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Application of gravity separators for enrichment of South Chah-Palang tungsten ore

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Abstract

In the present study, the possibility of concentrating tungsten-copper vein ore in South Chah-Palang was examined using gravity separators including Jig Machine (-2360+600 μm), shaking table (-600+120 μm), and multi-gravity separator (MGS)(-120 μm). The representative sample contains 1.5% WO_3 and 5.95% CuO. The main tungsten minerals were ferberite and wolframite and their appropriate liberation degree was approximately in the range of 250 μm. Box-Behenken and CCD response surface methods were applied to model and optimize jig machine and MGS results, respectively. Shaking table performance was modeled by full factorial design method. In Jig machine tests, the effects of water flow rate, frequency and feed particle size were investigated. Deck inclination, wash water, and feed water flow rate were operational parameters in shaking table. In the MGS testes, the effects of two parameters of tilt angle and wash water flow rate were inspected. In this set of experiments, WO_3 recovery and grade were considered as responses of each model. The maximum recovery of WO_3 in jig machine was obtained in water flow rate of 3.71 lit/min, frequency of 153rpm, and the particle size range of -2360+1700 μm. In this case, the grade and recovery of WO_3 were 2.85% and 94.33%, respectively. The maximum WO_3 recovery was 93.9% with grade of 8.20 % using shaking table in the deck inclination of 11 degree, feed water flow rate of 7 lit/min, and wash water flow rate of 8 lit/min. The maximum WO_3 recovery in MGS attained with 3.45 degrees tilt angle and wash water rate of 3.16 lit/min. The grade and recovery of WO_3 in the MGS method were 4.2% and 90.61%, respectively.

Keywords: *gravity separation, Jig Machine, MGS, shaking table, tungsten ore.*

1. Introduction

Most of the tungsten resources contain low contents of WO_3 [1], while appropriate concentrate should have 60-70 percent of WO_3 [2]. The valuable tungsten minerals are wolframite and scheelite [3]. According to tungsten properties such as high melting point and stiffness, tungsten has many applications in various industries, including steel manufacturing, electronics, cutting tools, excavating drills, aerospace, and dye manufacturing [1].

Regarding the common upgrading methods for tungsten ores, high density is their most important property. In addition, wolframite is a paramagnetic mineral [1]. Wolframite frigidity would cause it to be broken down in crushing stage, which produces thin flakes and ultrafine particles [4].

The main processes in tungsten concentrate production from its ores are gravity separation for gangue minerals removal with low density [5], magnetic separation to separate magnetic minerals (wolframite separation) [6, 7], flotation to remove sulfide minerals [7, 8], or scheelite separation [8, 9] and electrostatic separation to remove minerals with electrical property [6]. However, the various used machines for tungsten pre-concentration are jig machine, shaking table, heavy media, spiral, and sorting [2, 10].

Shaking table has been used in tungsten-tin ores upgrading and removing silicates and quartz [6]. In Degana ore in India, employing jig machine for coarse particle fraction (-2000 to +600 μm) and shaking table for fine particle fraction (-600 μm) led to better results compared to the case when only shaking table was used after de-sliming (-600 μm). Using one step jig machine for particles finer than 12 mm, a tungsten ore specimen WO_3 grade increased from 0.5% to 4.5% [11]. Gravity separation by shaking table on the jig crushed product, with size of -225 μm showed that about 62.7 percent of silica and 42 percent of sulphur were removed and the recovery was 70% WO_3 [11]. In gold-scheelite ore in Alaska, after performing one stage rougher and two stages cleaner by shaking table, the grade of WO_3 increased from 0.17% to 19.2% with 57% recovery [8].

For beneficiation of scheelite ore from Nezam Abad ore with total WO_3 grade of 0.11%, for feed size in the range of -600+125 μm, there are four stages of shaking table with total WO_3 recovery and grade of 50.86% and 27.5%, respectively [12]. Multi gravity separator (MGS) was used for upgrading celectite [13], chromite [14], and coal [14], in which for celectite, a concentrate with grade of 94% SrO_4 and 87% recovery was obtained [16]. By upgrading the fine particle fraction (-125+10 μm) in Panasqueira Mine by MGS, the grade increased from 0.41% to 7.67% WO_3. Also, performing one stage MGS after flotation of sulfides increased the grade from 15% to 47% WO_3 [7].

The two factorial and response surface methods have been used to investigate gravity separation methods. Two-level full factorial method has been used for concentration of celectite by shaking table [16], flotation of celectite, and calcite mixture [13]. Box-Behenken method has been used to model coal flotation process [13], optimization of celectite beneficiation by means of MGS [14], optimizing of scheelite enrichment by shaking table [12], and graphite concentrate production [17]. CCD method has been used for optimization of low grade Zn-Pb ore flotation [18], providing information for modeling of a three-product cyclone [18], gravity concentration of chromite [19], and coal concentration [15].

The Southern Chah Palang's copper-tungsten ore is located in southeast of Anarak, a city in Yazd province, Iran. The mineralization of this deposit is vein type. There is no document on upgrading of this deposit ore sample for concentration of copper-tungsten. Therefore, the main objective of the present study was to model and optimize of gravity separation methods such as jig machine, shaking table, and MGS for concentrating of wolframite. Besides, the effects of various operating parameters on tungsten recovery and grade were studied.

