J. S. Afr. Inst. Min. Metall., vol. 91, no. 5.
May 1991. pp. 169-174

Conditioning in the flotation of gold, uranium oxide, and pyrite

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SYNOPSIS

The effect of conditioning energy on the flotation of gold, U_3O_8, and pyrite was investigated in the range 0,1 to 100 kWh per tonne of dry ore for various combinations of conditioning time and impeller speed in a cylindrical conditioning tank. It was found that, when the conditioning energy was increased to between 5 and 10 kWh per tonne of dry ore, the total recovery and flotation rate of the valuable minerals (expressed as Klimpel parameters) increased substantially. The Klimpel parameters are dependent on conditioning energy, but are independent of conditioning time or impeller speed (at constant conditioning energy). The Klimpel parameters of the gangue are independent of conditioning energy.

SAMEVATTING

Die uitwerking van die kondisioneringsenergie op die flottasie van goud, U_3O_8, en piriet is met verskillende kombinasies van kondisioneertyd en stuwerspoed in 'n silindriese kondisioneertenk oor die strek 0,1 tot 100 kWh per ton droë erts ondersoek. Daar is gevind dat indien die kondisioneringsenergie tot tussen 5 en 10 kWh per ton droë erts verhoog word, die herwinning en flottasietempo van die waardevolle minerale (uitgedruk as Klimpelparameters) aansienlik toeneem. Die Klimpelparameters is afhanklik van die kondisioneringsenergie en onafhanklik van die kondisioneertyd of stuwerspoed (by 'n konstante kondisioneringsenergie). Die Klimpelparameters van die uitskot is onafhanklik van die kondisionereingsenergie.

Introduction

The effect of conditioning has been widely studied for agglomeration flotation and is discussed elsewhere[1]. Corresponding data for froth flotation are scarce and sketchy. However, it has been shown that conditioning energy, often expressed as conditioning time at constant impeller speed or as impeller speed at constant conditioning time, has a pronounced effect on the recovery and flotation rate of valuable minerals and on the grade of the concentrate[2-10]. The most important results are summarized below.

Flotation Rate. During the froth flotation of gold, U_3O_8, pyrite, and arsenide and sulphide minerals[3-9], the flotation rate can be increased by an increase in conditioning energy until a limit is reached. The flotation rate of the gangue (normally silica or silicate minerals) can decrease[3], or stay constant[6], or increase marginally[8], with increasing conditioning energy.

Recovery. The total recovery of nickel sulphide minerals[2] and copper minerals (mainly malachite)[10] can be increased by an increase in conditioning energy until a limit is reached. The equilibrium recovery of gold can either stay constant[3,7,9] or increase marginally until a limit is reached[5,6,8]. The equilibrium recovery of U_3O_8 can stay constant[3,6,8], or decrease[5], or decrease after an initial increase[7]. The equilibrium recovery of pyrite can either stay constant[3,6,7] or increase marginally[5,8] with increasing conditioning energy. The equilibrium recovery of arsenide and sulphide minerals is independent of conditioning energy[9]. The equilibrium recovery of gangue decreases with increasing conditioning energy[3,8].

Grade. Normally the grade of the flotation concentrate in the froth flotation of copper minerals (mainly malachite)[10], gold[3,5,6,8], U_3O_8[3,5,8], and pyrite[3,8] increases with increasing conditioning energy until a limit is reached. However, it can also stay constant in the froth flotation of gold[9], U_3O_8[6], pyrite[5,6], and arsenide and sulphide minerals[9]. The increase in grade can be ascribed to a reduced recovery of gangue, rather than to an increased recovery of valuable mineral.

Because conditioning forms an integral part of flotation and has a pronounced effect on both the recovery and the flotation rate of valuable minerals, and because of the financial implications consequently involved, it has become imperative to make a thorough investigation of the effect of conditioning on the flotation of Witwatersrand ore and to obtain an understanding of the more important parameters and mechanisms involved.

Experimental

Two samples of Witwatersrand ore (identified here as ore A and ore B) were used in this investigation. The particle size was minus 10 mm and the analysis was as shown in Table I. The samples were individually crushed in a jaw crusher to minus 10 mesh (minus 1,68 mm), were stored in drums, and were thoroughly mixed before use. Ore samples of 2 kg were milled with 1 litre of water (Rand Water Board) in a stainless-steel rod mill to 65 per cent minus 75 μm.

