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Prediction of coal recovery in tailings using fuzzy logic in a Knelson concentrator

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Abstract: It is recognized that the use of centrifugal gravity concentrators is more effective than conventional concentrators in recovering fine-grained coal tailing. In the Knelson concentrator study, fuzzy logic was used to investigate the prediction of ash content and combustible recovery. The Western Lignite Company (WLC) tailing sample was classified into -1+0.038, -1+0.212 and 0.212+0.038 mm size groups. In the prediction studies, centrifugal force (20, 30, 40 and 50 G) and flow rate (2, 3 and 4 L/min) were used as input variables. Then the results of the fuzzy logic prediction were compared with the actual values and found that the fuzzy logic system could be successfully applied to the Knelson concentrator enrichment results.

Keywords: coal tailing, Knelson concentrator, fuzzy logic

1. Introduction

In coal production processes, important amounts of uncovered fine-grained tailings are generated. Tailings are commonly grouped into three categories depending on the coal characteristics and the operational and technological processes applied (Fecko et al., 2013): (i) production of coal during the excavation and preparation of coal from the mine, (ii) fine-sized coal generated during beneficiation processes (e.g., sorting, washing, crushing), (iii) coal tailings from the commercial product manufacturing processes.

It is important for sustainable coal mining operations that these coal tailings are effectively recovered and utilized. However, the recovery of coal from fine tailings is costly. Nevertheless, it is possible to contribute these tailings to the economy and reduce environmental pollution with proper strategies and utilization techniques. As technology has improved, fine-sized coal can be effectively recovered with gravity methods using centrifugal force and flotation. In the flotation method, however, problems occur because of extra reagent costs and performance decreases in oxidized coals (Ghaffari and Farzanegan, 2017; Kokkılıc et al., 2015; Peer et al., 2002; Uslu et al., 2012). Hence, centrifugal separators are increasingly important in the recovery of fine coals, the amount of which is growing each passing period and leading to environmental problems.

Many studies have been carried out using the Knelson concentrator (KC), one of the centrifugal separators, for coal recovery. These studies have examined the operating parameters of the equipment, such as water flow rate, centrifugal force and feed rate have been studied by several researchers (Honaker and Das, 2004; Honaker et al., 1996; Majumder et al., 2007; Oney and Tanriverdi, 2016; Oney et al., 2020; Sabah and Koltka, 2014). Oney et al. (2020) obtained clean coal with approximately 12% ash content from 24% ash coal by beneficiation of -1+0.15 mm sized coal particles in Knelson concentrator. The effects of variables (bowl speed, fluidization water flow rate, solids ratio and feed flow rate) on concentrate yield, ash content and combustible recovery in the concentrate were investigated using a central composite design. The interactions of the responses were evaluated using regression models and three-dimensional graphs. In addition, experimental tests were also assessed by using upgrading curves.

A variety of techniques, e.g., flotation, multi-gravity separator (MGS), and gravity separation, were used by researchers to recover clean coal from coal tailing. Oruc et al. (2010) recovered the coal waste

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which was pre-enriched with hydrocyclone by falcon concentrator. It obtained clean coal with 36% ash content from coal waste with -0.1 mm particle size and 66% ash content. Ozgen et al. (2011) used MGS to recover coal waste from two different regions. Soma and Tuncbilek coals, with 52.65% and 66.21% ash content, respectively, were recovered as clean coal with 22.89% and 22.83% ash content with 60.01% and 49.32% combustible recovery. Chaurasia and Nikkam (2016) obtained clean coal with 16.24% ash content and 69.16% combustible recovery using MGS from 33.5% ash coal waste with relatively low ash content. Ozgen et al. (2019) utilized MGS to recover -0.5 mm particle sized coal waste with 71.58% ash content, 55.89% ash content and 67.81% combustible recovery. Jiang et al. (2016) used a reflux flotation cell and two-stage fast flotation to obtain 49% ash coal waste with 7.8% ash and 80% combustible recovery. Waste coals recovered by different methods have disadvantages and advantages very each other, such as sufficient cleaning, economic and environment problems.

