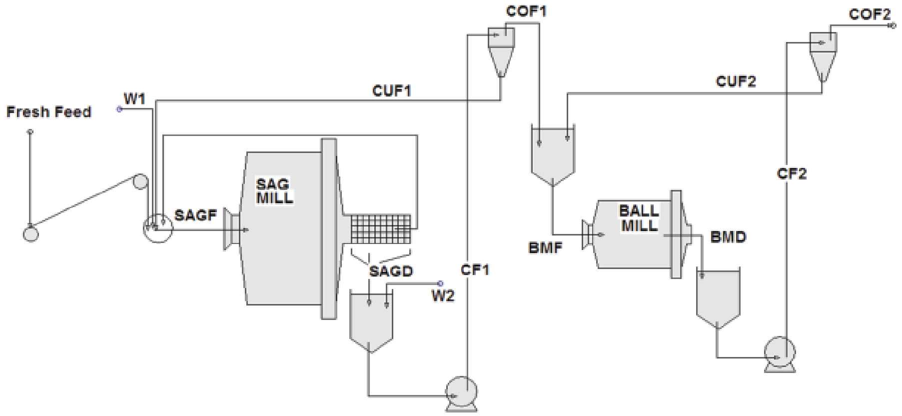

Fig. 10. First grinding circuit flowsheet proposed for Aghdarreh which includes installing a ball mill in closed circuit with a second hydrocyclone package following existing SAG mill circuit

The simulation results of first proposed circuit showed that for load volumes equal to 21% and 35 %, P_{80} will be reduced to 42.6 and 40 μm, respectively, which shows the impact of adding the proposed ball mill unit. Figure 11 is showing the particle size distribution of different streams.

In MILL model, the required ball mill power is estimated using Equation (18) based on Bond Work Index (W_i):

$$P = 65.4 \times W_i \tag{18}$$

The measured work index (W_i) for Aghdarreh mixed ore is 14.14 kWh/t, thus the required ball mill power calculated based on Equation (18) is equal to 925 kW which is less than 950 kW

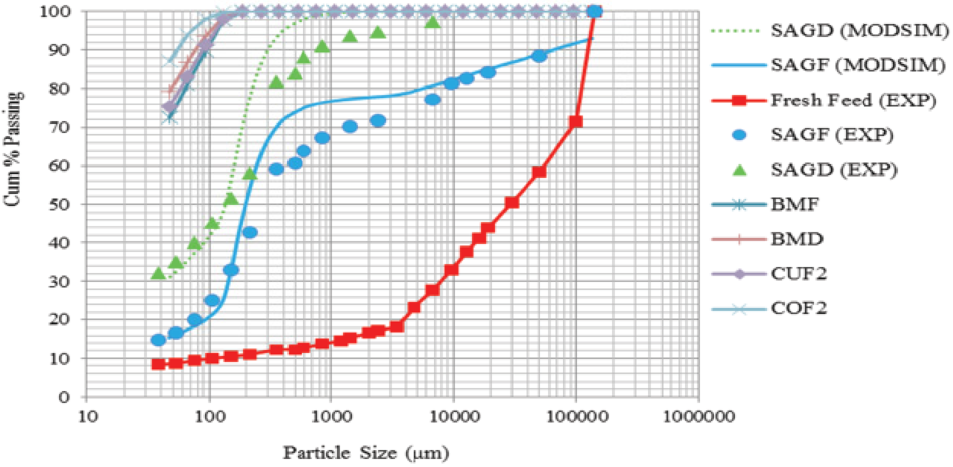

Fig. 11. PSD of various streams of first proposed grinding circuit for a load volume equal to 21%

(proposed ball mill power). Therefore the proposed ball mill is considered suitable for expansion of current grinding circuit.

4.8. Second grinding flowsheet design

In this flowsheet, the underflow of first hydrocyclone package enters the ball mill which its discharge is returned to hydrocyclone sump (Fig. 12).

The simulation results of second proposed circuit showed that for load volumes equal to 21% and 35%, P_{80} will be reduced to 46 and 42 µm, respectively. Figure 13 is showing the particle size distribution of various streams.

