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SIZE-DEPENDENT MODEL TO DETERMINE THE EFFECTS OF OPERATIONAL PARAMETERS ON THE PERFORMANCE OF THE FALCON CONCENTRATOR

The present study modelled the effects of operational parameters on the performance of the Falcon concentrator. For this purpose, the Falcon L40 concentrator was tested in narrow particle-size fractions (−600 + 425 µm, −425 + 300 µm, −300 + 212 µm, −212 + 150 µm, −150 + 106 µm, and −106 + 75 µm) at different washing water pressures and artificial gravity forces generated by a spinning bowl. The test samples were prepared artificially, comprising 2% magnetite (Fe3O4) and 98% calcite (CaCO3) by weight. The recovery and grade values of the 60 experimental conditions were investigated and compared for different operational parameters, including particle-size distributions, water pressures, and artificial gravity forces. Two empirical models were developed using non-linear regression analysis to indicate the effects of the operating parameter of the Falcon concentrator on its recovery and grade values. The operational parameters were found to impact the separation performance considerably. Therefore, the Falcon concentrator should operate under optimum conditions, which can be easily predicted using these models, to achieve improved recovery and grade values.

Keywords: Falcon concentrator; gravity concentration; artificial gravity force effect; empirical model

1. Introduction

Gravity separation methods have gained significant attention because they do not require any chemicals or excessive heating, and they are environmentally friendly. In addition, gravity separation methods do not require complicated operational processes, have easy control units, and produce clean concentrates and tailings at low costs. However, gravity separation has the disadvantage of lower efficiency with 100-µm particles [1-4]. Therefore, concentrators using centrifugal force for separation, such as spirals for finer sizes, have been used for more than half

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a century in the mineral processing industry. The Falcon concentrator (enhanced gravity separator) is generally considered superior to all the traditional gravity separation methods in terms of separation efficiency in finer sizes owing to its application of high artificial gravity force [5-6]. It has been used in industrial operations to upgrade metal and mineral ores, such as gold, sulfide, tin, and titanium. It can also be used to concentrate gold, platinum group metals, mineral sands, chromite, tin, tantalum, tungsten, iron ore, cobalt, and various other metals and minerals with adequate specific-gravity variation [7-8].

The Falcon concentrator creates an artificial gravity force with a fast-spinning bowl, which causes the separation of fine-sized minerals based on their density differences [9]. The magnitude of this artificial gravity force depends on the rotation speed (Fig. 1; data were obtained from the Falcon L40 manual).

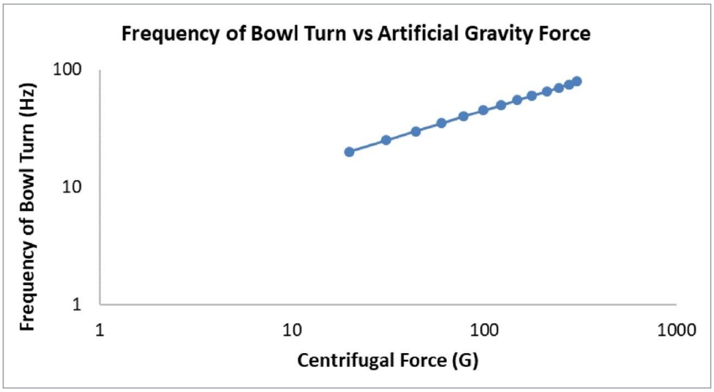

Fig. 1. Relationship between concentrator bowl spin frequency and generated artificial gravity force for gravity separation

The artificial gravity force can be increased by approximately 300 times compared to the force of gravity of the Earth [10-11].

