Physicochem. Probl. Miner. Process. 52(1), 2016, 252−267

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems
of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received January 20, 2015; reviewed; accepted April 24, 2015

APPLICATION OF D-OPTIMAL DESIGN FOR OPTIMIZING COPPER-MOLYBDENUM SULPHIDES FLOTATION

Fardis NAKHAEI*, Mehdi IRANNAJAD*, Abbas SAM, Ali JAMALZADEH****

* Department of Mining & Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran, Iranajad@aut.ac.ir

** Department of Mineral Processing, Engineering Faculty, Shahid Bahonar University, Kerman, Iran

Abstract: Froth flotation is widely used for concentration of base metal sulphide minerals in complex ores. One of the major challenges faced by flotation of these ores is selection of the type of flotation reagents. In this study, the D-optimal experimental design method was applied to determine the optimum conditions for flotation of copper and molybdenum in the rougher flotation circuit of the Sungun copper concentrator plant. The investigated parameters included types and dosages of collectors and frothers, diesel dosage and feed size distribution. The main effects on copper and molybdenum recoveries and grades were evaluated. Results of optimization showed that the highest possible grade and recovery were obtained for Z_{11} as a primary collector (20 g/Mg), R407 as a first promoter collector (20 g/Mg), X231 as a second promoter collector (7 g/Mg), A65 (15 g/Mg) and Pine oil as frothers (5 g/Mg), 20 g/Mg of diesel dosage, and d_{80} of feed size was equal to 80 µm. The analysis of variance showed that the primary promoter collector was the most significant parameter affecting the recovery of Cu, while diesel dosage and d_{80} were the most significant parameters influencing the Mo recovery.

***Keywords**: copper, molybdenum, flotation, chemical reagents, D-optimal, optimization*

Introduction

Although it seems that porphyry copper deposits are relatively simple, the geology of porphyry copper ores is almost complex and varies significantly within the ore body. Many copper sulphide ore deposits occur with molybdenum, mainly related to pyrite and silicate gangue minerals. Flotation is one of the most complex mineral processing operation, which is mainly applied to recover both copper and molybdenum sulphides, and it is affected by a very large number of variables (Pradyumna et al., 2005).

The efficiency of flotation process is highly dependent on reagent type and dosage as well as the feed size distribution, which directly influence the product grade and

http://dx.doi.org/10.5277/ppmp160122

recovery. Control of reagent additions is the most important aspect of the flotation strategy in commercial plants (Bulatovic, 2007). Selection of reagent and flowsheet used in actual plant practice is usually dictated by the nature and mineralogy of the ore, type of minerals present, flotation behaviour of gangue minerals, amount and occurrence of pyrite as well as the presence of clay minerals in the ore. Reagent used for treatment of porphyry copper and molybdenum ores usually involve lime as a modifier, xanthate as the primary and secondary collectors, which include dithiophosphates, mercaptans, thionocarbamates and xanthogen formats, and frothers, such as methyl isobutyl carbonyl, TEB (alkoxy paraffin and pine oil), Dow Froth 250, Dow Froth 1012 (glycols), HP700 and HP600 (alcohols in amine oxide) (Bulatovic, 2007).

The choice of secondary collector relies on a relatively large number of factors that are (a) type of copper minerals (i.e. single copper mineral or varieties), (b) composition of gangue minerals, (c) presence and type of clay minerals as well as (d) type of frother used. There is a wide variation in selection of the type of frother, and in many operating plants mixtures of either two or more frothers are used. The importance of frothers is enormous. It helps to stabilise bubble formation in the pulp phase, creating a stable froth to allow selective drainage from the froth of entrained gangue to increase flotation kinetics (Wills, 2007). Several studies have been carried out on various reagents in recovery of minerals by flotation (Malysa et al., 1981; Guy and Jia, 2000; Laskowski et al., 2003; Harvey et al., 2005; Melo, and Laskowski, 2006; Xia and Peng, 2007). The studies clearly show the importance of chemical factors that are type of collector, frother, and pH on flotation performance. Moreover, some parameters such as aeration, hold-up and froth height can also affect the flotation performance.

The experimental design method has been illustrated to be an effective for the improvement of quality and productivity in research and development (IIyas, 2010). It is a well-accepted technique that has been widely used for product design and process optimization in worldwide manufacturing and engineering (Kamaruddin et. al., 2004; Gopalsamy et. al., 2009; Rama and Padmanabhan, 2012; Sapakal and Telsang, 2012). Recently, the use of experimental design method has extended to include the mineral processing industry (Abali et al., 2006; Haghi et.al. 2009; IIyas et. al., 2010; Vazifeh et al., 2010). It provides a simplified systematic and efficient methodology for process optimization. There are several advantages of statistical design of experiments over classical one variable at a time method, where one variable is varied at time. The greatest advantage of this method is saving effort in conducting experiments, saving experimental time, reducing costs and discovering significant factors quickly (Trust and Nehta, 2014). The number of experiments that need to be done is greatly reduced, compared to those required by other traditional statistical methods. One of these statistical techniques is the factorial design test, which is employed to study several factors and determine their main effects and interactions.

The main goal of the present work is to use statistical techniques to optimize the types and dosages of flotation reagents and feed size distribution in the rougher circuit of the Sungun Copper Concentrator Plant to achieve the maximum Cu and Mo grades and recoveries. By using this procedure, the main effects of these reagents on flotation performance will be determined. Different steps of optimization strategy used in this study are:

a) designing experimental tests and performing them on laboratory scale (using D-optimal factorial design),

b) performing an analysis of the experimental results by ANOVA to determine the significant factors influencing the flotation process,

c) finding out optimum conditions for flotation to maximize the grade and recovery.