There are many factors involved in coal recovery, including material parameters such as particle size and ash content besides equipment operating parameters. Conventional methods for modelling and optimizing this process are usually based on deterministic techniques, which are unable to properly consider the existing uncertainties and non-linear relationships. Meanwhile, fuzzy logic is a strong tool for overcoming uncertain and undefined information and has been successfully applied in several ore recovery operations (Abshoshk et al., 2010; Ali et al., 2018; .Cai et al., 2021; Li et al., 2012; Savarani et al., 2014).

This study aims to develop a fuzzy logic- based approach to estimate the ash content, weight and combustible recovery of coal recovered from WLC tailing pond using a KC. In this way, the existing uncertainties and problems inherent to the equipment and coal encountered in the coal recovery process can be effectively considered with this approach. Moreover, a series of experiments were carried out to verify the effectiveness of the approach and to obtain a more powerful and accurate decision-making tool. In previous studies, coal tailings have been recovered using a KC, but no study utilized a decision-making system in coal tailings recovery. Therefore, this study using fuzzy logic will be an important reference for future studies.

2. Materials and methods

2.1. Material

The experimental materials were taken from Tailing Pond No. 4 of the WLC Plant, collected by the operating engineers and then transported to the Dumlupınar University Mining Engineering Department Laboratory. The materials were systematically mixed in a rigorous method to obtain sample homogeneity. A representative 400 kg sample was then carefully separated using standardized sample separation techniques and stored for experimental studies. Then, the materials were analysed to determine the properties of the material (Fig 1 and Table 1). The sample was classified into three size groups: -1+0.212, -0.212+0.038 and -1+0.038 mm and subjected to beneficiation experiments using a laboratory-scale KC.

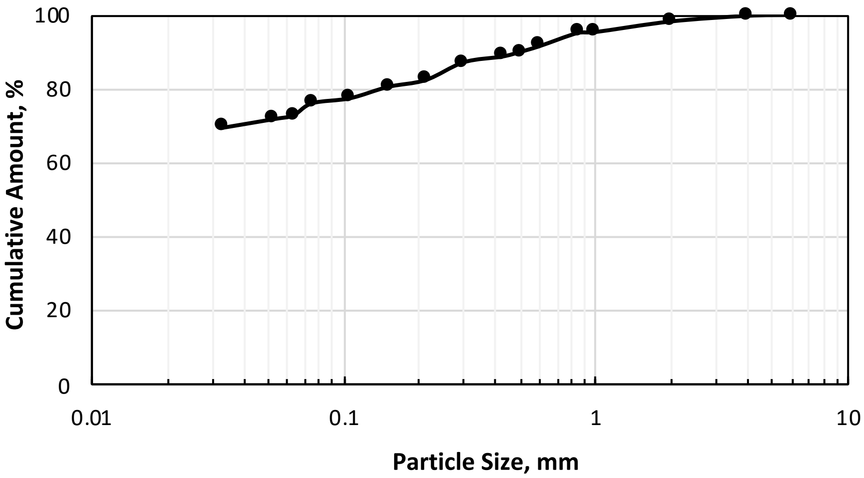

Fig. 1. Particle size distribution of the sample

Table 1. The results of moisture, sulphur, ash content, LCV and UCV of the sample

Particle Size (mm)	Ash (%)	*UCV (Kcal/kg)	*LCV (Kcal/kg)	Sulphur (%)	Moisture (%)
+4	27.25	5191	4763	1.07	3.80
-4+2	24.83	5441	4944	1.16	4.70
-2+1	20.41	5731	5233	1.19	4.30
-1+0.85	25.45	5170	4710	1.23	4.30
-0.85+0.6	22.31	5468	4980	1.24	4.40
-0.6+0.5	26.00	5260	4803	1.28	4.20
-0.5+0.425	26.66	5031	4564	1.26	4.60
-0.425+0.3	33.64	4859	4451	1.20	4.00
-0.3+0.212	40.04	4519	4133	1.33	4.20
-0.212+0.150	37.78	4670	4251	1.33	4.60
-0.150+0.106	47.10	3933	3680	1.43	2.20
-0.106+0.075	48.03	3358	3086	1.39	3.10
-0.075+0.063	40.07	3598	3263	1.31	3.90
-0.063+0.053	50.69	3127	2870	1.12	3.10
-0.053+0.038	58.81	2531	2333	1.11	2.50
-0.038	81.91	-	-	0.34	1.70
Total	68.01	-	-	0.62	2.35