TABLE I
ANALYSIS OF THE ORE SAMPLES

Constituent	Sample A	Sample B
Gold, g/t	7,6 ± 0,46	7,3 ± 0,88
U_3O_8, g/t	172 ± 2	141 ± 1
Sulphur, %	1,74 ± 0,01	1,77 ± 0,01

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 SA ISSN 0038-223X/ 3.00 + 0.00. Paper received 12th June, 1990; modified paper received 19th December, 1990.

The experimental conditioning tank consisted of a cylindrical PVC container with an inside diameter of 300 mm, a flat bottom, a height of 600 mm, and four vertical baffles that were one-twelfth the tank diameter (25 mm) at 90° to one another and that ended 10 mm from the bottom. This size is the minimum for experimental work[11] if scale-up problems are to be avoided. The impeller shaft was mounted centrally in the conditioning tank, and was driven by a variable-speed electric motor. The motor, driving gear, and gearbox formed a unit that was mounted vertically on a vertically adjustable platform. The impeller speed was measured by a photo-electric tachometer.

The conditions during conditioning (Table II) were kept constant, while the items shown in Table III were varied. The conditioning time was measured from the moment of reagent addition, and included only the time the pulp was conditioned in the conditioning tank.

TABLE II
EXPERIMENTAL CONDITIONS DURING CONDITIONING

Flotation condition	Value
Mass of ore, kg	10
Height of pulp, mm	300
Density of pulp, kg/m^3	1300
Temperature, °C	25
pH	11,5
Reagents, g/t	
$CuSO_4$	100
Sodium n-propyl xanthate	60
Aeropromoter 3477	15

TABLE III
EXPERIMENTAL VARIABLES

Variable	Range
Pitched-blade impeller	
N, r/min	300 to 1100
t_c, min	4,5 to 72
D, mm	75 to 150
D/D_t	0,25 to 0,50
Number of tests: Ore A	72
Ore B	44
LIGHTNIN A310 impeller	
N, r/min	500 to 1100
t_c, min	4,5 to 72
D, mm	96 to 160
H/D_t	0,32 and 0,53
Number of tests, Ore B	17

The conditioning occurred in the turbulent region, i.e. $Re > 10\,000$, with Re defined[11] as

$$Re = \rho D^2/N/\mu.$$

(All the symbols used are defined at the end of the paper.) The power dissipated during conditioning is given[11] by

$$P = N_p \rho N^3 D^5,$$

with N_p as a function of the system geometry and Re[11].

In the turbulent region, N_p is independent of Re, and is a function only of impeller type and system geometry. For the suspension of solids, it is necessary to use an axial-flow impeller[11] such as the pitched-blade impeller or the hydrofoil or aerofoil impeller (e.g. the LIGHTNIN A310 impeller). At standard geometry, N_p is a constant for each impeller type, e.g. 1,37 for the standard four-blade pitched-blade impeller[11] and 0,30 for the LIGHTNIN A310 impeller[12]. By different combinations of these variables, the conditioning energy in the tests was varied over three orders of magnitude (0,1 to 100 kWh per tonne of dry ore).

After the conditioning, the contents of the conditioning tank were split in a sample splitter, and 40 per cent was used for flotation. Care was taken so that heavy particles could not stay behind and consequently cause large losses of gold and pyrite.

Flotation was conducted in a laboratory-size 9-litre Denver 12 flotation cell at an impeller speed of 1500 r/min and at constant air-feed rate. Approximately 13 g/t of tri-ethoxy butane was added to the conditioned pulp, and the conditioning lasted for roughly 1 minute. Exactly 2 minutes after the conditioning had been completed, the air inlet was opened and flotation started, the flotation time being measured from that moment. Care was taken to ensure a constant procedure and rate of froth removal because of the sensitivity of flotation rate to both the rate and the method of froth removal.

Five samples of concentrate were taken for the following periods: 0–1 min, 1–2 min, 2–4 min, 4–8 min, and 8–12 min. The five samples and the tailings were prepared and analysed for gold, U_3O_8, and sulphur (and thus pyrite).

