

OPTIMIZATION OF OIL AGGLOMERATION BEHAVIOUR OF COAL BY TAGUCHI DESIGN

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Abstract

It is possible to evaluate the excessive amount of fine-size coal, which is produced by increasing of mechanised excavation in the coal mining, by oil agglomeration method. In this study, the possible beneficiation of Alpagut-Dodurga (Corum) coal with oil agglomeration under different conditions was investigated. Oil type and amount, pH, agglomeration time and stirring speed were selected as operating parameters of oil agglomeration method. Sixteen agglomeration tests were carried out under different conditions with the Taguchi (L_{16}) experimental design and the test results were evaluated by the combustible recovery (CR) depending on their ash contents.

The signal/noise (S/N) ratios of each test were calculated and optimization test was performed under the conditions recommended by the Minitab 16.0. From the test results, the highest CR and S/N ratio were obtained from Test 8 and compared to the verification test. The S/N ratio and average CR were obtained as to be 28.98 and 59.24%, respectively. In addition, the contributions of each factor to oil agglomeration of coal were determined with variance analysis (ANOVA).

Keywords: Taguchi method, oil agglomeration, coal, Minitab 16.0

1. INTRODUCTION

Energy plays a major role in the economic and social development of countries. Therefore, it is necessary to reduce the external dependency on energy and to evaluate the natural resources more efficiently. Fossil fuels are widely used as energy resources. Coal is one of these fossil sources and it is produced widely as fine sized unintentionally in production, preparation and enrichment processes. The fine sized coal produced in coal preparation plant is either wasted or used in thermal power plants. The thermal value of some of these coals is high.

The gravity methods such as jigging, dense medium separation, shaking table, cyclone, etc. are widely used in the industrial enrichment of coarse coal. However, as grain size decreases below -0.5 mm, the efficiency of these methods decreases (Kemal and Aslan, 2000). Specific gravimetric enrichment methods have been developed under the influence of centrifugal force which is more effective for this size of coal (Ozbayoglu and Mamurekli, 1994; Aktas, 2002).

Flotation is one of the enrichment methods that can be applied to fine size coals. In this method, the differences in the surface properties of the coal and inorganic components are utilized to separation (Aktas, 2002). The oil agglomeration method is also developed as an alternative to flotation. It can be applied to very fine coal such as 5 μm (Labuschagne, 1986) and provides high efficiency and selectivity when compared to flotation method. (Yoon, 1991; Yamik et al., 1994; Hacifazlıoğlu, 2008).

The oil agglomeration method is based on the difference in surface properties of hydrophobic coal and hydrophilic inorganic materials (Laskowski and Yu, 2000). In this method, the coal must have high hydrophobicity. By adding a small amount of oil in the suspension, hydrophobic coal particles are coated with oil selectively and come together to form the agglomerate structure (Capes and Darcovich, 1984). These agglomerates can be separated from other minerals by screening (Gurses, et al., 1996; Sahinoglu and Uslu, 2008). Many parameters such as hydrophobicity of coal surfaces, oil type, amount of oil, particle size, solid concentration, pH, stirring speed, agglomeration time are effective in the oil agglomeration method (Laskowski and Yu, 2000; Kilinc-Aksay, et al., 2010; Gryglewicz et al., 2002; Alonso et al., 1999; Bensley et al., 1977; Labuschagne, 1986).

Experimental studies where many parameters are used require a large number of experiments to be able to identify the effect of each factor. Different results can be achieved with fewer experiments by using experimental design methods (Taguchi, 1987; Roy, 1995; Donmez et al., 1998; Ata et al., 2001; Demir and Donmez, 2008; Safarzadeh et al., 2008). Taguchi experimental design and response surface methodology (RSM) are frequently used in the determination of the oil agglomeration behaviour of coal (Chary and Dastidar, 2010; 2012; Aslan and Unal, 2009; Cebeci and Sonmez, 2006; Duzyol, 2018).