* LCV: Lower Calorific Value; UCV: Upper Calorific Value

2.2. Methods

The study consists of two parts: in the first stage, experiments were carried out using KC, and then the obtained data were predicted using fuzzy logic. In the first part of the study, a series of experiments were conducted in all three size groups to determine the effect of centrifugal force and wash water flow rate. The experiments were carried out with a laboratory-scale KC at centrifugal forces of 20, 30, 40 and 50 G and wash water flaw rates of 2, 3 and 4 L/min. Feed flow rate and solids content were kept constant in these experiments.

In the second part of the study, ash content, combustible recovery and clean coal weight prediction, which are important in coal beneficiation, were determined using fuzzy logic.

2.2.1. Methodology of fuzzy logic system

Fuzzy logic was first presented by L.A. Zadeh (1965) as a decision-making mechanism. Fuzzy logic is used to mathematically model expressions that cannot be described using known methods. Fuzzy logic is one of the methods to acquire decision-making ability from computers. It is expressed in fuzzy logic at many levels in the range of 0-1, not in two stages of 0 and 1 as in classical logic. The membership values defining the membership level between the sets are in the close range of [0,1], and a value of 1 indicates that the membership is fully accepted, or on the contrary, a number of 0 values indicates the opposite. Three stages of fuzzy logic are involved: Defuzzification, inference and stabilization. Defuzzification is the step of converting normal input variable values into linguistic expressions. Inference consists of matching inputs to linguistic output values using fuzzy if-then rules and logical operations. The decision-making criteria of the computer are determined after a rule table is created. Finally, fuzzy output values are rinsed and digitized in the output unit (Fig 2).

Mamdani method was used in the study by using the fuzzy logic module of the MATLAB program. The Mamdani method, one of the two most widely used inference methods (the other is the Takagi-Sugeno-Kang (TSK) method), was chosen because it is more familiar to human perception and relatively easy to use and interpret. In the modelling process, centrifuge forge and wash water flow rate were defined as input (independent) variables. The output (dependent) variable is the predicted coal recovery parameters. The input and output variables used in the model are shown in Fig 3.

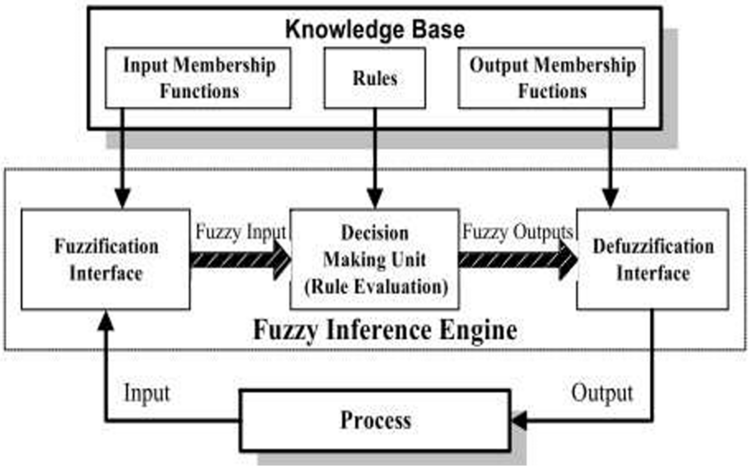

Fig 2. General structure of fuzzy inference system (Nasr et al., 2012)