2. Materials and Method

2.1. Sample preparation

A 150 kg ore sample was prepared from southern Chah-Palang deposit was located in Yazd province of Iran. The XRD analysis showed that the ore includes ferberite, wolframite, scheelite, atacamite, malachite, azurite, quartz, goethite, hematite, pyrite, chalcopyrite, apatite, and calcite. Tungsten minerals were present as inclusion in quartz and also locked in iron oxide minerals and secondary copper minerals. The results of chemical analysis of XRF and ICP on prepared sample are given in Table 1.

According to mineralogical studies on polished and thin sections, appropriate liberation degree for the tungsten minerals was about 250 µm. The feed sample with a d_{80} of 10 mm was crushed to less than 2360 µm by a roll crusher. Then, the sample was sieved by 1700, 600, and 120 µm screens. The purpose of this classification was to prevent WO_3 disposal in produced slimes, and also the aim of limiting particle size range of feed was to increase the efficiency of gravity separation methods. The grade of WO_3 in different feed size fractions are given in Table 2.

Table 1. Chemical analysis of southern Chah-Palang tungsten- copper ore sample

component	SiO_2	Fe_2O_3	WO_3*	CuO	Al_2O_3	CaO	SO_3	MgO	P_2O_5	L.O.I
Sample 1 (%)	43.15	14.41	1.47	5.8	11.90	4.98	3.57	2.15	2.36	8.30
Sample 2 (%)	43.45	14.36	1.51	6.1	11.47	4.96	3.15	2.06	2.41	8.53
Average (%)	43.30	14.39	1.49	5.95	11.69	4.97	3.36	2.11	2.39	8.42

* WO_3 grade is measured by ICP and it was 1.5%

Table 2. Size and WO_3 distribution in different feed size fractions

Method	particle size range (µm)	Weight (%)	Grade (%WO_3)	Distribution of WO_3 (%)
Jig machine	-2360+1700	18	1.59	18.9
	-1700+1180	16	1.64	17.3
	-1180+600	21	1.22	16.9
Shaking table	-600+120	33	1.57	34.2
MGS	-120	12	1.61	12.7
Average grade of sample (%WO_3)		1.50		

2.2. Experimental methods

In this research, different gravity separation methods, including jig machine, shaking table, and MGS, were used for concentration of wolframite ore. Restriction in the feed particle size range could result in better performance in each gravity separator [20]. To do so, the feed size range of -2360 +600 µm was classified into three size fractions of -2360+1700 µm, -1700+1180 µm, and -1180 +600 µm in order to carry out jig experiments. This classification was performed to investigate the effect of particle size range on jig efficiency. Also, fraction of -600+120 µm was used as the shaking table test feed and the finer than 120 µm size was employed as the MGS feed (Table 2).

The approach of this study is that the experiments were designed based on response surface (Box-Behenken and CCD), and full factorial methods to develop an experimental model for predicting the recovery of tungsten. In jig gravity separation tests, the effects of water flow rate, frequency, and particle size range were investigated. Deck inclination, wash water, and feed water flow rate were considered as shaking table parameters. In the MGS testes, the effects of two parameters of tilt angle and wash water flow rate were investigated. The parameters and their levels for jig machine, shaking table, and MGS are shown in Tables 3, 4, and 5, respectively. All Jig experiments were performed by laboratory Denver H469A Jig machine of 5cm×3.5cm size with feeding rate of 150g/min. The shaking table experiments were carried out by Wilfley Table No. 13 with 105cm × 50cm size. Feed flow rate was fixed at 250g/min and amplitude range was 5mm. The MGS tests were done using a MGS model C900 produced by Mozley Corporation under constant conditions of feed flow rate (150g/min), amplitude range (15mm), and frequency (280rpm).

3. Results and Discussion

Initial concentration stages were carried out to produce a concentrate with high levels of valuable mineral recovery. In order to reach this goal, the recovery of WO_3 was studied as the response of experiments, in addition to the grade of WO_3. Tables 6, 7, and 8 show the conditions and results of jig machine, shaking table, and MGS experiments, respectively.

Among existing models, the quadratic and linear models were fitted on the recovery and grade of WO_3 by jig machine, shaking table, and MGS, respectively. The models were developed based on coded factors. On this basis, the coefficients of factors were comparable and indicated the impact factors in each model. In other words, a factor which has the greater coefficient (than the other factor) is more effective in relative process [21]. The final equation based on coded factors for recovery and grade of WO_3 have been presented in Equations (1) and (2) for jig machine, (3) and (4) for shaking table, and (5) and (6) for MGS, respectively.