The resultant force, which acts on an individual particle, depends on several hydrodynamic and physical forces such as the artificial gravity force, the mass of the particle, linear velocity, radius of the Falcon bowl, angle between the horizontal axis and bowl, and Earth's gravity force; whereas the water force depends on the water pressure and total cross-sectional area of the waterhole. When the slurry is fed into the separator from the top, it is first drained as a thin film on the separator wall, and then the heavier particles replace the lighter particles. If the resultant force acting on an individual particle according to its mass is greater than the water force, the particle adheres to the concentrator wall; otherwise, it escapes from the concentrator [12-13]. Therefore, particles can be separated based on their differential sedimentation rates faster than the usual settling time, even for fine particle sizes. This action transports the heavy particles toward the interior channels of the container, whereas the light particles are transported out of the bowl with water [14-15].

The parameters of the Falcon concentrator that affect the separation performance include particle size, artificial gravity force, solid ratio, and water pressure. These factors play a significant role in the separation efficiency, and the operational conditions of the concentrator have unique effects that vary for each particle size [16-17]. Therefore, the Falcon concentrator must be operated under optimum conditions that vary for different particle-size distributions. Accordingly, models have been developed to determine the specific operational conditions for mineral processing methods to achieve better recovery and grade values. Developing a model is extremely important to determine the effects of process parameters on the operational performance of the Falcon concentrator. By using the model, more efficient processes can be developed; valuable minerals that cannot be recovered using traditional gravity separation methods can be reclaimed into the economy; and a new alternative can be introduced to the inefficient gravity enrichment methods, especially for finer grain sizes.

2. Material and methods

An L40 Falcon concentrator was used for the tests. The concentrator has maximum capacities of 0.25 t/h for solids and 2.3 m^3 for slurries, and it can consume 1.2 m^3 of washing water when the water pressure is 3 bar. The Falcon L40 enhanced gravity concentrator was designed for laboratory testing; it has a bowl with a diameter of 30 mm at the bottom and 95 mm at the top at 73.5° angles, a height of 110 mm, and a total surface area of 0.03 m^2 (Falconer 2003). The Falcon concentrator and an upside view of its bowl are shown in Fig. 2.

Fig. 2. Falcon L40 concentrator and top view of the concentrator bowl

For the tests, artificial samples were prepared manually at a ratio of 2% magnetite (Fe_3O_4) and 98% calcite ($CaCO_3$) by weight. These samples were chosen as experimental material to eliminate the unrecovered particle performance losses, prevent the effects of model calculations, and facilitate easy analysis of test results. The model is size-dependent and depends on operational parameters, such as washing water pressure and centrifugal force. However, all other material parameters, such as the grade and recovery, were kept constant so that the relationship between the particle-size distribution and ratio of artificial gravity force to washing water pressure (G/P) could be neglected. In the tests, 2% magnetite was used because the amount of magnetite should not exceed the inside volume of the Falcon bowl at the laboratory scale. However, the amount should not be too small because of the sensitivity of the analysis. Therefore, an average grade (2%) was selected. The basic methodology used for the Falcon L40 tests are as follows. First, the sample was crushed or ground to a target size as needed, sieved to narrow particle-size distributions, mixed with water to create a slurry, and then agitated in an overhead tank. The slurry was fed from the mixing tank into the concentrator at a consistent rate while the equipment was on. Once the test was complete, the target minerals, which had higher specific gravities, were collected along the concentration bed of the bowl as concentrates. In contrast, the gangue minerals, which had lower specific gravities and were washed out by water, were collected in a separate container as tailings.

The Falcon separator was tested with six different size fractions: −600 + 425 μm, −425 +300 μm, −300 + 212 μm, −212 + 150 μm, −150 + 106 μm, and −106 + 75 μm under varying operational parameters, such as artificial gravity force (20-305 g) and washing water pressure (1.5-0.5 bar). The feed solids content was kept constant at 45% by weight.