In this study, the possible of enrichment of the Alpagut-Dodurga (Corum) coal with oil agglomeration method was investigated by Taguchi (L_{16}) experimental design. Experimental parameters were selected as oil type, amount of oil, pH, agglomeration time and stirring speed. The test results were evaluated using the Minitab 16.0 program with ash contents of agglomerate and combustible recovery (CR). In addition, analysis of variance (ANOVA) was applied to determine the contribution of each factor to agglomeration of coal.

2. MATERIALS AND METHODS

2.1. Materials

The coal sample used in the oil agglomeration experiments was obtained from the Alpagut-Dodurga (Corum) region. The sample was ground to under the particle size of 212 μm . The proximate analysis of the coal sample was given in Table 1. In Table 1; VM is volatile matter; FC is fixed carbon; LHV is lower heating value. As seen from Table 1, the coal sample had a low ash content and high LHV.

Table 1. Proximate Analysis of Coal

Sample	Ash, (%)	VM, (%)	FC, (%)	LHV, (kcal/kg)
Coal	12.65	36.31	51.04	5782

2.2. Methods

2.2.1. Agglomeration test

Oil agglomeration experiments were carried out in a glass vessel. Approximately 5 g of coal sample and 300 cm^3 volume of distilled water were mixed for 2 minutes in order to reach well dispersion. Hydrochloric acid (HCl) and sodium hydroxide (NaOH) was used for the adjusting of pH. After pH adjustment, an oil was added into the suspension and the slurry was stirred at desired agglomeration time. After the system was stopped, the obtained agglomerates were recovered with a test sieve (-212 μm) and washed with tap water to allow separation of non-agglomerated particles. The filtered agglomerates were dried in an oven at 105 $^{\circ}\text{C}$. After the weighing of agglomerates, ash analyzes were performed. The CR values of agglomerates were calculated by using Equation 1.

$$\text{Combustible Recovery (CR, \%)} = \frac{M_c(1 - A_c)}{M_f(1 - A_f)} \times 100 \quad (1)$$

Where; A_c : Ash content of clean coal, A_f : Ash content of feed, M_c : Mass of clean coal, M_f : Mass of feed.

2.2.2. Experimental design

Taguchi design method, which introduced in 1950, is known as the identification technique to the best (Taguchi, 1987). It is possible to find out factor levels that give the best performance characteristics with fewer experiments by using the orthogonal array series. In this study, the L_{16} (45) orthogonal plan chart (Table 2) was used. In this plan, the factor levels were 5 and the levels were 4 for each factor.

For multi-parametric studies it is necessary to determine the S/N (signal/noise) ratios. The signal-to-noise ratio (S/N) indicates the sensitivity of the quality characteristic to noise factors (Roy, 1995). Generally, three different S/N equations are used depending on performance characteristics. These are defined as "the smallest - the best", "the highest - the best" and "the target - the best" (Roy, 1995, Atil and Unver, 2000, Zolfaghari et al., 2011). In this study, the S/N ratio giving the "highest - the best" condition for the highest combustible recovery (CR, %) desired was given in Equation 2.

$$\frac{S}{N} = -\log_{10} \left[\frac{1}{n} \sum \left(\frac{1}{CR_i} \right)^2 \right] \quad (2)$$

where, n is the number of iterations of each experiment and CR_i is the percentage combustible recovery observed in the i^{th} repetition of the experiment. The larger S/N ratio implies the better achievement of treatment goal. All experiments performed were repeated twice at least, and the factors and levels selected for the experiments were given in Table 3.

Table 2. $L_{16}(4^5)$ orthogonal design

Factors and Levels					
Test	F₁	F₂	F₃	F₄	F₅
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

Table 3. Experimental factors and their levels

Factor	Description	Level 1	Level 2	Level 3	Level 4
F ₁	Oil type	Kerosene	Mineral oil	Sunflower oil	Diesel
F ₂	Concentration, mL	0.5	1.0	2.0	3.0
F ₃	pH	3	5	7	10
F ₄	Agglomeration time, min	3	5	7	10
F ₅	Stirring speed, rpm	500	750	1000	1250

3. RESULTS AND DISCUSSION

This experimental research was based on the methodology of Taguchi (L₁₆ orthogonal array) experimental design (DoE). Five controllable process variables were examined for each variable at four different levels (as shown in Table 3). The Taguchi experimental design plan included the parameters of each test, which were generated using the Minitab 16.0 and determined by the Taguchi L₁₆ test design plan. The CR values obtained from these experiments and the S/N ratios were given in Table 4.