Table 3. List of variables and their levels in the Jig experiments

No	Variables	symbol	Levels		
			Low (-1)	Center (0)	High (+1)
1	Water flow rate (lit/min)	A	2	3	4
2	Frequency (cycle/min)	B	150	200	250
3	Particle size range (μm)	C	+600-1180	+1180-1700	+1700-2360
		Average (μm)	841	1422	2003

Table 4. List of variables and their levels in shaking table experiments

No	Variables	symbol	Levels		
			Low (-1)	Center (0)	High (+1)
1	Wash water flow rate (lit/min)	D	8	9	10
2	Feed water flow rate (lit/min)	E	6	6.5	7
3	Deck inclination (degree)	F	9	10	11

Table 5. List of variables and their levels in MGS experiments

No	Variables	symbol	Levels				
			Lowest(-β)	Low (-1)	Center (0)	High (+1)	Highest (+β)
1	Wash water flow rate (lit/min)	G	1.59	2	3	4	4.41
2	Tilt angle (degree)	H	1.17	2	4	6	6.83

Table 6. Process factors, their levels and results of conducted Jig experiments

Test No.	Conditions			Observed results	
	A	B	C	Recovery (%)	Grade (% WO_3)
1	-1	-1	0	81.48	2.81
2	+1	-1	0	86.73	3.03
3	-1	+1	0	87.13	2.54
4	+1	+1	0	76.43	2.76
5	-1	0	-1	86.68	2.08
6	+1	0	-1	82.20	2.28
7	-1	0	+1	86.48	3.48
8	+1	0	+1	89.02	2.59
9	0	-1	-1	81.54	2.21
10	0	+1	-1	89.05	1.95
11	0	-1	+1	91.76	2.92
12	0	+1	+1	79.25	1.80
13	0	0	0	89.23	2.48
14	0	0	0	89.78	2.54
15	0	0	0	89.21	2.64

Table 7. Process factors, their levels and results of conducted shaking table experiments

Test No.	Conditions			Observed results	
	D	E	F	Recovery (%)	Grade (% WO_3)
1	+1	+1	+1	82.51	10.01
2	-1	+1	+1	94.53	8.88
3	-1	+1	-1	89.84	6.12
4	+1	-1	-1	89.13	5.53
5	+1	+1	-1	88.60	6.18
6	-1	-1	+1	90.10	7.53
7	-1	-1	-1	86.90	5.53
8	+1	-1	+1	86.00	12.98
9 (center test)	0	0	0	92.79	7.11

Table 8. Process factors, their levels and results of conducted MGS experiments

Test No.	Conditions		Observed results	
	G	H	Recovery (%)	Grade (% WO_3)
1	-1	-1	63.80	4.43
2	+1	-1	70.20	5.34
3	-1	+1	54.40	5.95
4	+1	+1	49.25	6.45
5	- β	0	54.30	4.12
6	+ β	0	74.30	5.23
7	0	- β	60.73	3.87
8	0	+ β	40.12	7.06
9	0	0	90.30	4.20
10	0	0	89.10	4.23

Jig Machine

$$WO_3 \text{ Recovery } (\%) = +89.14 - 0.93\,A - 1.2\,B + 0.88\,C - 3.99\,AB + 1.76\,AC - 5.01\,BC - 2.85\,A^2 - 3.54\,B^2 \quad (1)$$

$$WO_3 \text{ Grade } (\%) = +2.57 - 0.13\,B + 0.40\,C - 0.27\,AC + 0.19\,A^2 - 0.15\,C^2 \quad (2)$$

Shaking Table

$$WO_3 \text{ Recovery } (\%) = +88.45 - 1.89\,D - 1.42\,DE - 2.14\,DF \quad (3)$$

$$WO_3 \text{ Grade } (\%) = +7.85 + 0.83\,D + 2.01\,F + 0.82\,DF \quad (4)$$

MGS

$$WO_3 \text{ Recovery } (\%) = +89.69 + 3.96\,G - 7.21\,H - 12.73\,G^2 - 17.48\,H^2 \quad (5)$$

$$WO_3 \text{ Grade } (\%) = +4.23 + 0.37\,G + 0.59\,H + 0.27\,G^2 + 0.94\,H^2 \quad (6)$$

In the above mentioned models, all factors are coded, and A, B, C, D, E, F, G, and H are the main parameters and AB, AC, BC, DE, DF, and GH are interactions between main parameters. The level of confidence for analysis of experiments was 95% ($P<0.05$). The results of analysis of variance of fitted models for jig machine, shaking table and MGS are presented in Tables 9, 10, and 11, respectively. These results show that the models are significant at confidence level of 95%. In models, the lack of fit is not significant which indicates the suitability of fitted models.

A good indicator of fitted models evaluation is the diagram with model predicted values versus actual values. These diagrams are shown in Figures 1a, 1b, 1c, 1d, 1e, and 1f for recovery and grade of WO_3 in jig machine, recovery and grade of WO_3 in shaking table, and recovery and grade of WO_3 in MGS, respectively. These figures confirmed the goodness of fitness applying the predicted models. In these figures, the value of R^2 (data correlation coefficient) and adjusted R^2 (the R^2 of factors of model to actual values) proved the suitability of the models.

The results of Tables 9, 10, and 11 reveal that for models of WO_3 recovery and grade, the F-values for recovery and grade in jig machine are 28.16 and 15.77, in shaking table are 24.87 and 10.04, and in MGS are 22.92 and 59.72, respectively. The high F-value and also the low P-value indicate the validity of proposed models.

