Fuel 109 (2013) 373–378

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Use of the grey analysis to determine optimal oil agglomeration with multiple performance characteristics

Nevzat Aslan *

Mining Engineering Department, Cumhuriyet University, 58140 Sivas, Turkey

HIGHLIGHTS

- The multi-objective optimization of oil agglomeration process was accomplished.
- The analytical data was generated by using Taguchi array design with four parameters.
- Optimal levels of process parameters were identified using grey relational analysis.
- The contribution of each parameter was weighted according to its importance.

ARTICLE INFO

Article history:
Received 1 November 2010
Received in revised form 27 February 2013
Accepted 28 February 2013
Available online 15 March 2013

Keywords:
Oil agglomeration
Grey relational analysis
Multi-objective optimization

ABSTRACT

This paper presents a novel effective method for the optimization of oil agglomeration process of Zonguldak/Turkey bituminous coal with multiple performance characteristics based on the grey relational analysis (GRA). Oil agglomeration parameters including solid content, amount of oil, agitation time and agitation rate were optimized based on multiple performance characteristics. The characteristics of interest are the grade and the recovery of the agglomerates. Nine experiments were conducted using GRA to optimize the settings for oil agglomeration parameters to generate various quality characteristics. Analysis of the grey relational grade indicates the parameter significance and the optimal parameter combination for the oil agglomeration process. The analytical results from two confirmation experiments using the optimal parameters confirm that the above performance characteristics in oil agglomeration process can be improved effectively through this approach.

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1. Introduction

Present techniques of mining produce large quantities of coal fines [1]. New environmental regulations as well as loss of valuable combustible matter with fine coal do not allow the current practice of discarding the coal fines with refuse [2,3]. The higher the coal utilization the higher are the adverse impacts on the global environment. Hence, it is an important subject to deal with these environmental issues by reducing the air emissions, recovering the suspended coal fines and minimizing solid waste. In the recent years, lots of research activities are in progress in developing the technique of oil agglomeration, in which coal fines are beneficiated as well as recovered, thereby minimizing the air and water pollution along with solid waste management. The disadvantage with conventional techniques like jigging, heavy media separation, spiral concentrators, cyclones is that they can process coal fines of size greater than 75 μm [4].

The technique of oil agglomeration involves preferential wetting of organic matter of coal by oil from coal–water slurry in an agitated condition. The pure coal particles being hydrophobic are agglomerated by the oil droplets and the mineral matter being hydrophilic is retained in the water phase, thereby affecting the separation. Several other factors were found to affect the agglomeration process, which include amount of oil, agglomeration time, coal particle size, pH, pulp density of slurry, surface properties of coal and oil, ionic strength of aqueous medium, etc. [5–23]. Success of the oil agglomeration depends on the selection of suitable operating parameters. Therefore it is very important to determine the operating parameters at which the responses reach their optimum.

The general practice for determining the important operating parameters for agglomeration is by varying one parameter and keeping the others at a constant level. This is the one-variable-at-a-time technique. The major disadvantage of this technique is that it does not include interactive effects among the variables and, eventually, it does not depict the complete effects of various parameters on the process [24,25]. In order to overcome this problem, optimization studies using design of experiments assumes great importance. A number of designs/techniques available in

* Tel.: +90 346 2191010x1574; fax: +90 346 2191173.
E-mail address: naslan@cumhuriyet.edu.tr

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.02.069

literature are particularly useful, where large number of experiments cannot be done due to high cost or fractional availability of raw materials. Robust design methods reduce the effects of variation in input on a system output to improve the quality. They are particularly important when one is interested in designing a system that gives consistent outputs despite the variation of uncontrollable factors [26]. Chary and Dastidar have used Taguchi method for optimization of experimental conditions for recovery of coking coal fines by oil agglomeration technique [4]. Response surface methodology (RSM) has been adopted by Aslan and Ünal for optimizing the parameters that affect the agglomeration performance of Zonguldak bituminous coal by oil agglomeration [5].

The optimization studies mentioned above about some processes so far have been mainly aimed at the optimization of the single quality characteristic such as grade or recovery at a time. It has been found that the optimum parameter settings for one quality characteristic may deteriorate other quality characteristic such as grade and recovery. But it is always desired to optimize the multiple quality characteristics, i.e. grade and recovery, of the product or process at the same time [23].

Grey relational analysis (GRA) was first proposed by Deng [24] in 1982 to deal with poor, incomplete, and uncertain systems. As implied by its name, which implies a shade between the absolutes of black and white, GRA can effectively recommend a method of optimizing the complicated inter-relationships among multiple performance characteristics [25]. The GRA method can process numerous attributes with different value types, physical measurement units, and score attributes, including attributes with limited accuracy and reliability. Notably, GRA can be applied to multi-objective evaluation problems. Tarng et al. [26] demonstrated that GRA of signal/noise (S/N) ratios can convert optimized multiple performance characteristics into an optimized single performance characteristic.