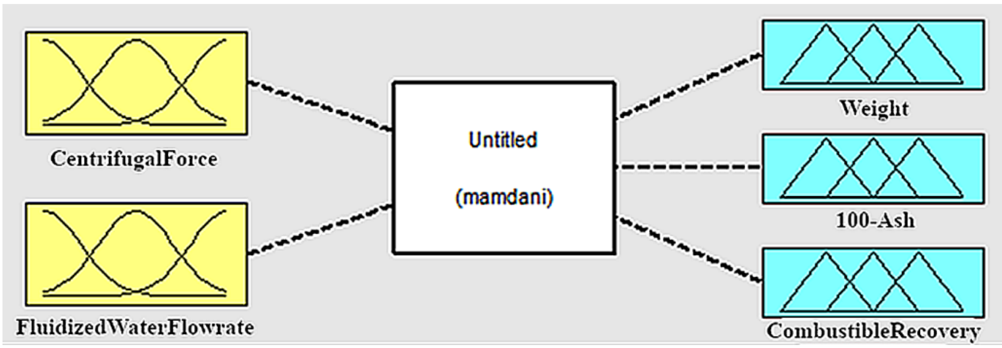

Fig. 3. Input and output variables

Membership functions define fuzzy sets. According to the geometry of the membership cluster, the degree of membership is calculated. Since it provides the best results in the study, the triangular method was used and the membership degree was calculated using Equation 1. There are given the membership function names of the parameters as weak, medium, strong and very strong for centrifugal force and low, normal, high and very high for washing water flow rate (Fig 4). The placement of the linguistic values in these intervals is a subjective interpretation. In fact, fuzzy logic generates from subjective interpretations. Thus, it defines an interval that can be expanded or narrowed according to the output results obtained with varying parameters, depending on the material used in the actual experiment.

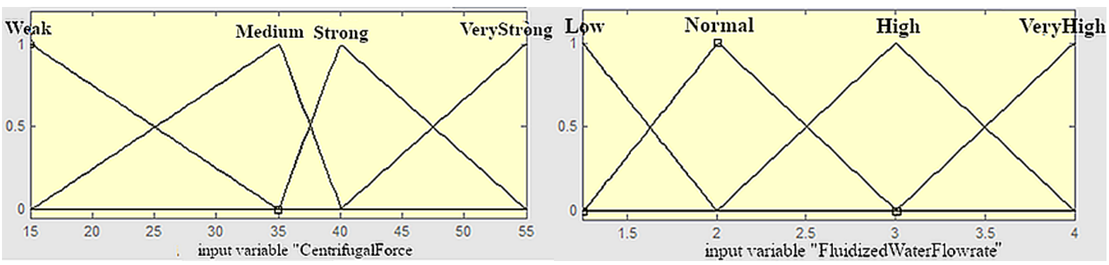

Fig. 4. Membership functions of parameters

$$\mu_a(X) = \begin{cases} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases} \tag{1}$$

It defines the linguistic relationships between input variables and output variables. All relation (between input variables in the rule table) is created with the conjunction "and". In the assignment of the membership degree of the output set, the conjunction "and" means the assignment of the smallest value of the input membership degrees. It is determined by multiplying the number of rules by the number of each function of the two input variables. There are 16 association rules for each fraction in this work (Fig 5). The interference process is defined based on the min-max inference rule. The widely used centroid of gravity (COG) method for rising was using in the study.