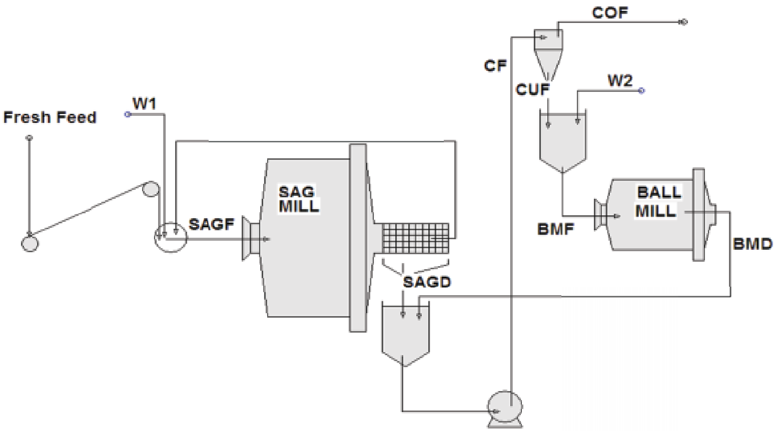

Fig. 12. Second grinding circuit flowsheet proposed for Aghdarreh which includes installing a ball mill in closed circuit with the existing hydrocyclone package after SAG mill circuit

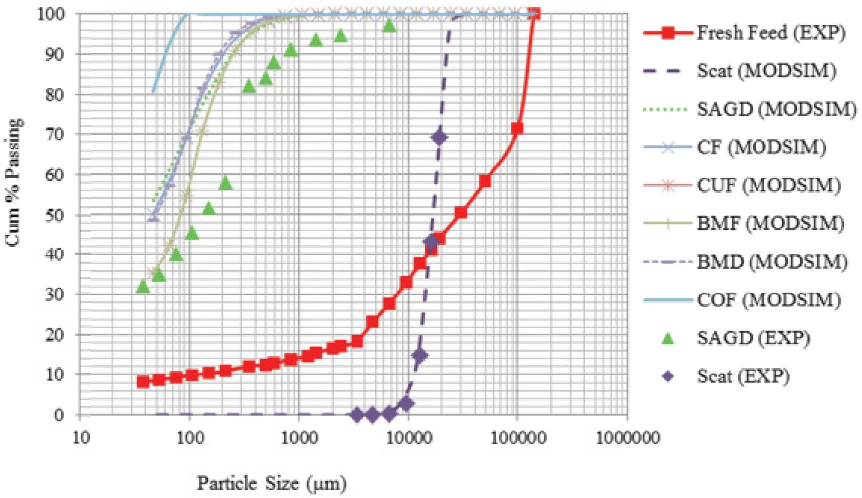

Fig. 13. PSD of various streams of second proposed grinding circuit for a load volume equal to 21%

Similar to previous flowsheet design, ball mill power is estimated using Equation (19):

$$P = 32 \times W_i \tag{19}$$

Hence, the required ball mill power in this case is equal to 453 kW which indicates the proposed ball mill is suitable for expansion of current grinding circuit.

5. Conclusions

Simulations carried out based on the current grinding circuit flowsheet with vortex and spigot diameters equal to 82 and 70 mm, respectively, 6 hydrocyclones in operation and volumetric mill load equal to 35 % showed that P_{80} can be reduced to 51 μm. These results indicate that volumetric mill load has the maximum influence on P_{80} reduction because of increased residence time to 12 min and further chance of particles to be broken due to increased contact frequency. Mill power drawn can be increased to 2067 kW. Also, separation sharpness (m) can be increased to 0.7 that shows improvement of hydrocyclone performance relative to current practice.

The simulations results for the two proposed new circuits showed that P_{80} can be reduced further to 40 μm and 42 μm for the first and second proposed circuits, respectively. Based on capital and operational costs, it can be concluded that the second proposed circuit is a suitable option for plant grinding flowsheet modification.

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