The performance of the Falcon concentrator depends on specific test conditions; for example, all the materials were washed out even at a minimum washing water pressure (0.5 bar) because of the artificial gravity value of 305 G, which was maximum in finer sizes (−75 μm). In contrast, the concentrator was choked up by low artificial gravity force values even at the 1.5 bar washing water pressure, which was maximum in coarser sizes (+600 μm). Therefore, the limits of the particle-size intervals were determined to be between 600 μm and 75 μm for this artificial feed. Thus, the minimum washing water pressure and maximum artificial gravity forces were used for finer sizes, whereas the maximum water pressure and minimum artificial gravity forces were used for coarser sizes. The experiments showed that the effects of artificial gravity force (G) and water pressure (P) are inversely proportional. Therefore, a new parameter, G/P, was defined to comparatively evaluate the test results and was used as the main parameter in the model. Thus, the relationships between G/P, recovery, and grade values at different particle-size distributions were investigated, and models were developed by fitting the original data, recoveries vs. G/P, and grades vs. G/P, with the simulated data for different particle-size distributions.

All studies were conducted using batch tests. Concentrate and tailing discharge units were present in the system. First, the samples were fed directly into the separator, and then the products were separated and collected as concentrates and tailings. The products were then dried and weighed for analysis. Magnetite was obtained using a roll magnetic separator and weighed. Before each test, the equipment was cleaned, controlled, and then operated according to the new test conditions. All tests were performed using the same method. The test conditions are listed in TABLE 1.

TABLE 1

Test conditions for determining the performance of the Falcon concentrator

Particle Size (μm)	Water pressure (bar)	Artificial gravity force (G)
−600 + 425	1.5	20–78
−425 + 300	0.5/1/1.5	20–123
−300 + 212	0.5/1/1.5	20–176
−212 + 150	0.5/1/1.5	20–305
−150 + 106	0.5/1/1.5	20–305
−106 + 75	0.5/1/1.5	123–305

3. Results and discussion

The recovery values are proportional to the *G*/*P* parameter, and this dependency indicates differences in the particle size of the feed. However, the general tendencies of these relationships were uniform. Therefore, the first step in developing a model was defining the recovery values as a function of the *G*/*P* parameter and then implementing this relationship into a simple empirical equation (Eq. (1)). Additionally, the actual and simulated recovery values were fitted (Fig. 3).

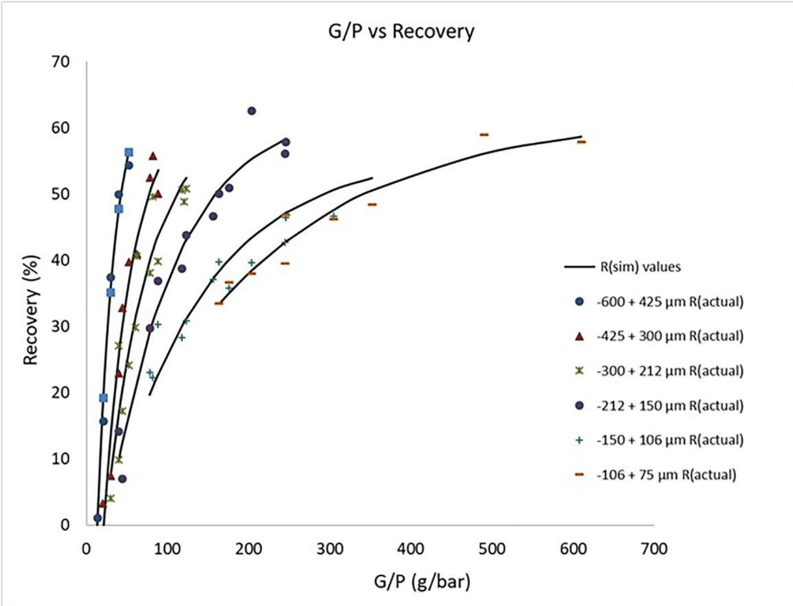

Fig. 3. Fitting of actual recovery and simulated recovery data for different particle sizes versus the ratio of artificial gravity force to washing water pressure (*G*/*P*)

In Fig. 3, the lines represent the simulation data, and the dots represent the actual data. In addition, the coefficients *a*, *b*, and *c*, calculated by non-linear regression analysis, were modelled to determine their relationships with the particle-size distributions and fitted by minimising the total square of differences between simulated and actual recovery values (Figs. 4, 5, and 6).