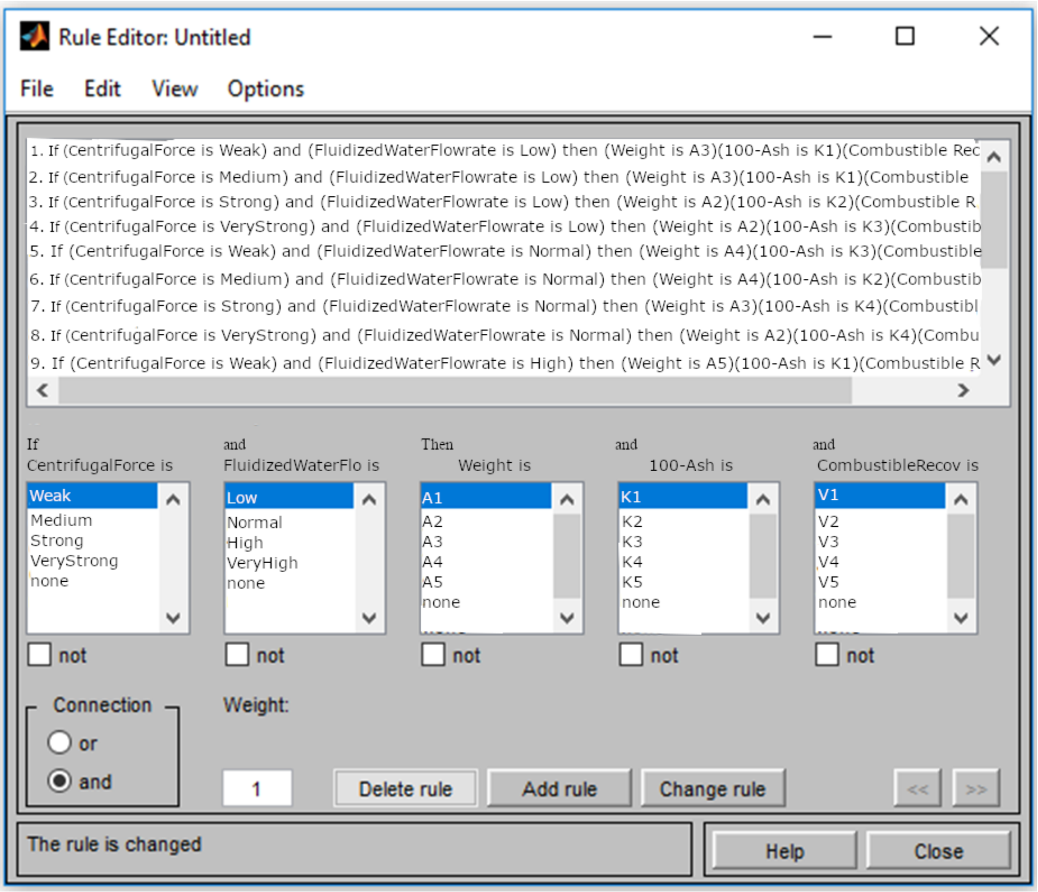

Fig. 5. Model rules

The fuzzy logic method was applied to the experimental results for three different groups of tailing coal beneficiated using KC. The Absolute Fraction of Variance (R^2), Mean Absolute Percentage Error (MAPE) and Root Mean Squared (RMS) error criteria were used for comparison to investigate the size at which the KC had the best results in three different groups (Ozcan et al., 2009). Afterward, it was calculated these values in Excel.

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}(t_i - o_i)^2}{\sum_{i=1}^{N}(o_i)^2}\right) \tag{2}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}|t_i - o_i|^2} \tag{3}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{t_i - o_i}{o_i}\right| * 100 \tag{4}$$

3. Results of experimental studies

Mamdani model developed in this study, which aims to estimate 100-ash content, combustible recovery and clean coal weight with fuzzy logic, determined the shape and number of membership functions belonging to both input and output variables and the rule table created according to the closeness of the results to be obtained. Thus, by inputting the data into the model, a significant degree of weight, 100-ash and combustible recovery estimation could be obtained. The results gathered experimentally were divided into two groups. The first group was used for prediction and the second group, 10%of the total number of experiments, was used for testing the model. The prediction results of the model run can be seen in Figures 6, 7 and 8.

Fig 6 shows the effect of the input parameters, centrifugal force and fluidized water flow rate on the weight of clean coal entering the concentrate for all size groups. In the -1+0.212 mm size group obtained by removing the fine-size product, the material entering the concentrate increases as the centrifugal force decreases, with no significance of the fluidized water flow rate. However, the other two sizes containing fine-sized products are also affected by the fluidized water flow rate, and the material entering the concentrate decreases significantly with increasing centrifugal force (Fig 6).