A curve was fitted to the cumulative recoveries of the valuable minerals at the different flotation times so that the Klimpel parameters, R and k, used in the Klimpel flotation-rate equation[13],

$$r = R[1 - (1/kt_f)(1 - e^{-kt_f})],$$

could be determined.

Results

The Klimpel parameters for ore A are depicted in Figs. 1 and 2 as a function of the natural logarithm of the conditioning energy. Similar results were obtained for ore B.

From the results it is clear that the conditioning energy has a pronounced effect on both the equilibrium recovery and the flotation rate of the valuable minerals (gold, U_3O_8, and pyrite). If the conditioning energy is increased to more than 5 to 10 kWh per tonne of dry ore, the equilibrium recovery of the valuable minerals can be improved as shown in Table IV.

If the conditioning energy is increased by the same amount, the Klimpel flotation rate constant can also be increased substantially, as shown in Table V.

From Fig. 1 it is clear that the relationship between the natural logarithm of the conditioning energy and both Klimpel parameters follows an S-shaped curve for the three valuable minerals, which can be represented by the modified Gompertz equation[14]. For the system in which the Klimpel parameters are a function of the logarithm of the conditioning energy, this equation can be written as

$$\ln[(\phi^{max} - \phi)/(\phi^{max} - \phi^{min})] = -k_c^{*}E^{\gamma}.$$

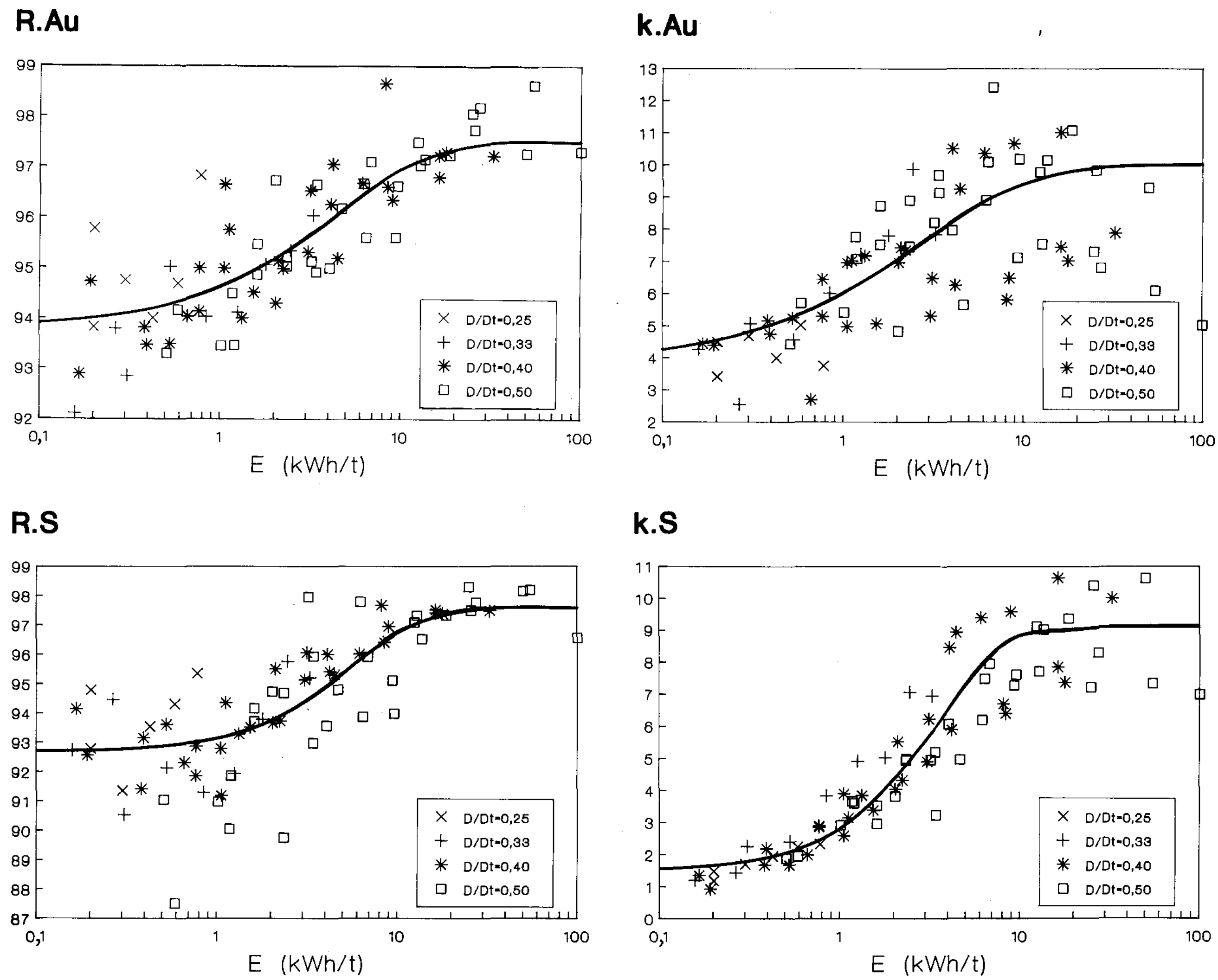