Experimental

Sungun copper concentrator plant

The Sungun copper ore body is located in the eastern Azerbaijan province, northwest of Iran. The total minable ore based on mine design and production scheduling is 400 Tg (400 million tons) with an average Cu grade of 0.62% (Vazifeh et al., 2010). Figure 1 shows the flotation circuit of the Sungun concentrator plant. The process consists of grinding circuit with their associated flotation circuits. The grinding circuit products with d_{80} about 90 μm are transferred to the rougher conditioner tank and then enter 12 rougher flotation tank cells, which are grouped into 6 banks of 2 cells each. Lime, collectors of Z_{11} (isopropyl xanthate sodium) and R407 (a mixture of mercapto benzothiazole and dithiophosphate) are added to the ball mill feed. The pH level of the feed with respect to rougher is measured in this conditioner tank and then lime slurry is added. The AF65 (hydrogen-terminated polypropylene glycol) and AF70 frothers are added to the conditioner tank. Further reagents (collectors) are added to the flotation cells of 3, 5 and 9. The collector distribution pattern is 32% for ball mill feed, 32% for the third rougher flotation cell, 20% for the fifth rougher flotation cell and 16% for the ninth rougher flotation cell (Vazifeh et al., 2010)

The final plant tailing consists of the last rougher flotation bank tailing and scavenger one. The rougher and scavenger concentrates are pumped to hydrocyclone clusters. Hydrocyclone underflow, after lime addition, reports to the regrind ball mill. The hydrocyclone overflow (d_{80} about 40 μm) is transferred to two cleaner column cells. The cleaner column concentrate is transferred to the re-cleaning column cell to produce the final concentrate with a 30% (nominal) copper grade and 84% recovery.

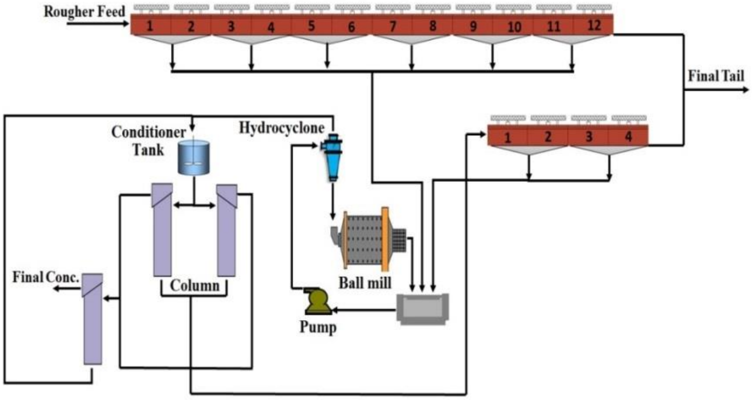

Fig. 1. The flow sheet of flotation circuit of the Sungun industrial plant

Materials

The cooper ore sample used in this study was taken from the SAG mill feed. The minerals of ores were defined by means of microscopy (Table 1). Chalcocite, chalcopyrite, covellite and pyrite were the primary sulfide minerals.

Table 1. Sulfide minerals composition (wt. %) of copper ore

Component	Cu_2S	CuS	$CuFeS_2$	FeS_2	MoS_2	ZnS
%	0.262	0.341	0.426	6.55	0.023	0.424

The ore sample was ground using jaw and roll crushers as well as ball mill so that 80% of the sample reached less than 120, 100 and 80 μm for the flotation tests. The chemical analysis of sample is shown in Table 2.

Table 2. Main chemical analysis results of ore sample

Component	Cu	CuO	Fe	Mo (%)
%	0.74	0.07	3.35	0.013

Flotation reagents used is this work were: collectors: Z_{11} (sodium isopropyl xanthate), Z_6 (potassium amyl xanthate), R407 (a mixture of mercaptobenzothiazole and dithiophosphate), Nascol (a mixture of mercaptobenzothiazole and di-n-butyl sodium dithiophosphate), Flomin 7240 (mixture of mercaptobenzothiazole and butyl sodium dithiophosphate), Flomin C4132 (isopropyl-n-ethyl thionocarbamate), X231 (thionocarbamate) and diesel (non-thiol collector); frothers: AF65 (hydrogen-terminated polypropylene glycol), DF 250 (methyl-terminated polypropylene glycols), Flomin 742 (polypropylene glycol), AF70, MIBC (methyl isobutyl carbonyl) and pine oil.

Flotation procedure

The flotation tests were performed according to the D-optimal factorial design of experiments. The considered variables in this study are: type of collectors (A, B and C), type of frothers (D and E), collector and frother dosages (H, J, K, L and M), dosage of diesel (F) and flotation feed size (G). The levels of variables are given in Table 3. The main advantage of employing D-optimal design is reduction in the number of experimental runs, which are required to evaluate multiple variables. Moreover, it has the ability to identify interactions statistically. It is able to overcome the shortcomings of the traditional formulation method (Muteki et al., 2007).

Table 3. Experimental parameters and their relative levels

Collector			Frother		Diesel	d_{80}	Reagent Dosage				
					g/Mg	%	g/Mg				
A	B	C	D	E	F	G	H	J	K	L	M
Z_{11}	R407	0	A65	A70	0	80	10	15	0	5	5
Z_6	Nascol	C4132	DF 250	MIBC	10	100	15	20	7	10	10
	A7240	X231	Flomin 742	Pine Oil	20	120	20	25	15	15	15

Since the objective of this study was to select the type and dosage of collector and frother, the region of their dosages used in 150 operating days in the plant were considered in the experimental design in all tests. Table 4 shows dosages of collectors and frothers employed in all tests.