The geometric mean was used for particle sizes in the model calculations.

$$R(sim) = a\left[b - \exp\left(-c \times \left(\frac{G}{P}\right)\right)\right] \tag{1}$$

where *R* (sim) is the simulation (calculated) value of recovery, *G* is the artificial gravity force, and *P* is the water pressure.

a, *b*, and *c* are the coefficients that were calculated by non-linear regression analysis separately for each particle-size distribution. In the model, the physical implication of the product (*a*. *b*) of the constants *a* and *b* is defined as the speed at which the maximum recovery values are

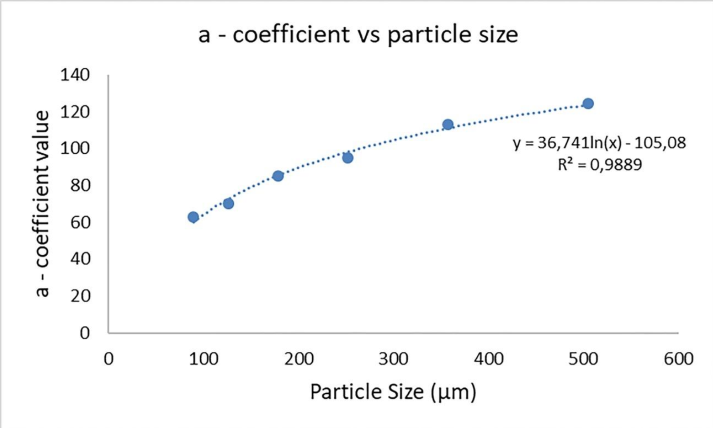

Fig. 4. Relationship between coefficient *a* and particle-size distribution in the empirical equation representing the particle recovery values as a function of the *G*/*P* parameter

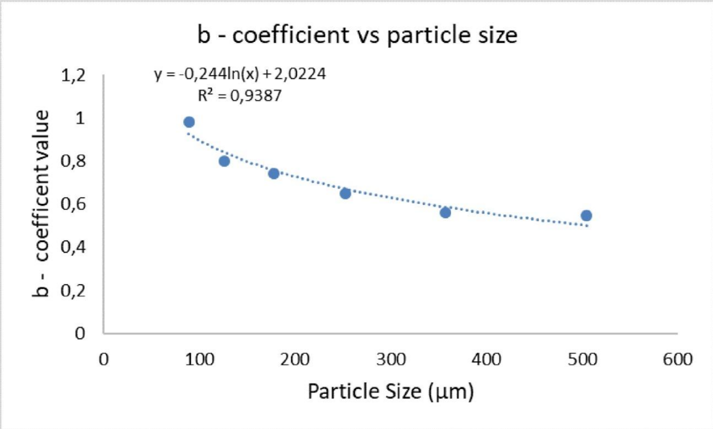

Fig. 5. Relationship between coefficient *b* and particle-size distribution in the empirical equation representing the particle recovery values as a function of the *G*/*P* parameter

reached for the determined particle size in its asymptote. Moreover, the constant *c* represents the maximum recovery asymptote of the determined particle size. The particle size and constant *c* exhibited a linear relationship.