Table 4. Taguchi L₁₆ orthogonal experimental design and S/N ratios

Test	F ₁	F ₂	F ₃	F ₄	F ₅	CR ₁ , %	CR ₂ , %	S/N
1	Kerosene	0.5	3	3	500	8.6645	8.0990	18.4519
2	Kerosene	1.0	5	5	750	10.3148	11.6138	20.7539
3	Kerosene	2.0	7	7	1000	9.3063	9.8652	19.6215
4	Kerosene	3.0	10	10	1250	12.2088	9.5843	20.5563
5	Mineral oil	0.5	7	5	1250	9.9011	9.6169	19.7853
6	Mineral oil	1.0	10	3	1000	12.5654	10.1324	20.9491
7	Mineral oil	2.0	3	10	750	15.0286	11.1887	22.0706
8	Mineral oil	3.0	5	7	500	33.6223	24.6484	28.9781
9	Sunflower oil	0.5	10	10	750	13.0121	15.0932	22.8837
10	Sunflower oil	1.0	7	7	500	15.8668	8.9882	20.8751
11	Sunflower oil	2.0	5	3	1250	13.4687	11.2204	21.7213
12	Sunflower oil	3.0	3	5	1000	12.9376	17.6985	23.3881
13	Diesel	0.5	5	10	1000	11.1778	10.7685	20.8021
14	Diesel	1.0	3	7	1250	11.5904	12.9071	21.7242
15	Diesel	2.0	10	5	500	11.5934	13.2418	21.8233
16	Diesel	3.0	7	3	750	12.1596	9.7477	20.6329

As shown from Table 4, the highest CR and S/N ratios were obtained from Test 8. When comparing the best (Test 8) and the worst (Test 1) experiment results, there was a difference between CR and S/N ratios. In Test 8, it could be said that the difference in type and amount of oil, the agitation time and the increase of pH affected the agglomeration behaviors of the coal positively. As the amount of oil and the

agglomeration times increased, the contact times also increased. Therefore, the coal surfaces with the oil-coated coal particles were increased and the size of the agglomerates become larger.

It can be also said that the long-term mixing at low speed caused the growth of the size of the agglomerates (Duzyol, 2016). Kumar et al., (2015) observed an increase in organic matter recovery with rising the pH of solution, 3 to 6. By the long-term mixing not only cause the increasing in the agglomerate size but also the increasing the ash content due to the sticking of the inorganic materials in the agglomerates form. (Chary and Dastidar, 2010; Sahinoglu and Uslu, 2008; Duzyol, 2015).

Using the Minitab 16.0 program, the meaningful response of the S/N ratios at certain levels of all the parameters determined by the Taguchi design was given in Table 5 and the effect of the factors that could be controlled according to these reactions was determined (Fig. 1).

Table 5. Response Table for S/N Ratios (the higher is better)

Level	F ₁	F ₂	F ₃	F ₄	F ₅
1	19.85	20.48	21.44	21.41	22.53
2	22.95	21.08	21.44	23.06	21.59
3	22.22	221.31	23.30	20.23	21.19
4	21.25	23.39	21.08	21.55	20.95
Delta	3.10	2.91	2.86	2.84	1.59
Rank	1	2	3	4	5