Table 4. Ranges of collector and frother dosages used in all tests

Collector (g/Mg)			Frother (g/Mg)	
Primary (A)	First promoter (B)	Second promoter (C)	D	E
10-20	15-25	0-15	5-15	5-15

Laboratory flotation tests were conducted in a Denver mechanical cell using 35% solids conditioned for 3 min. The pH value was then adjusted to 11.8 using lime before adding the reagent. The slurry was further conditioned after addition of each reagent, i.e. 2.5 min for the collector and 1 min for the frother. The agitation speed of 1300 rpm and flotation time of 16 min (which was scaled down from the Sungun plant rougher flotation time of 33 min) were used for all the experiments. The froth and tailing were collected, filtered, dried and analysed for copper grade and recovery calculations. Tap water was employed throughout the experiments.

The collector distribution patterns of 32, 32, 20, 16% as the current distribution in the plant, corresponding to the ball mill feed, third rougher flotation cell, fifth rougher flotation cell and ninth rougher flotation cell respectively were examined in the laboratory tests (Vazifeh et al., 2010). The froth collecting time of 16 min was divided into 160 s for simulating the first and second rougher flotation cells, 160 s for simulating the third and fourth rougher flotation cells, 320 s for simulating the fifth to eighth rougher flotation cells and 320 s for simulating the ninth to twelfth flotation cells.

Analysis of variance

An analysis of variance (ANOVA) is a standard statistical tool that can be used to interpret experimental data. The DX7 software is used to analyse the experimental data. The analysis of variance is performed to evaluate the significance of the main effects among the investigated factors. The effect is considered to be significant if its significance level is greater than 95%, what means that the model with a P-value lower than 0.05 could be considered. To evaluate the fitness of model, a regression-based determination coefficient R^2 should be determined (Haider and Pakshirajan, 2007; Liu and Wang, 2007). When the values of R^2 are close to 1, the model offers an appropriate explanation of the variability of experimental values to the predicted values (Sayyad et al., 2007). The residuals, as differences between observed and predicted responses, are examined using the normal probability plots of the residuals. If the model is adequate, the points on the normal probability plots of the residuals should form a straight line.

Results and discussions

D-optimal factorial design

The D-optimal factorial is designed for using categorical factors as an alternative to the general factorial design method. The general factorial design builder may produce designs with more runs than are willing to run. The D-optimal design will choose an ideal subset of all possible combinations based on the specified model. The statistical design of experiments is used when the effects of several factors are to be studied in order to determine the main effects. When the effect of a factor depends on the level of another factor, two factors are said to interact. In this study, to design the experiments, the D-optimal factorial design was employed. In this paper, the main effects were taken into consideration. As illustrated in Table 5, 29 tests using D-optimal method were designed. From Table 5, it can be seen that the highest recovery of Cu of 92.03% with grade of 3.25% in the concentrate occurred in the 11th experiment run (primary collector = Z6, first promoter collector = R407, frothers = A65 and A70, diesel dosage = 0 and d_{80} = 120 μm) and the lowest recovery of copper (80.22%) with grade of 3.84% was recorded in the 5th experiment run. For Mo the maximum recovery was 77.06% with grade of 0.057% achieved in the 22rd experimental run (primary collector = Z11, first promoter collector = Nascol, second promoter collector = C4132, frothers = Flomin 742 and pine oil, diesel dosage = 20 g/Mg and d_{80} = 80 μm).

Table 5. Factorial design with results of Cu and Mo recoveries and grades in flotation tests