According to Table 9, the following parameters are effective in each set of experiments: water flow rate, frequency, and particle size range for WO_3 recovery. Frequency and particle size range for WO_3 grade are effective parameters for jig machine, respectively.

According to Table 10, the parameter of wash water flow rate for WO_3 recovery, wash and feed water flow rate for WO_3 grade are effective parameters for shaking table, respectively.

Finally, Table 11 shows that the two parameters of wash water flow rate and tilt angle for WO_3 recovery and grade are effective parameters for MGS, respectively.

Table 9. Results of ANOVA for fitted model on WO_3 enrichment using Jig machine

Objective	source	Sum of square	DOF	Mean square	F Value	p-value	
Recovery	Model	272.85	8	34.11	28.16	0.0003	Significant
	A	6.89	1	6.89	5.69	0.0544	
	B	11.59	1	11.59	9.57	0.0213	
	C	6.21	1	6.21	5.13	0.0641	
	AB	63.82	1	63.82	52.68	0.0003	
	AC	12.34	1	12.34	10.18	0.0188	
	BC	100.23	1	100.23	82.74	0.0001	
	A^2	30.11	1	30.11	24.86	0.0025	
	B^2	46.66	1	46.66	38.52	0.0008	
	Residual	7.27	6	1.12	-	-	
	Lack of fit	7.06	4	1.76	16.67	0.0574	not significant
Grade	Model	1.91	5	0.38	15.77	0.0006	significant
	B	0.11	1	0.11	4.43	0.0686	
	C	1.02	1	1.02	42.30	0.0002	
	AC	0.30	1	0.30	12.28	0.0080	
	A^2	0.13	1	0.13	5.21	0.0519	
	C^2	0.073	1	0.073	3.01	0.1211	
	Residual	0.19	8	0.024	-	-	
	Lack of Fit	0.18	6	0.030	4.60	0.1892	not significant

Table 10. Results of ANOVA for fitted model on WO_3 enrichment using shaking table

Objective	source	Sum of square	DOF	Mean square	F Value	p-value	
Recovery	Model	81.32	3	27.11	24.87	0.0048	Significant
	D	28.58	1	28.58	26.22	0.0069	
	DE	16.19	1	16.19	14.85	0.0182	
	DF	36.55	1	36.55	33.54	0.0044	
	Residual	4.36	4	1.09	-	-	
Grade	Model	42.99	3	14.33	10.04	0.0247	significant
	D	5.51	1	5.51	3.86	0.1208	
	E	32.16	1	32.16	22.54	0.0090	
	DF	5.31	1	5.31	3.72	0.1258	
	Residual	5.71	4	1.43	-	-	

Table 11. Results of ANOVA for fitted model on WO_3 enrichment using MGS

Objective	source	Sum of square	DOF	Mean square	F Value	p-value	
Recovery	Model	2320.25	4	580.06	22.92	0.0021	Significant
	G	106.03	1	106.03	4.31	0.0926	
	H	441.58	1	441.58	17.45	0.0087	
	G^2	723.46	1	723.46	28.58	0.0031	
	H^2	1680.44	1	1680.44	66.39	0.0005	
	Residual	126.55	5	25.31	-	-	
	Lack of fit	125.83	4	31.46	43.69	0.1129	not significant
Grade	Model	9.15	4	2.29	59.72	0.0008	significant
	G	1.11	1	1.11	28.99	0.0058	
	H	1.67	1	1.67	43.62	0.0027	
	G^2	0.32	1	0.32	8.45	0.0438	
	H^2	3.19	1	3.19	83.24	0.0008	
	Residual	0.15	4	0.038	-	-	
	Lack of Fit	0.15	3	0.051	113.12	0.0690	not significant