Where Eqs. (2), (3) and (4) indicate the mathematical expression of a, b and c coefficients in Fig. 4, 5 and 6, respectively, while the x values indicate particle sizes.

$$a = y = 36{,}741 \ln x - 105{,}05 \tag{2}$$

$$b = y = -0{,}244 \ln x + 2{,}0224 \tag{3}$$

$$c = y = 10^{-4} x - 0{,}0044 \tag{4}$$

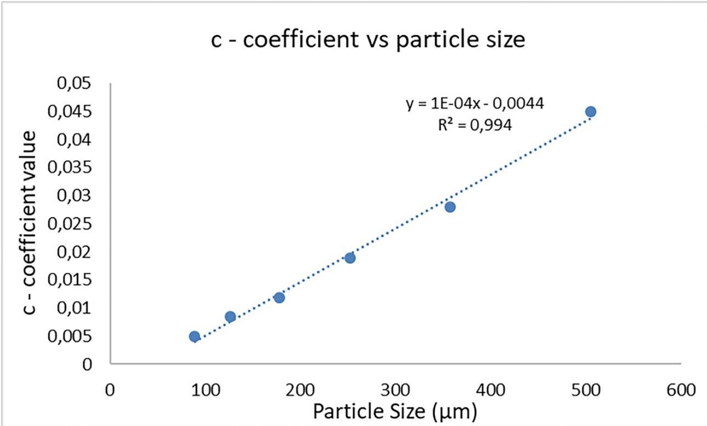

Fig. 6. Relationship between coefficient c and particle-size distribution in the empirical equation representing the particle recovery values as a function of the G/P parameter

The simplest relationship between G/P and recoveries is exponential, whereas that of particle-size distribution with coefficients a, b is logarithmic, and that with c is linear. The coefficients a, b, and c can be determined using Figs. (4), (5), and (6) for a specific particle size, and the recovery values can then be calculated using the model presented in Eq. (1).

However, the grade values are also related to the G/P parameter, and a different model was required to define this relationship. In the developed model, the grade values were defined as a function of G/P as in Eq. (1), and this relationship was implemented into a different empirical equation (Eq. 5). In addition, the actual and simulated grade values were fitted (Fig. 7).

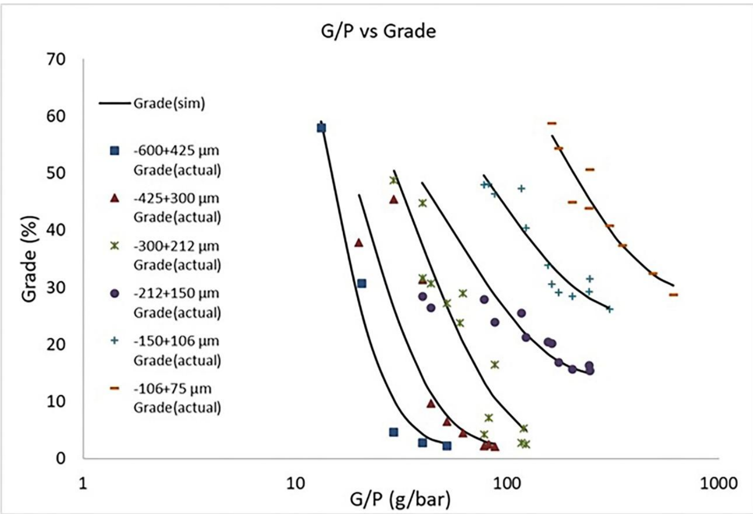

Fig. 7. Fitting of actual grade and simulated grade values for different particle sizes versus the ratio of artificial gravity force to washing water pressure (G/P)

In Fig. 7, the lines represent the simulation data, whereas the dots represent the actual data. In addition, the coefficients *d*, *e*, and *f*, calculated by non-linear regression analysis, were modelled to determine their relationships with the particle-size distributions and fitted by minimising the total square of the differences between the simulated and actual grade values (Figs. 8, 9, and 10).