Run	Collector			Frother		Diesel dosage	d_{80}	Reagent Dosage					Recovery		Grade	
	A	B	C	D	E	F	G	H	J	K	L	M	Cu	Mo	Cu	Mo
						g/Mg	µm	g/Mg					%	%	%	%
1	z11	A7240	X231	D250	Pine Oil	10	120	15	25	7	15	10	82.27	60.97	5.89	0.053
2	z11	R407	Without	A65	A70	0	100	15	15	0	5	5	86.15	53.7	3.98	0.044
3	z6	A7240	X231	A65	A70	0	80	15	15	7	10	10	85.69	58.9	3.86	0.050
4	z6	A7240	X231	D250	MIBC	10	80	10	25	15	15	15	85.07	68.78	4.11	0.048
5	z11	A7240	X231	Flomin 742	A70	10	120	10	25	7	5	15	80.22	60.42	3.84	0.048
6	z11	Nascol	Without	A65	A70	20	100	20	15	0	10	10	87.09	58.77	4.64	0.045
7	z11	R407	Without	Flomin 742	MIBC	10	80	20	15	0	10	5	86.09	67.73	4.65	0.048
8	z6	A7240	C4132	D250	Pine Oil	20	80	10	20	7	15	10	85.15	75.03	4.31	0.052
9	z6	R407	X231	Flomin 742	MIBC	0	80	20	15	15	5	5	89.93	61.63	2.79	0.045
10	z11	R407	Without	A65	Pine Oil	20	80	15	20	7	15	5	88.99	69.77	5.14	0.046
11	z6	R407	Without	A65	A70	0	120	20	20	0	10	15	92.03	47.1	3.25	0.040
12	z6	Nascol	X231	A65	MIBC	20	120	20	20	15	5	10	89.41	58.12	3.52	0.044
13	z6	R407	C4132	Flomin 742	A70	10	100	20	15	15	15	10	88.94	67.09	3.7	0.044
14	z6	R407	X231	Flomin 742	Pine Oil	20	100	15	15	15	10	5	88.63	70.52	3.56	0.047
15	z6	R407	C4132	A65	MIBC	10	120	20	20	7	10	5	90.94	69.09	3.39	0.043
16	z6	Nascol	C4132	Flomin 742	MIBC	10	100	10	20	7	10	15	85.09	70.62	3.26	0.046
17	z11	A7240	Without	D250	MIBC	10	100	15	20	0	10	10	83.81	60.31	5.12	0.043
18	z11	Nascol	C4132	A65	Pine Oil	10	80	15	20	15	10	15	87.98	69.19	4.74	0.058
19	z11	Nascol	X231	D250	MIBC	0	100	10	15	7	15	15	85.14	58.61	4.55	0.050
20	z6	Nascol	Without	A65	A70	10	80	10	25	0	5	5	87.27	60.91	2.69	0.041
21	z11	A7240	C4132	A65	MIBC	20	120	20	15	15	10	5	82.95	64.89	5.07	0.048
22	z11	Nascol	C4132	Flomin 742	Pine Oil	20	80	10	25	7	10	10	83.57	77.06	4.5	0.057
23	z6	Nascol	Without	Flomin 742	Pine Oil	20	120	15	15	0	15	15	84.03	61.8	4.24	0.042
24	z6	A7240	Without	A65	MIBC	0	120	10	20	0	15	5	86.32	44.85	4.75	0.040
25	z6	Nascol	X231	D250	Pine Oil	10	100	20	20	7	5	5	90.91	69.12	2.82	0.048
26	z11	R407	Without	D250	MIBC	0	80	10	25	0	5	10	85.09	56.73	3.29	0.048
27	z11	R407	X231	D250	A70	20	80	15	25	15	5	15	86.99	73.77	3.1	0.051
28	z6	R407	C4132	A65	MIBC	0	100	15	20	7	5	15	89.94	61.09	3.27	0.048
29	z11	Nascol	Without	D250	A70	0	120	15	25	0	15	5	84.27	50.98	4.77	0.042

Cu recovery and grade

According to the analysis of variance (Table 6), the Fisher *F*–test with a very low probability values $P_{Model}<0.05$ indicates that the models for Cu recovery and grade are highly significant. The recovery and grade models present high determination coefficients of $R^2 = 0.99$. The adjusted determination coefficients (Adj. $R^2 = 0.93$ and 0.96) are also satisfactory and confirm the significance of the models.

Table 6. Analysis of variance for Cu recovery and grade

	Source		*F* value	*P*-value Prob > F
Cu Recovery	Model		19.93	0.0018
	Variables	A	16.80	0.0094
		B	20.29	0.0040
		D	10.15	0.0174
		H	9.81	0.0186
		J	8.44	0.0249
	CV = 0.85%; R^2 = 0.99; Adj. R^2 = 0.93, C-E-F-G-K-L-M = not significant			
Cu Grade	Model		31.19	0.0006
	Variables	A	138.57	< 0.0001
		B	16.69	0.0061
		D	13.82	0.0092
		E	13.18	0.0102
		H	8.90	0.0225
		L	46.14	0.0006
	CV = 4.2%; R^2 = 0.99; Adj. R^2 = 0.96. C-F-G-J-K-L-M = not significant			

The normal probability plots of the residuals and the plots of the residuals versus the predicted response for Cu recovery and grade are shown in Figs. 2 and 3, respectively. Figure 2 shows that the residuals generally lie on a straight line referred to the normal distribution of errors. It implies that the proposed models were adequate.

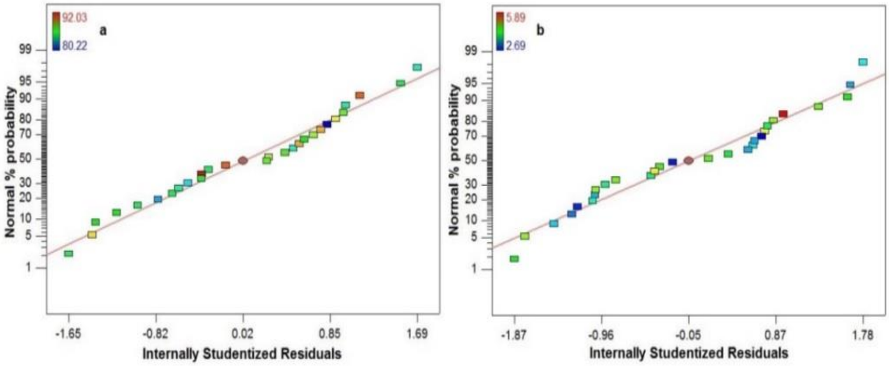

Fig. 2. Normal probability plot of residuals for Cu (left) recovery and (right) grade

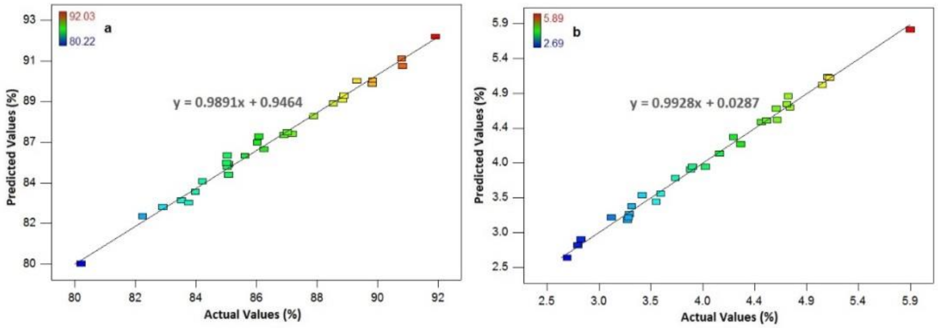

Fig. 3. Comparison of predicted and experimental results obtained for Cu (left) recovery and (right) grade