Fig. 1—Klimpel parameters for gold and sulphur as a function of conditioning energy (pitched-blade impeller at standard geometry, ore A)

TABLE IV
EQUILIBRIUM RECOVERY OF VALUABLE MINERALS

Ore	Mineral	Without conditioning %	With conditioning %	Improvement %
Ore A	Gold	93,8	97,5	3,7
	U_3O_8	40,1	47,9	7,8
	Pyrite	92,7	97,6	4,9
Ore B	Gold	95,8	97,7	1,9
	U_3O_8	37,6	42,4	4,8
	Pyrite	95,7	97,9	2,2

TABLE V
KLIMPEL FLOTATION RATE CONSTANT OF THE VALUABLE MINERALS

Ore	Constituent	Without conditioning min^{-1}	With conditioning min^{-1}	Improvement (factor)
Ore A	Gold	3,8	10,0	2,6
	U_3O_8	1,4	3,0	2,1
	Pyrite	1,5	9,1	6,1
Ore B	Gold	4,7	11,1	2,4
	U_3O_8	0,95	2,7	2,8
	Pyrite	1,7	11,3	6,6

This curve is characterized by a very small initial slope, i.e. nearly constant minimum values of the Klimpel parameters (R^{min} and k^{min}), followed by a period of rapidly increasing slope (0,5 to 1 kWh/t), which gives way to an interval of nearly constant slope, succeeded by a period of rapidly decreasing slope approaching zero slope (at above 5 to 10 kWh/t). The Klimpel parameters then level off at a constant maximum value (R^{max} and k^{max}). R^{min}, R^{max}, k^{min}, and k^{max} are functions of both the type of mineral and the type of ore.

Some scattering of the data occurs as a result of the normal variability encountered in flotation testwork.

The minimum conditioning energy required for optimum flotation results lies in the range 5 to 10 kWh per tonne of dry ore. This is in accord with the results of previous investigators. Weston[15,16] suggested the follow-