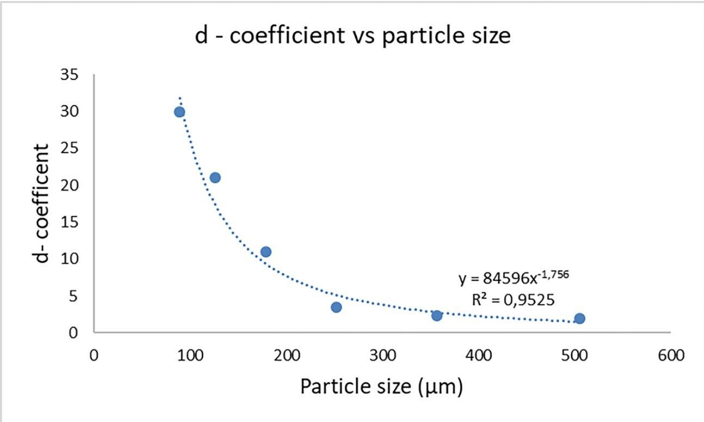

Fig. 8. Relationship between coefficient *d* and particle-size distribution in the empirical equation representing the particle grade values as a function of the *G*/*P* parameter

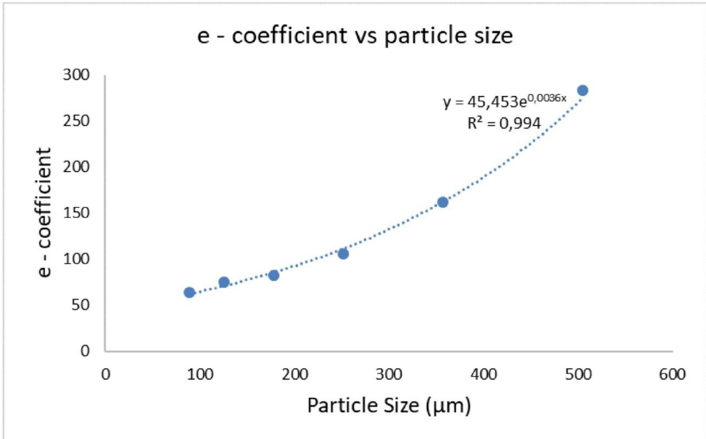

Fig. 9. Relationship between coefficient *e* and particle-size distribution in the empirical equation representing the particle grade values as a function of the *G*/*P* parameter

$$Grade(sim) = \left[d + e \times \exp\left(f \times \left(\frac{G}{P} \right) \right) \right] \tag{5}$$

where Grade (sim) is the simulation (calculated) value of grade, *G* is the artificial gravity force, and *P* is the water pressure.

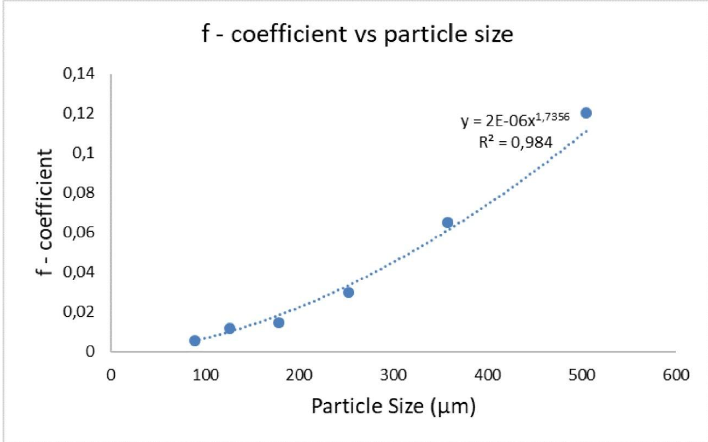

Fig. 10. Relationship between coefficient f and particle-size distribution in the empirical equation representing the particle grade values as a function of the G/P parameter

d, e and f are the coefficients that were calculated separately for each particle-size distribution by non-linear regression analysis. In the model, the physical implication of the product ($e.f$) of the constants e and f is defined as the speed of reaching the minimum grade values for the determined particle size in its asymptote. Moreover, the constant d represents the point of location of the minimum grade asymptote with the particle-size distribution.