The A, B, D, H and J variables indicate a significance effect for Cu recovery. The order of influences is B > A > D > H > J. The A, B, D, E, H and L variables indicate a significant effect on the Cu grade. The order of influences is A > L > B > D > E > H. For both grade and recovery, the A, B, D and H are identified as the important factors. Figure 4 shows the effect of flotation process parameters on Cu recovery and grade. In general, lower recovery of Cu is obtained when Z_{11} rather than Z_6 is used as the collector. Also, R407 is a better choice than Nascol and A7240. According to Fig. 4, the primary promoter collector type has the maximum effect on the Cu recovery. Furthermore, the highest recovery could be achieved with the A65 as the frother. As shown in Fig. 4, the Cu recovery increased by increasing the primary collector (factor A) dosage and reached its maximum value at 20 g/Mg. Also the maximum value of Cu recovery is obtained when 20 g/Mg of the first promoter collector is employed. The first level of primary collector, third level of first promoter collector, A65 and pine oil as frothers represent the optimum levels of various turning process parameters to obtain the maximum Cu grade. The best reagent dosages are found to be 20 g/Mg of first promoter collector and 15 g/Mg of frother (factor D) to attain the maximum Cu grade.

Mo recovery and grade

In order to quantify the influence of process parameters on the Mo recovery and grade, the variance analysis is performed. The analysis of variance for Mo recovery and grade (ANOVA) is given in Table 7. Based on the results the models are significant. It is evident that the C, D, F, G, K and M variables are significant at 95% confidence level in ANOVA of Mo recovery. Also, the A, C, E and G variables are significant at 95% confidence level in ANOVA of Mo grade. The F and G variables significantly affect the Mo recovery. The order of factors from high to low contribution in Mo grade is A, G, E and C.

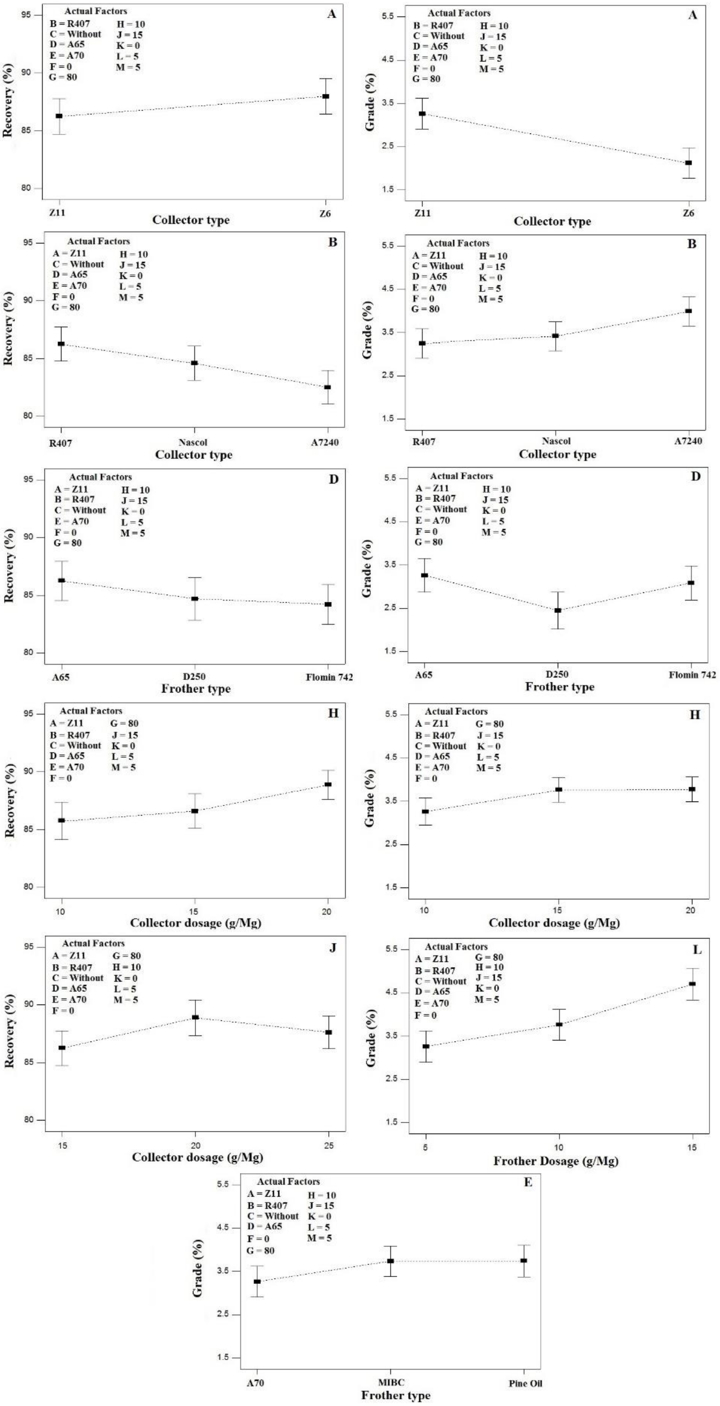

Fig. 4. Effect of process parameters on Cu recovery and grade

The design of experimental analysis assumes that the residuals are normally and independently distributed with the same variance in either each treatment or factor level. The deviation from this assumption means that the residuals contain a structure that is not accounted for the model. The residual plots given in Fig. 5 are used to check the assumption. Since the residuals lie approximately along a straight line, it is concluded that the residuals are normally and independently distributed. No particular trend in residual values against the test numbers indicates any systematic errors in the performed tests. Systematic errors cause the residual values either increase or decrease. As it is seen, the obtained model for Mo recovery and grade matches well with the performed experiments results. The observed Mo recovery and grade and their predicted values are shown in Fig. 6. The R^2 values for Mo recovery and grade are 0.99 and 0.98, respectively.