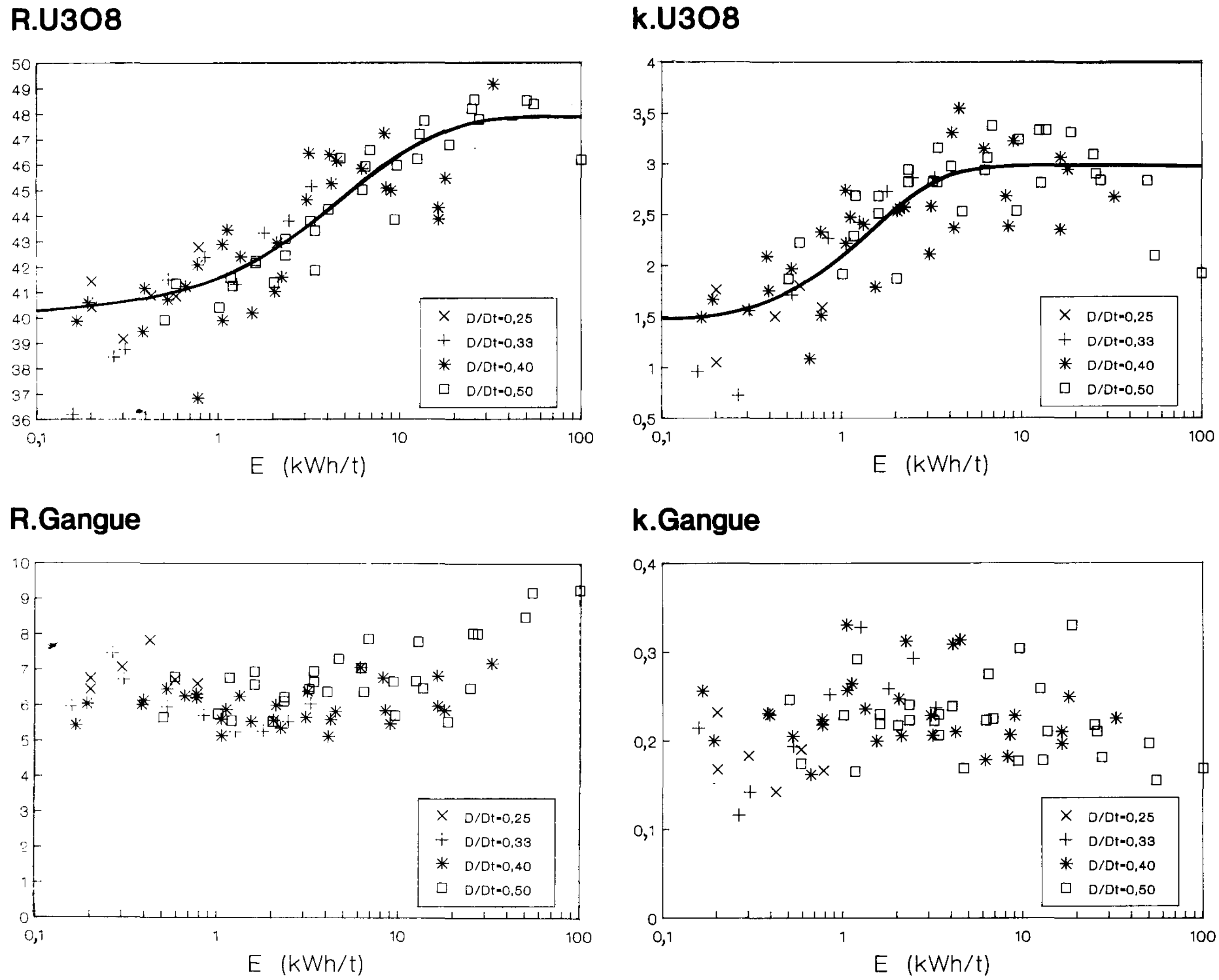

Fig. 2—Klimpel parameters for U_3O_8 and gangue as a function of conditioning energy (pitched-blade impeller at standard geometry, ore A)

ing for froth flotation: 0,3 to 2,0 kWh/t for copper sulphide minerals, 0,15 to 0,6 kWh/t for molybdenum sulphide minerals, and 0,6 to 4,0 kWh/t for nickel sulphide minerals, but alleged that the energy may amount to as much as 5 kWh/t. For agglomeration flotation, conditioning energies of the same order have been determined[1].

No correlation between the amount of conditioning and the Klimpel parameters of the gangue could be detected.

Possible Reaction Mechanism

No attempt has thus far been made to propose a mechanism to explain the effect of conditioning upon froth flotation.

It has been found[17] that the repulsive energy barriers between collector molecules and mineral surfaces in agglomeration flotation can be overcome by the hydrodynamic forces encountered during conditioning.

The Klimpel parameters of the valuable minerals show an increase with increasing conditioning energy, but the Klimpel parameters for the gangue show no corresponding decrease, which would have been expected with a mechanism of reagent transfer from particles of gangue to particles of valuable minerals with increasing conditioning energy[18]. It is therefore concluded that there is *no transfer of reagents*. This is in accordance with the results of Karjalahti[19] for the agglomeration flotation of apatite.

There is some indication of support for an *attrition mechanism*, by which the collector is desorbed from the surface of mineral particles at very high conditioning intensity or energy[20,21]. This would result in decreasing Klimpel parameters at very high conditioning energy as displayed by k_{Au} and $k_{U_3O_8}$. These decreases are very small but may be caused by attrition. This very high conditioning energy at which attrition takes place is probably the result of the large energy needed to break the very strong chemical bond between the xanthate and the surfaces of the valuable minerals[17].