Most of the engineering applications or processes encountered in the real world comprise of multiple responses. This is also true for coal or mineral concentration plants. A marginal improvement in all in a single step may be economically remarkable. Thus, an approach to optimize all quality characteristics simultaneously is very important in these processes. In this context, the multi-objective optimization of grade and recovery using Taguchi quality loss function has been done for chromite concentration by using multigravity separator and the concentration performance has been improved [23].

While the grey relational analysis has found wide application areas for determining the optimal parameters different production processes, optimization studies for mineral processing parameters are rather lacking using the GRA. The purpose of the present work is to introduce the use of grey relational analysis in selecting optimal oil agglomeration conditions for Zonguldak bituminous coal on multi-performance characteristics, namely; the grade and the recovery of the agglomerate. The setting of oil agglomeration parameters was accomplished using the Taguchi experimental design method. Moreover, the most effective factor and the order of importance of the controllable factors to the multi-performance characteristics in the oil agglomeration process were determined by using grey relational grade.

2. Experimental procedure

2.1. Materials used

Turkish bituminous coal from Zonguldak colliery was chosen for the investigation. The coal (run of mine, ROM) was first crushed to less than 5 mm diameter in a crusher. A ball mill was provided to achieve further particle size reduction. The milled sample was sieved and particles of less than 63 μm diameter were collected and stored in sealed plastic bags. The particles were dispersed in a standard laboratory beaker having sufficient amount of distilled water. An ultrasonic probe was used to help disperse samples for 30 s. The particles are introduced to the analyzer beam in a sample presentation cell in the optical unit. Kerosene was used as the bridging agent in the oil agglomeration process. Specific density of kerosene is 0.7912 g cm^{-3}.

2.2. Oil agglomeration

Agglomeration tests were carried out in a 1000 ml stainless steel cylindrical vessel (inside height: 180 mm and diameter: 95 mm) with four removable vertical baffles. The agitation of vessel contents was performed using overhead stirrer equipped with three pitched on a central shaft.

In the present study, a design of experiment methodology was used to examine a different set of process variables like solid content (5–15 wt.%/vol.%), amount of oil (5–25 wt.%/vol.%), agitation time (5–15 min) and agitation rate (1250–1750 rpm).

Initially, requisite amount of distilled water was poured into the agglomeration vessel to prevent the dry coal feed sticking to the bottom and walls of the vessel. Water in the vessel was agitated at low agitation rate (≈1200 rpm) by the impeller. Requisite amount of coal sample to be agglomerated was added to the agglomeration vessel using a beaker while the water was being agitated. This operation was performed over a short time period, but was mixed well at 1200 rpm for 3 min in order to wet the surfaces of the particles. The desired amount of bridging oil was then added to the slurry and the mixture was agitated at the requisite speed for the desired time period.

At the end of the experiment, it was observed that the agglomerates collected on the surface of the water and the mineral rich matter (tailings) settled to the bottom of the vessel. The agglomerates and tailings in the vessel were poured over a 160 μm sieve to separate agglomerates from water and mineral rich matter. A substantial amount of distilled water was used to wash the agglomerates, which meant that some mineral matter on the surfaces of the agglomerates was removed to obtain a cleaner product. The agglomerates were transferred to a clean surface and allowed to dry in air for 24 h. The harvested agglomerates were dried and analyzed gravimetrically for determination of grade and recovery.

Both the agglomerates and mineral rich material were washed with acetone (25 ml of solvent for per gram of solid) to remove the bridging oil at room temperature. The oil free materials, coal and mineral rich materials, were dried in a vacuum oven at 80 ± 5 °C overnight. At the end of drying, the solids were weighed and stored in sample bottles for the ash analyses. The ash contents of the agglomerates and mineral rich matter were determined separately to obtain the recovery and grade of the final product and check the ash balances. The recovery (R), percent, and grade (G) [5,23] of the agglomerates were defined as:

$$\text{Recovery}(R) = \frac{C_a}{C_f} \times 100 \tag{1}$$

$$\text{Grade}(G) = 1 - \frac{A_a}{A_f} \tag{2}$$

where C_a and C_f are the dry ash free coal contents in the agglomerates (oil free) and the original feed coal; A_a and A_f are the ash content of the agglomerates and the original feed coal, respectively.

This study examines four oil agglomeration parameters (solid content, amount of oil, agitation time and agitation rate) to obtain multiple quality characteristics (the grade and recovery of agglomerate). Oil agglomeration process factors and their levels are given

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