Table 7. Analysis of variance for Mo recovery and grade

	Source		F value	P-value Prob > F
Mo Recovery	Model		32.97	0.0005
	Variables	C	15.94	0.0068
		D	6.55	0.0401
		F	54.62	0.0004
		G	22.83	0.0031
		K	7.98	0.0278
		M	5.32	0.0478
CV = 1.92%; R2 = 0.99; Adj. R2 = 0.96, A-B-E-H-J-L = not significant				
Mo Grade	Model		15.07	0.0034
		A	46.60	0.0010
		C	5.48	0.0442
	Variables	E	12.85	0.0107
		G	16.35	0.0064
CV = 2.71%; R^2 = 0.98; Adj. R^2 = 0.92, B-D-F-H-J-K-L-M = not significant				

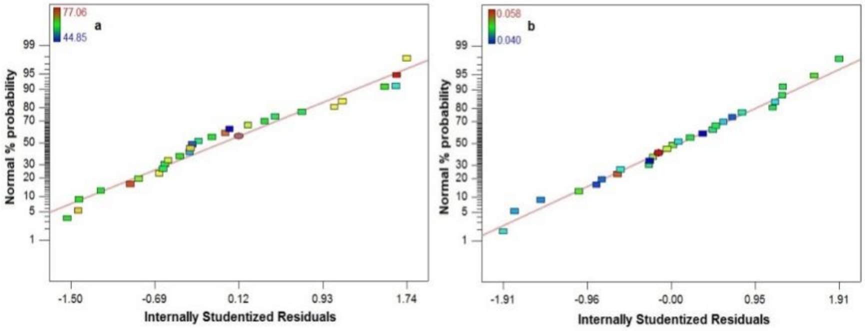

Fig. 5. Normal probability plot of residuals for Mo (left) recovery and (right) grade

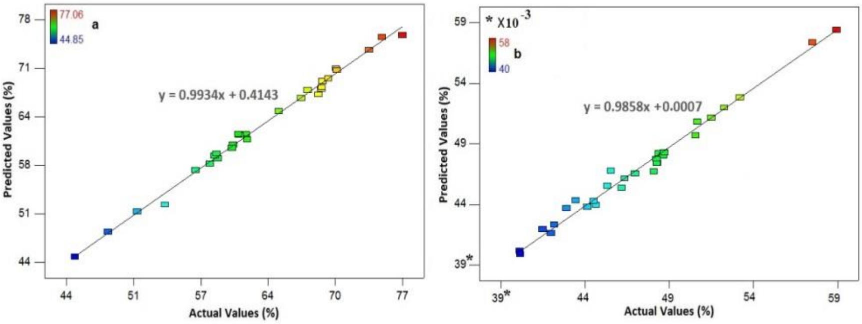

Fig. 6. Comparison of predicted and experimental results obtained for Mo (left) recovery and (right) grade

Figure 7 shows the role of effective parameters on Mo recovery and grade. The highest Mo recovery is obtained when C4132 (7 g/Mg) is used as a second promoter collector as well as the diesel dosage and d_{80} of feed are equal to 20 g/Mg and 80 μm, respectively. Also, using either Flomin 742 or DF250 with dosage of 15 g/Mg is better alternative than A65 in order to obtain high Mo recovery. In general, pine oil is a better choice than A70 and MIBC in order to make the concentrate with high Mo grade. The highest grade could be achieved with the d_{80} equal to 80 μm. As the effect of size (factor G) on recovery and grade is highly negative, the size is kept at the low level for process optimization.

Process optimization

The considered conditions for responses of optimal conditions and parameters are given in Table 8. The optimum levels of variables to maximize recovery within the studied range are obtained using the DX7 software. Table 9 shows the optimum level of each parameter to achieve the highest Cu and Mo grades and recoveries within the corresponding ranges. Based on software prediction, a product with Cu and Mo recoveries equal to 91.70 and 72.33%, respectively, will be obtained. Also, Cu and Mo grades equal to 5.67 and 0.055% respectively will be obtained. In order to verify the adequacy of the model prediction, two confirmation experiments were performed with optimal conditions. The tests results are given in Table 10. The validation tests proved the optimization results obtained from the D-optimal design experiment.