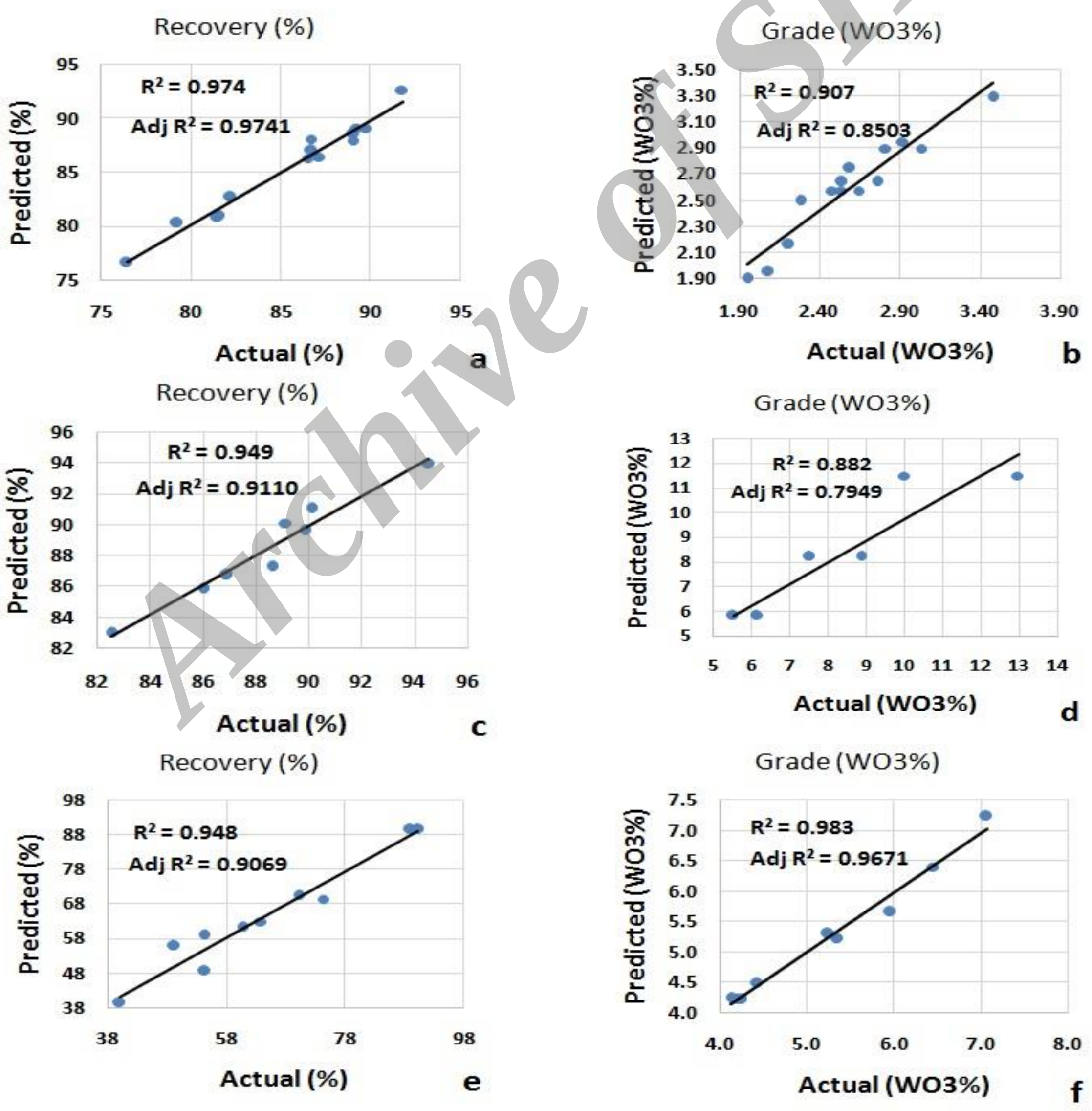

Fig. 1. Relation between experimental and predicted concentrate values for (a) recovery of WO_3, (b) grade of WO_3 in jig machine, (c) recovery of WO_3, (d) grade of WO_3 in shaking table, (e) recovery of WO_3 and (f) grade of WO_3 in MGS

3.1. The effect of different parameters on the responses in jig machine

3.1.1. WO_3 recovery

According to Equation (1), water flow rate (A), frequency (B), and particle size range (C) together with their interactions (AB, AC, BC), A^2, and B^2 have significant effects on the recovery of WO_3.

The effect of water flow rate and frequency in the middle size range (-1700+1180 µm) on WO_3 recovery is shown in Figure 2a. It was observed that maximum recovery of 87.58% was obtained at water flow rate of 3.5 lit/min and 150 rpm frequency. On the other hand, minimum recovery was 76.63% in water flow rate of 4lit/min and 250 rpm frequency.

The effect of water flow rate and particle size range on WO_3 recovery at 200rpm is shown in Figure 2b. It is observed that the maximum recovery of 90.08% is obtained at water flow rate of 3.25 lit/min and the coarse size fraction (-2360+1700µm), while the minimum recovery is 82.73% at water flow rate of 4 lit/min and the fine size fraction (-118-+600).

The effect of frequency and particle size range at water flow rate of 3 lit/min on WO_3 recovery is shown in Figure 2c. Maximum recovery is detected at 150 rpm frequency for the coarse size fraction (-2360+1700µm) which equals 92.69% and minimum recovery of 80.27% occurs in frequency of 250rpm for the coarse size fraction (-2360+1700µm).

3.1.2. WO_3 Grade

According to equation (2), it was observed that frequency (B) and particle size range (C) together with coupled effect of water flow rate and particle size range (AC), A^2, and C^2 have significant effects on WO_3 grade.

As it can be seen from Figure 2-d, maximum WO_3 grade was 3.29% for feed in size range of -2360+1700 µm with 2 lit/min water flow rate. In contrast, minimum WO_3 grade was 1.95% at the same water flow rate, but for feed in size range of -1180+600µm.