Where Eqs. (6), (7) and (8) indicate the mathematical expression of d, e and f coefficients in Figs. 8, 9 and 10, respectively, while the x values indicate particle sizes.

$$d = y = 84596x^{-1,756} \tag{6}$$

$$e = y = 45,453e^{-0,0036} \tag{7}$$

$$f = y = 2\times10^{-6}x^{-1,7356} \tag{8}$$

The relationship between the G/P parameters and grades is exponential, whereas that of the particle-size distribution with coefficients d and f are power functions, and that with e is exponential. The coefficients d, e, and f can be determined from Figs. 8, 9, and 10 for a specific particle size, and the grade values can then be calculated using the model presented in Eq. (5). The model parameters (constants) can be changed for different ore types, which are dependent on their physical properties, such as density, recovery size, and grade. In this study, the particle-size dependence of the Falcon concentrator efficiency was determined, which is often ignored in the industry. This dependency is also expressed mathematically in the present study.

5. Conclusion

In this study, Falcon separator experiments were conducted under different operational conditions (artificial gravity, water pressure, and particle size) with artificial feed, prepared manually at a ratio of 2% magnetite (Fe_3O_4) to 98% calcite ($CaCO_3$) by weight. The performance of the Falcon concentrator depends on some specific test conditions; for example, all the materials with finer sizes (−75 µm) were washed out, whereas the concentrator choked up for coarser sizes (+600 µm). Thus, the minimum washing water pressure and maximum artificial gravity force were used for finer sizes, whereas the maximum water pressure and minimum artificial gravity force were used for coarser sizes. Therefore, the limits of the particle-size intervals were determined to be between 600 µm and 75 µm for this artificial feed. These models were developed to be particle-size-dependent. However, if the models are applied to ores that have higher density differences between valuable minerals and tailings, the particle-size limits may be extended to finer grain sizes. Moreover, the models would require improvements to apply density difference as a parameter. Thus, more useful models can be developed for Falcon concentrators. The experiments show that the effects of artificial gravity (*G*) and water pressure (*P*) are inversely proportional. Therefore, a new parameter, *G*/*P* was defined to comparatively evaluate the test results and was applied as the main parameter in the models.

Thus, the relationships between the *G*/*P* parameter, recovery, and grade values for different particle-size distributions were investigated, and a simple empirical model was developed by minimising the total square of differences between the simulated and actual values to calculate recoveries that is $Recovery(sim) = a\left[b - \exp\left(-c \times \left(\frac{G}{P}\right)\right)\right]$ and another empirical model was developed to calculate grades as $Grade(sim) = \left[d + e \times \exp\left(f \times \left(\frac{G}{P}\right)\right)\right]$.

In an investigation on Gumushane-Mastra gold ore, the particle size effect on fractional recovery was examined and revealed that the 53-micron particle size had a critical value for concentration due to the liberation degree of ore [18]. Also, another investigation on ultrafine particles fluid dynamics model in Falcon concentrator had indicated that the probability of particle trajectory depends on the fluid velocity, particle diameter and the azimuthal direction for recovering a particle with the Falcon [19]. In a gold mine in Texada-Island, Canada, the pilot plant was established by an earlier Falcon concentrator model that was B12 and exposed that under 74 microns feed had the best results [20]. Although a few scientific investigations focus on the particle size effect on Falcon concentrator performance, none of them have revealed a model which depends on particle size. On the other hand, this study presents an improvable empirical size-dependent model.

Based on this experiment, Figs. 4, 5, and 6 can be used to determine the coefficients *a*, *b*, and *c*, and the recovery values can be calculated using the model presented by Eq. (1) for a specific particle size. Moreover, the coefficients *d*, *e*, and *f* coefficients can be determined from Figs. 8, 9, and 10, and the grade values can be calculated by the model represented by Eq. (5). The effective performance of the models can be verified by investigating Figs. 3 and 7 (where the simulated/calculated data are presented as lines and the actual data are indicated by dots).

Acknowledgments

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