Based on the findings of this investigation, the following mechanism is postulated to explain the effect of conditioning on the flotation of Witwatersrand ore:

(1) dispersion of the reagents into the pulp
(2) specific adsorption of the collector onto the surfaces of all the mineral particles according to the relative repulsive energy barriers and relative affinities of the different minerals for the collector

(3) saturation of all the mineral surfaces with the collector
(4) desorption of the collector from the surfaces of the valuable-mineral particles and of the gangue particles at very high levels of conditioning energy by attrition.

The following equation (regression model) for both Klimpel parameters has been developed[1]:

$$\ln[(\phi^{max} - \phi)/(\phi^{max} - \phi^{min})] = -k_c(P/V)^{\gamma}_c t_c$$

with ϕ equivalent to any Klimpel parameter (R or k).

Application of Regression Model

The constants ϕ^{min}, ϕ^{max}, k_c, and γ in the above equation were determined by minimizing the expression for the residual sum of squares for the regression model, as shown in Table VI.

TABLE VI
COEFFICIENTS FOR REGRESSION MODEL (FUNCTION OF CONDITIONING POWER AND TIME)

Ore	ϕ	ϕ^{min}	ϕ^{max}	k_c $(W/m^3)^{-\gamma}min^{-1}$	γ	Coefficient of determination R^2
Ore A	R_{Au}	93,8	97,5	0,0167	1,0	0,7061
	k_{Au}	3,8	10,0	0,0244	1,4	0,4556
	$R_{U_3O_8}$	40,1	47,9	0,0150	1,0	0,7646
	$k_{U_3O_8}$	1,4	3,0	0,0440	1,4	0,7068
	R_S	92,7	97,6	0,0100	1,25	0,6103
	k_S	1,5	9,1	0,0161	1,1	0,8420
Ore B	R_{Au}	95,8	97,7	0,0288	1,0	0,5045
	k_{Au}	4,7	11,1	0,0229	1,4	0,6367
	$R_{U_3O_8}$	37,6	42,4	0,0172	1,05	0,7885
	$k_{U_3O_8}$	0,95	2,7	0,0273	1,4	0,5939
	R_S	95,7	97,9	0,0207	1,0	0,5888
	k_S	1,7	11,3	0,0133	1,15	0,8959

R^2 (the coefficient of determination[22]) is the fraction of the total variation that is accounted for by the regression model. A very high percentage (up to 90 per cent in the case of k_S for ore B) of the variability of the data is explained by the equation.

In the case of R_{Au} and R_S, the improvement as a result of conditioning is only a few percentage points, and the normal variability as a results of the testwork is therefore relatively large compared with the total variability. In the case of k_{Au} and $k_{U_3O_8}$, a large fraction of the variance is not explained by the model equation. This is believed to be the result of attrition at high conditioning energy.

The closeness of γ to the exponent of the conditioning time[2] suggests that the regression model may be approximated as a function of conditioning energy, $E^{\gamma} \propto (P/V)^{\gamma} t_c^{\gamma}$, giving

$$\ln[(\phi^{max} - \phi)/(\phi^{max} - \phi^{min})] = -k_c^{*} E^{\gamma}.$$

The coefficients listed in Table VII were obtained by minimizing the residual sum of squares for this equation.

There is a close correlation between the Klimpel parameters and the conditioning energy, and this equation can be used for the accurate prediction of both Klimpel parameters for all three valuable minerals as a function of the conditioning energy. The Klimpel parameters predicted by the regression model using the coefficients given in Table VII are given as solid black lines in Figs. 1 and 2.