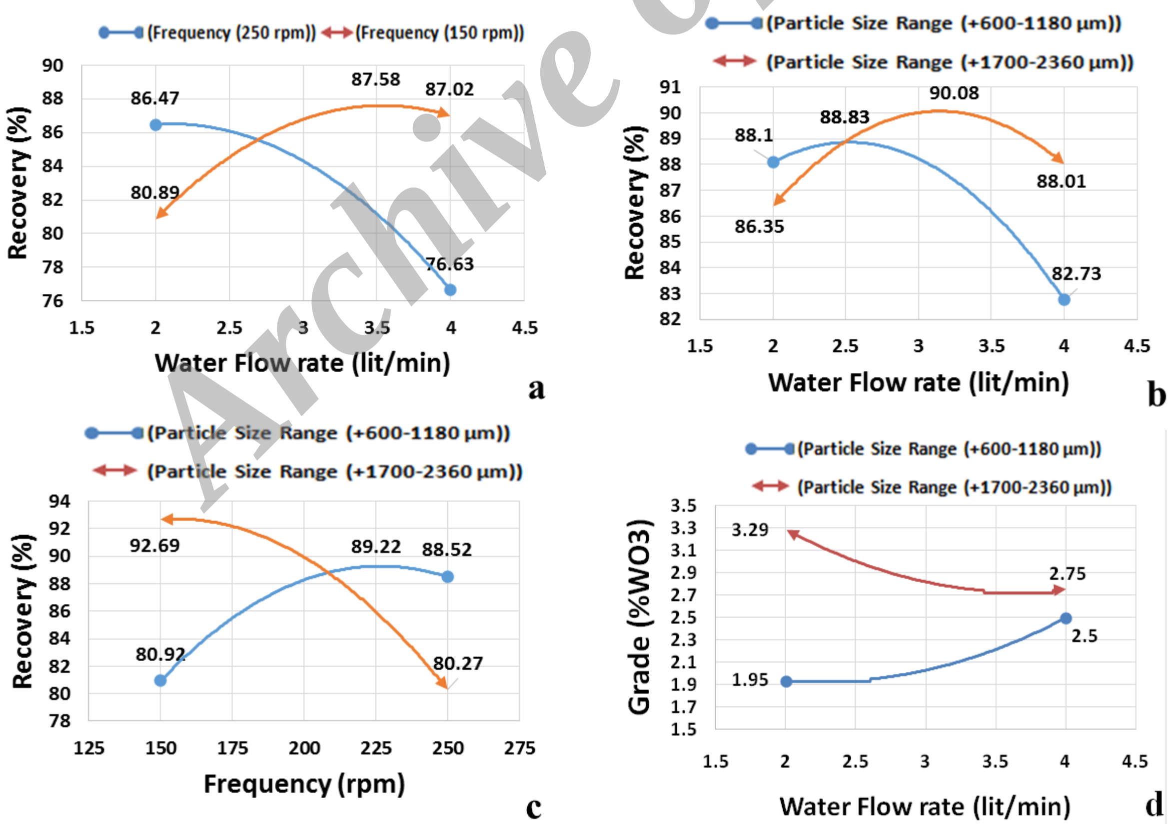

Fig. 2. The effect of different parameters on WO_3 responses by jig machine, (a) effect of water flow rate and the frequency on WO_3 recovery in particle size range (-1700+1180µm), (b) effect of water flow rate and particle size range on WO_3 recovery at the frequency of 200rpm, (c) effect of frequency and particle size range on WO_3 recovery at the water flow rate of 3 lit/min, (d) effect of water flow rate and particle size range on WO_3 grade at frequency of 200rpm

3.2. The effect of different parameters on the responses in shaking table

3.2.1. WO_3 recovery

Equation (3) shows that wash water flow rate (D) and its interactions with feed water flow rate (DE) and deck inclination (DF) have significant effect on WO_3 recovery. The effect of the wash and feed water flow rate at deck inclination of 10 degree on the WO_3 recovery is shown in Figure 3a. It was observed that maximum recovery of 97.77% was obtained at wash and feed water flow rate of 8 lit/min and 7lit/min, respectively, while the minimum recovery of 85.14% was obtained in the wash water flow rate of 10 lit/min for the same feed water flow rate.

The effect of the wash water flow rate and deck inclination on WO_3 recovery at the feed water flow rate of 6.5 lit/min is shown in Figure 3b. It was observed that the maximum recovery of 92.48% was obtained at wash water flow rate of 8 lit/min and deck inclination of 11 degree. On the other hand, minimum recovery of 84.43% achieved for the wash water flow rate of 10 lit/min and deck inclination of 11 degree.

3.2.2. WO_3 grade

According to Equation (4), it was observed that the wash water flow rate (D), deck inclination (F), and their interaction (DF) have significant effect on WO_3 grade. It should be noted that deck inclination (F) is the most important parameter to increase WO_3 grade in beneficiation with shaking table.

As it can be seen in Figure 3c, there is negligible increment on WO_3 grade of product when wash water flow rate increased from 8 lit/min to 10 lit/min at the same deck inclination (9 degree), while there is about 40% relative improvement on WO_3 grade from 8.21% to 11.5% when deck inclination was fixed at 11 degree and wash water flow rate increased from 8 lit/min to 10 lit/min.