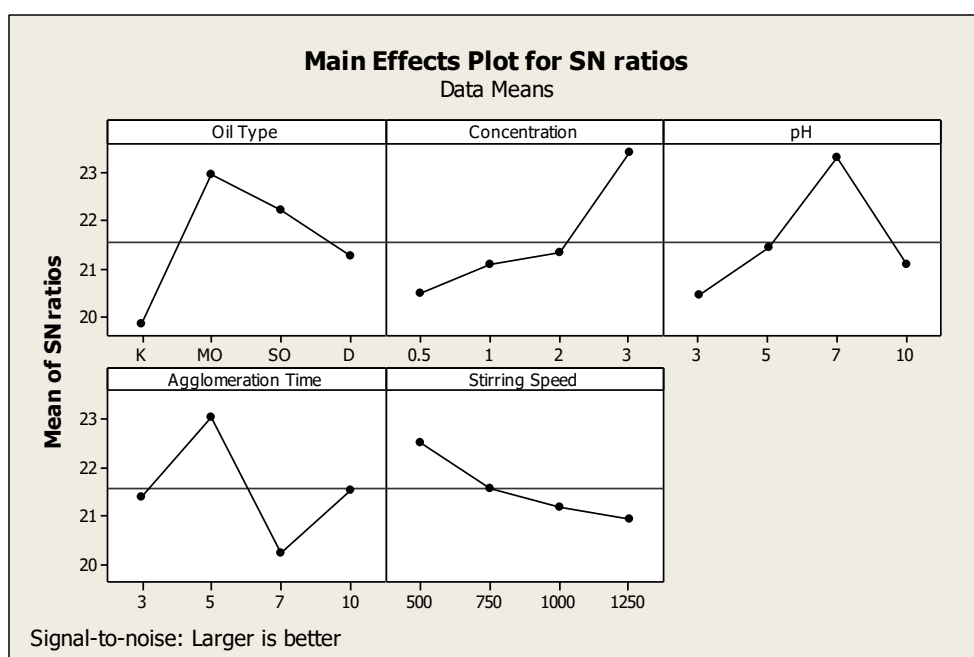


Figure 1. The effect of controllable factors on the S/N ratio.

The aim of to use any design of experiment is to achieve optimal results. While, optimal results may sometimes be within existing experiments given in the design, sometimes the experiment suggested by the design can be the best. Therefore, the verification test must be done and the conclusions are compared. Based on the results obtained from the Taguchi design and Minitab 16.0 program, the verification experiment was performed by considering the highest S/N values of the controlled

parameters. The CR value and S/N ratio obtained from verification experiment were recalculated and compared with Test 8 and given in Table 6.

Table 6. Optimum experimental conditions of CR, %.

	F ₁	F ₂	F ₃	F ₄	F ₅	CR ₁ , %	CR ₂ , %	S/N
Test 8	Mineral oil	3.0	5	7	500	24.6484	33.6223	28.9781
Optimization	Mineral oil	3.0	7	5	500	58.4870	60.0001	28.9810

When the optimization and Test 8 results were compared, it was seen that the mixing speed, the oil type and oil amount not changed. On the contrary, the decrease was seen in the agglomeration time. It was clearly seen that the verification test result was better. The CR values were increased approximately 2.5 fold under optimum conditions.

Variance analysis (ANOVA) method was applied to the results and the contribution percentage of each factor was determined (Table 7). Where; DoF_F : is the number of freedom level for each factor; SS_F : the factorial sum of squares of the factors; ρ_F : percentage of each factor; SS_T , total sum of squares and V_{Er} is the variance of error. Under the investigated conditions, while the most effective factor was oil concentration, the less effective factor was oil stirring speed.

Table 7. Percentage contribution of each factor (for CR%)

Factor	DoF_F	SS_F	ρ_F (%)	SS_T	V_{Er}
Oil type	3	153.332	22.74033	662.02	0.939
Concentration, mL	3	162.098	24.06634		
pH	3	139.771	20.68899		
Agglomeration time, min	3	115.820	17.06599		
Stirring speed, rpm	3	90.060	13.16934		

4. CONCLUSIONS

In this experimental study, the oil agglomeration behavior of the Alpagut-Doduga (Corum) coal was investigated using the Minitab 16.0 program and the Taguchi experimental design and the following results were obtained.

The best result was achieved with the optimization experiment suggested by Taguchi experimental design.

Optimum conditions; oil type, oil concentration, pH, aging time and stirring speed were determined as to be mineral oil, 3.0 mL, 7, 5 min. and 500 rpm, respectively.

It was also concluded that the CR of the obtained agglomerates was about 60%.

It was determined that the most effective parameter was oil concentration.

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