TABLE VII
COEFFICIENTS FOR REGRESSION MODEL (FUNCTION OF CONDITIONING ENERGY)

Ore	ϕ	ϕ^{min}	ϕ^{max}	k_c^{*} $(kWh/t)^{-\gamma}$	γ	Coefficient of determination R^2
Ore A	R_{Au}	93,8	97,5	0,24	0,90	0,7077
	k_{Au}	3,8	10,0	0,43	0,75	0,4238
	$R_{U_3O_8}$	40,3	47,7	0,21	0,90	0,7668
	$k_{U_3O_8}$	1,4	3,0	0,57	1,2	0,6530
	R_S	92,7	97,6	0,093	1,3	0,6137
	k_S	1,5	9,1	0,18	1,3	0,8542
Ore B	R_{Au}	95,7	97,7	0,275	1,3	0,5126
	k_{Au}	4,6	11,1	0,26	1,05	0,5258
	$R_{U_3O_8}$	37,6	42,4	0,16	1,25	0,7973
	$k_{U_3O_8}$	0,95	2,7	0,41	0,85	0,4545
	R_S	95,7	97,9	0,17	1,3	0,5979
	k_S	1,7	11,3	0,215	0,90	0,8924

A comparison of the coefficients of determination given in Tables VI and VII reveals that both regression equations (i.e. as a function of E^{γ} and $P^{\gamma} t$ respectively) account for the variability in the data with the same degree of adequacy. It is therefore not clear whether the Klimpel parameters are functions of the conditioning energy or of the intensity of conditioning. This result is in accord with that of previous investigators. Runnolinna *et al.*[23] alleged that the flotation result of conditioning depends only on the conditioning energy, and that it is independent of the method and rate of conditioning. However, Lapidot and Mellgren[20] and Karjalahti[19] found that the intensity of conditioning, rather than the total energy input, was the important variable for that type of ore, but that this difference is rather small[19].

Coefficients were obtained for the regression model with varying impeller height (Z_a/D), varying pulp height (H/D_t), and the LIGHTNIN A310 impellers, and it was found[1] that this equation can be used for the accurate prediction of the Klimpel parameters for non-standard geometry or other types of impellers.

Limited published data on the use of conditioning in the flotation of other minerals are available. When such coefficients were used in the regression model for copper minerals (mainly malachite), gold, arsenide and sulphide minerals, manganese oxide minerals, and ilmenite, it was found[1] that this equation also accurately predicts the effect of conditioning energy on the flotation of other minerals.

Recommendations

There is enough reason to believe that an equation of the type of the modified Gompertz equation presented here, or a more general equation[1], for the Klimpel parameters accurately predicts the influence of other variables during flotation. It is well-known that the recovery and flotation rate of many minerals follow an S-shaped curve with the logarithm of variables such as collector concentration, hydrogen-ion concentration (or pH), activator concentration, frother concentration, temperature, etc. The applicability of this equation in describing the effect of these variables must be investigated. A great deal of insight would be gained if it were known how these other variables effect the constants in the regression model.

From practical experience, it is known that the Klimpel parameters depend on many variables, and an enormous amount of research is being directed towards the optimization of these variables. At higher levels of conditioning energy, lower additions of reagents may be possible. Alternatively, lower conditioning energies and higher reagent additions may be more economical. These equations[1] may assist in the research to find the economic optimum between conditioning energy and other flotation variables (e.g. pulp density, grind, pH, and reagent additions).

Symbols Used

D Impeller diameter, m
D_t Tank diameter, m
E Conditioning energy, kWh/t of dry ore
H Pulp height, m
k Klimpel flotation rate constant, min^{-1}
k_c Proportionality constant in equation for Kimpel parameters, $(W/m^3)^{-\gamma} min^{-1}$
k_c^* Proportionality constant in equation for Klimpel parameters, $(kWh/t)^{-\gamma}$
N Impeller speed, s^{-1}
N_p Power number
P Power, W
r Recovery
R Equilibrium recovery or Klimpel equilibrium recovery
R^2 Coefficient of determination
Re Impeller Reynolds number
t Time, min
V Pulp volume, m^3
Z_a Impeller height above tank bottom, m
γ Exponent of power in equation for Klimpel parameters
μ Pulp viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
ρ Pulp density, $kg \cdot m^{-3}$
ϕ Any Klimpel parameter, min^{-1} or dimensionless

Subscripts
c Conditioning
f Flotation

Superscripts
min Minimum
max Maximum

Acknowledgements

This paper is published by permission of Anglo Vaal Research Laboratory. The author is indebted to K. Doig and S. Mphailane for their invaluable assistance in the experimental work.

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