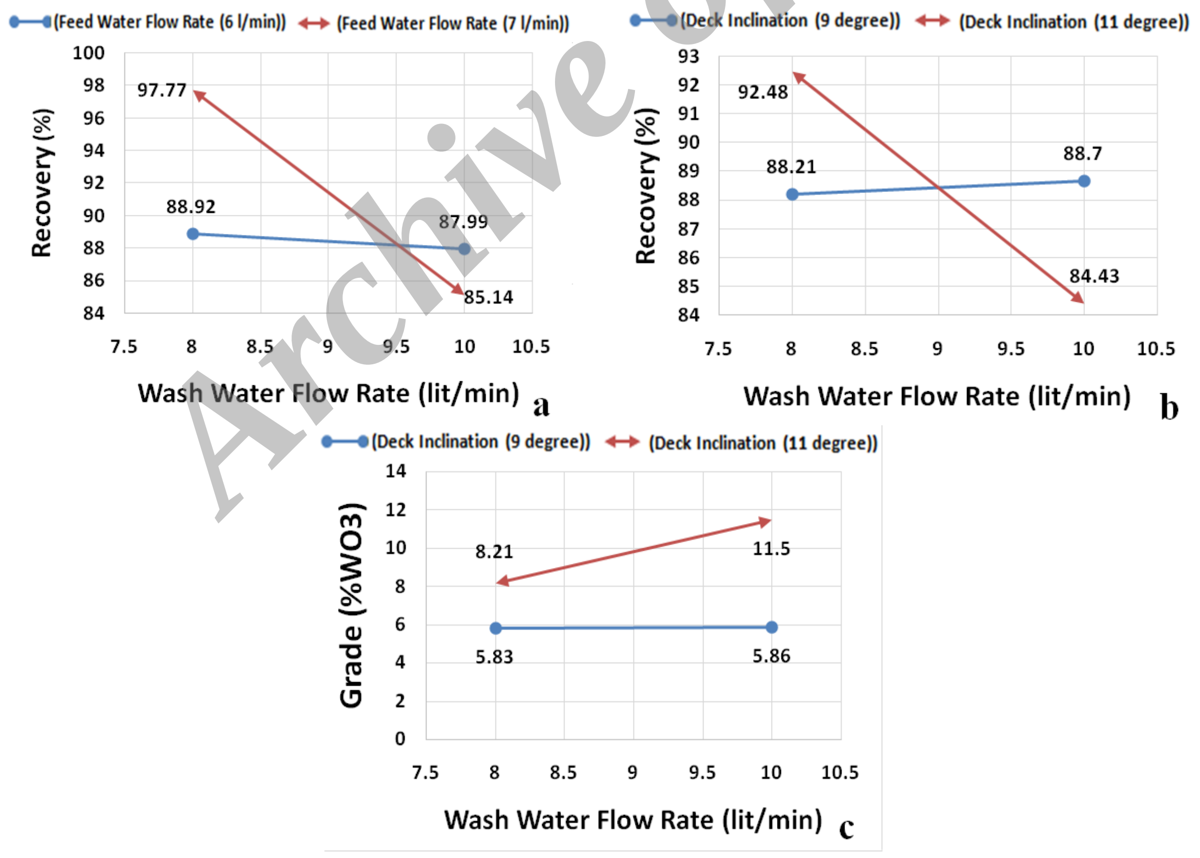

Fig. 3. The effect of different parameters on WO_3 responses by shaking table, (a) effect of the wash water and feed water flow rate on WO_3 recovery at deck inclination of 10 degree, (b) effect of the wash water flow rate and deck inclination on WO_3 recovery at feed water flow rate 6.5 lit/min, (c) effect of wash water flow rate and deck inclination on WO_3 grade at feed water flow rate of 6.5 lit/min

3.3. The effect of different parameters on the responses in MGS

According to Equations (5) and (6), wash water flow rate (G), tilt angle (H), G^2, and H^2 have significant effects on WO_3 recovery and WO_3 grade. The effect of different parameters on WO_3 recovery and WO_3 grade in enrichment using MGS are shown in Figures 4a and 4b, respectively. According to Figure 4a, maximum recovery (90.45%) is achieved at wash water flow rate of 3 lit/min and tilt angle of 3.6 degree. The minimum recovery (48.58%) is attained at wash water flow rate of 2lit/min and angle of 6 degree. In Figure 4b, it is also postulated that the best wash water flow rate for different tilt angle is 4 lit/min. Maximum WO_3 grade (6.41%) came off on tilt angle of 6 degree.

3.4. Optimization

Determination of suitable conditions to obtain the optimum response is important. Optimum response should be resolved to clearly clarify the amount of the minimum or maximum response as a function of design parameters. One of the methods of optimization is RSM [19]. The purpose of optimization in DX7 software is to find an optimum space in the overall spaces of experiments. The purpose of optimization of responses was to find the maximum recovery or grade of WO_3 in concentrate (target 1 and 2 respectively) or maximizing both recovery and grade of WO_3 (target 3). The results of optimization for jig machine, shaking table and MGS are shown in Tables 12, 13, and 14.