Table 8. Optimization criteria for different variables and responses

Variables	Goal
A-B-C-D-E-F-G-H-J-K-L-M	is in range
Cu recovery	maximum
Mo recovery	maximum
Cu grade	5.5-5.9
Mo grade	550-580

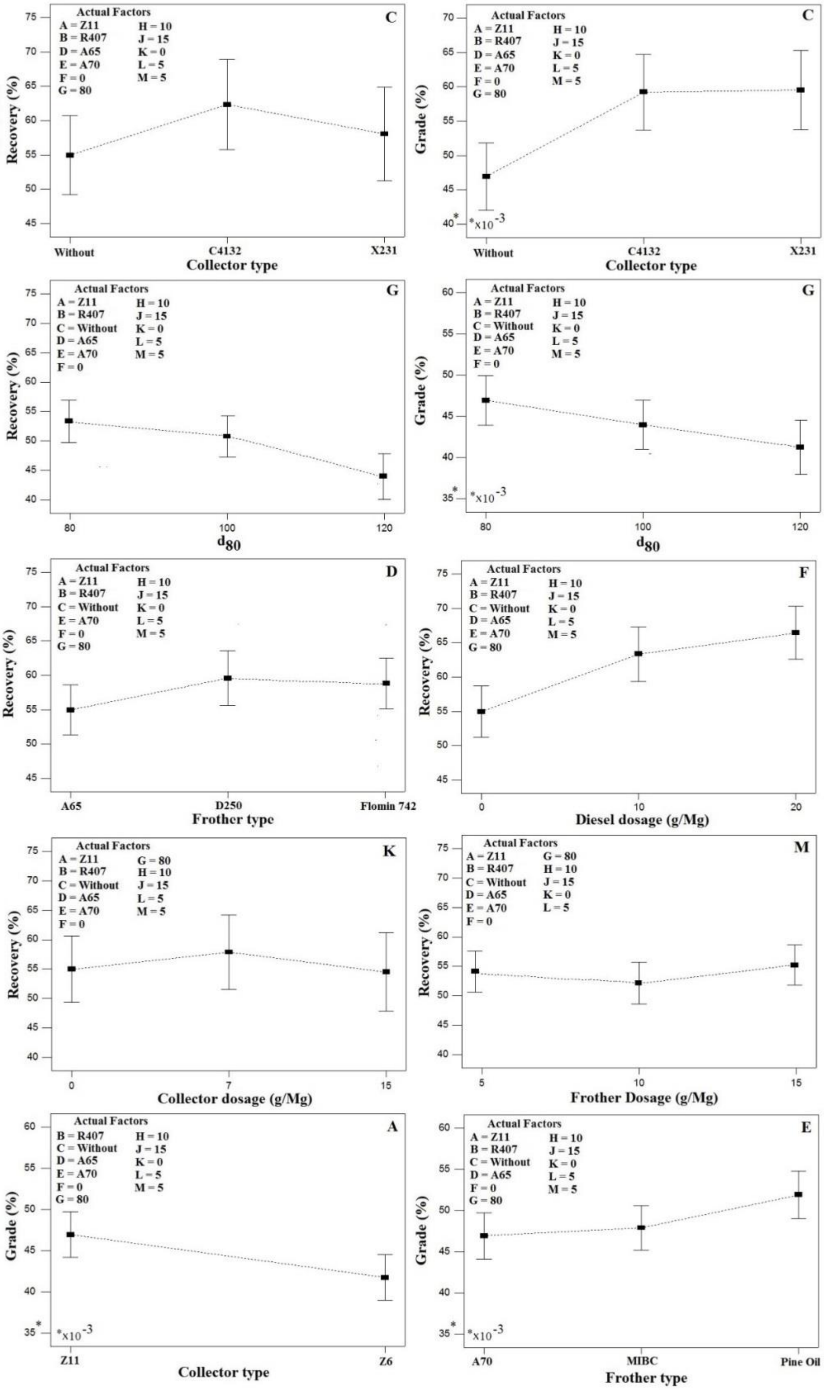

Fig. 7. Effect of process parameters on Mo recovery and grade

Table 9. Optimum level of each parameter

A	B	C	D	E	F	G	H	J	K	L	M	Recovery		Grade		Desirability
												Cu	Mo	Cu	Mo	
					g/Mg	µm	g/Mg					%				
Z_{11}	R407	X231	A65	Pine Oil	20	80	20	20	7	15	5	91.70	72.33	5.67	0.055	0.911

Table 10. Validation tests results with optimal condition

Test	Cu rec (%)	Mo rec (%)	Cu grade (%)	Mo grade (%)
1	90.65	70.39	5.83	0.053
2	90.42	71.18	5.54	0.054

Conclusions

In this paper, the D-optimal design method was used for modelling and optimizing grade and recovery of copper and molybdenum in the rougher flotation circuit of the Sungun copper concentrator plant. The investigated parameters included types and dosages of collectors and frothers, diesel dosage and feed size distribution. The following conclusions were drawn from the present study within the levels of process parameters selected.

1. Based on ANOVA and at 95% confidence level, the first promoter collector type had maximum effect on the Cu recovery. R407 (20 g/Mg) was a better choice than Nascol and A7240. Lower recovery of Cu was obtained when Z_{11} rather than Z_6 was used as the collector. Higher grade of Cu was obtained when Z_{11} rather than Z_6 was used as the collector. Also, Pine oil and A65 were better than other frothers to achieve the product with high copper grade. The best reagent dosages were found to be 20 g/Mg of the first promoter collector and 15 g/Mg of A65 to obtain the maximum Cu grade.

2. ANOVA of flotation parameters indicated that diesel dosage and d_{80} had the most significant effect on the recovery of Mo during flotation. The highest Mo recovery was obtained when C4132 (7 g/Mg) was used as the promoter collector and diesel dosage and d_{80} of feed were equal to 20 g/Mg and 80 µm, respectively. As the effect of size on recovery was highly negative, the size was kept at low level for optimizing the experiment. In general, pine oil was a better choice than A70 and MIBC in order to make the concentrate with high Mo grade. The highest Mo grade could be achieved with the feed size (d_{80}) equal to 80 µm.