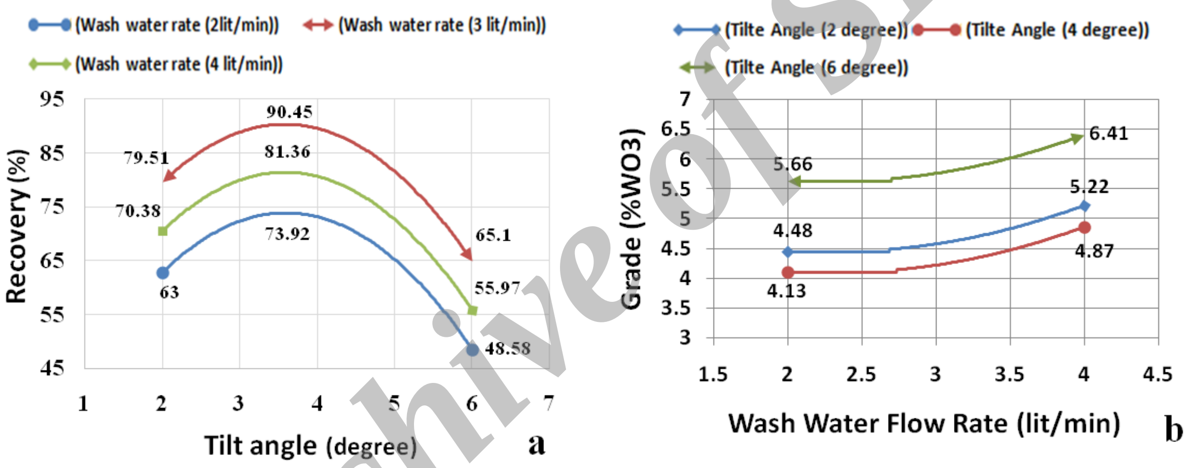

Fig. 4. The effect of different parameters on WO_3 responses by MGS, (a) effect of wash water flow rate and tilt angle on WO_3 recovery, (b) effect of wash water flow rate and tilt angle on WO_3 grade

Table 12. Results of the optimization for WO_3 enrichment in Jig machine

Target	A	B	C	Predicted value		Desirability
				Recovery (%)	Grade (%WO_3)	
1	3.71	153	-2360+1700	94.33	2.85	1.000
	2.93	194	-1700+1180	89.25	2.59	0.915
	2.10	238	-1180+600	91.44	1.95	0.979
2	2.00	150	-2360+1700	85.02	3.42	0.960
	4.00	150	-1700+1180	90.25	2.92	0.636
3	2.83	150	-2360+1700	91.76	3.01	0.831
	2.00	183	-2360+1700	86.70	3.34	0.809
	2.15	169	-2360+1700	87.61	3.28	0.796

Target 1: Maximizing of Recovery
Target 2: Maximizing of Grade
Target 3: Maximizing of Grade and Recovery

Table 13. Optimum conditions for WO_3 enrichment in shaking table

Target	D	E	F	Predicted value		Desirability
				Recovery (%)	Grade (%WO_3)	
1	8.00	7.00	11	93.90	8.20	0.948
2	10.0	6.09	11	85.60	11.50	0.801
	9.74	7.00	11	84.44	11.06	0.742
3	9.28	6.00	11	87.73	10.30	0.596
	8.20	7.00	11	92.80	8.54	0.588
	10.00	6.00	11	85.86	11.49	0.573
	8.94	6.02	11	88.60	9.76	0.536

Target 1: Maximizing of Recovery
Target 2: Maximizing of Grade
Target 3: Maximizing of Grade and Recovery

Table 14. Optimum conditions for WO_3 enrichment in MGS

Target	G	H	Predicted value		Desirability
			Recovery (%)	Grade (%WO_3)	
1	3.16	3.45	90.61	4.20	1.000
2	4.00	6.00	55.97	6.41	0.778
3	3.85	4.90	76.86	5.20	0.593
	3.61	5.73	67.93	5.77	0.558

Target 1: Maximizing of Recovery
Target 2: Maximizing of Grade
Target 3: Maximizing of Grade and Recovery

4. Conclusion

In this research, various gravity separation experiments were performed on representative tungsten ore provided from south Chah-Palang deposit located in Yazd province in Iran. Outstanding results of the study may be summarized as follows:

1. The head sample contained 1.5% WO_3 and 5.95% CuO. The main tungsten minerals were ferberite and wolframite. Major copper minerals were atacamite, malachite, and azurite. The appropriate liberation degree of tungsten minerals was in the approximate range of 250 µm.
2. For enrichment tests, Jig Machine (-2360+600 µm), shaking table (-600+120 µm), and multi-gravity separator (-120 µm) were applied.
3. The most effective parameters on WO_3 recovery and grade in Jig Machine were interaction of water flow rate and frequency (AB), particle size range (C), and C^2, respectively. The maximum recovery of WO_3 in jig machine was achieved in water flow rate of 3.71 lit/min, frequency of 153rpm, and the particle size range of -2360+1700 µm. In this case, the grade and recovery of WO_3 were 2.85% and 94.33%, respectively.
4. The most effective parameters on WO_3 recovery and grade in shaking table were interaction of water flow rate and deck inclination (DF) and deck inclination (F), respectively. The maximum WO_3 recovery was 93.9% with grade of 8.20%, using shaking table in the deck inclination of 11 degree, feed water flow rate of 7 lit/min, and wash water flow rate of 8 lit/min.
5. The most effective parameter on WO_3 recovery and grade in MGS was the second power of tilt angle (H^2). The maximum WO_3 recovery in MGS was acquired with tilt angle of 3.45 degrees and wash water rate of 3.16 lit/min. The grade and recovery of WO_3 in mentioned conditions were 4.2% and 90.61%, respectively.

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