3. Results of optimization showed that the highest possible Cu and Mo grades and recoveries were obtained when Z_{11} (20 g/Mg) as the primary collector, R407 (20 g/Mg) as a first promoter collector, X231 (7 g/Mg) as the second promoter collector, A65 (15 g/Mg) and Pine oil (5 g/Mg) as frothers, 20 g/Mg of diesel dosage and d_{80} of feed size equal to 80 µm were used.

Acknowledgments

The authors would like to acknowledge the support of the Department of Research and Development of the Sarcheshmeh and Sungun Copper Plants for this research.

References

ABALI, Y., COPUR, M., YAVUZ, M., 2006. *Determination of the optimum conditions for dissolution of magnesite with H2SO4 solutions*, Indian Journal of Chemical Technology, Vol.13, pp. 391-397.

BULATOVIC S.M., 2007. H*andbook of flotation reagents chemistry, theory and practice: flotation of sulfide ores*. Elsevier Science & Technology.

GOPALSAMY, B.A., MONDAL, B., GHOSH, S., 2009. *Taguchi method and ANOVA: An approach for process parameters optimization of hard machining while machining hardened steel*, Journal of scientific and Industrial Research, Vol. 68, pp. 686-695

GUY, H. H., JIA, R., 2000. *An improved class of flotation frothers*, Int. J. Miner. Process, vol. 58, pp. 35–43.

HAGHI, H., GHADYANI, A., BIRANVAND, B., SHAFEI, S.Z., 2009. *Optimization of Apatite flotation using Taguchi method*, 7th industrial Minerals Symposium and Exhibition, 25-27 February, Turkey.

HAIDER, M.A., PAKSHIRAJAN, K.K. 2007. *Screening and optimization of media constituents for enhancing lipolytic by a soil microoraganism using statically designed experiments*. Appl Biochem Biotech, 141: 377−390.

HARVEY, P.A., NGUYEN, A.V., JAMESON, G.J., EVANS, G.M., 2005. *Influence of sodium dodecyl sulphate and Dowfroth frothers on froth stability*, Minerals Engineering, vol. 18, pp. 311–315.

IIYAS, S., BHATTI, H.N., BHATTI, I.A., SHEIKH, M.A., and GHAURI, M.A., 2010. *Bioleaching of metal ions from low grade sulphide ore: Process optimization by using orthogonal experimental array design*, African Journal of Biotechnology, Vol. 9(19), pp. 2801-2810.

KAMARUDDIN, S., KHAN, Z.A., WAN, K.S., 2004. *The use of the Taguchi method in determining the optimum plastic injection moulding parameters for the production of a consumer product*, Jurnal Mekanikal, Bil.18, pp. 98-110.

Malysa, K., Barzyk, W., Pomianowski, A., 1981. *Influence of frothers on floatability. I. Flotation of single minerals (Quartz and synthetic chalcocite)*, International Journal of Mineral processing, vol. 8, pp. 329-343.

MUTEKI K., MACGREGOR J. F., and UEDA T., 2007. *Mixture designs and models for the simultaneous selection of ingredients and their ratios*, Chemometrics and Intelligent Laboratory Systems, vol. 86, 1, pp. 17–25.

LASKOWSKI, J. S., TLHONE, T., WILLIAMS, P., DING, K., 2003. *Fundamental properties of the polyoxypropylene alkyl ether flotation frothers*, Int. J. Miner. Process, vol. 72, pp. 289– 299.

LIU, G.C., WANG. X.L., 2007, *Optimization of critical medium components using response surface methodology for biomass and extra cellular polysaccharide production by Agaricus blazei*. Appl Microbiol Biotechnol, 74: 78−83.

MELO, F. and LASKOWSKI, J. S, 2006. *Fundamental properties of flotation frothers and their effect on flotation*, Minerals Engineering, vol. 19, pp. 766–773.

PRADYUMNA, K., NAIK, P, REDDY, S.R., VIBHUTI, N., 2005 *Interpretation of interaction effects and optimization of reagent dosages for fine coal flotation*, Int. J. Miner. Process. 75 83– 90.

RAMA, R.S. and PADMANABHAN, G., 2012. *Application of Taguchi methods and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5%SiC composites*, International Journal of engineering Research and Application (IJERA), Vol.2, Issue 3, pp. 192-197.

SAPAKAL, S.V., and TELSANG, M.T., 2012. *Parametric optimization of MIG welding using Taguchi Design Method*, International Journal of Advanced Engineering Research and Studies, Vol.1, Issue IV, pp. 28-30

SAYYAD, S.A., PANDA, B.P., JAVAD S, ALI M., 2007. *Optimization of nutrient parameters for lovastatin production by monascus purpureus MTCC 369 under submerged fermentation using response surface methodology*. Appl Microbiol Biotechnol, 73: 1054−1058.

TRUST T. M. Willie N., *2014. Flotation of nickel-copper sulphide ore: optimisation of process parameters using Taguchi method*, Proceedings of the International Conference on Mining, Material and Metallurgical Engineering Prague, Czech Republic, August 11-12, Paper No. 113.

VAZIFEH1, Y., JORJANI1, E., BAGHERIAN A., 2010. *Optimization of reagent dosages for copper flotation using statistical technique*, Trans. Nonferrous Met. Soc. China 20, 2371−2378

XIA Y. K. and PENG, F. F., 2007. *Selection of frothers from residual organic reagents for copper-molybdenite sulfide flotation*, Int. J. Miner. Process. vol. 83, pp. 68–75.

WILLS, B. A., and NAPIER-MUNN, T. J., 2006. *An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*, in *Wills' Mineral Processing Technology*, 7th ed., pp. 267 - 352.