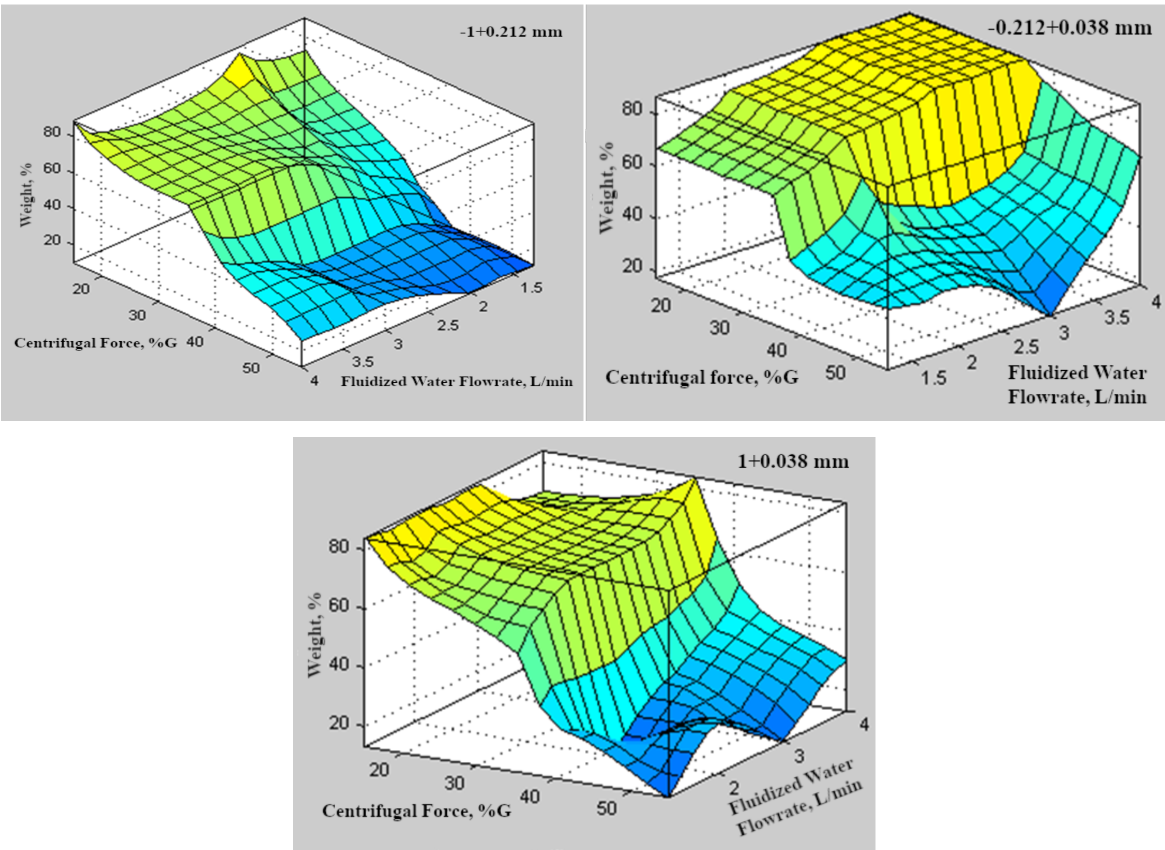

Fig. 6. Weight plots of experiments performed at (a) -1+0.212 mm, (b) -0.212+0.038 mm and (c) -1+0.038 mm

Fig 7 shows the effect of centrifugal force and fluidized water flow rate on the 100-ash content of clean coal in three size groups. In Fig 7(a), similar results were obtained with the weight of clean coal entering the concentrate in the size group -1+0.212 mm. indeed, as the centrifugal force decreased, the ash in clean coal was removed. In Fig 7(b), in the size group -0.212+0.038 mm, the clean coal with the minimum ash content was obtained at the lowest centrifugal force and the highest fluidized water flow rate. In Fig 7(c), in the size group of -1+0.038 mm, the fluidized water flow rate has no effect on the 100-ash value at a low centrifugal force. However, with increasing centrifugal force, ash enters the clean coal with the effect of the force affecting a wide range of particles. This situation emphasized that the feed product should be in a close size range in gravity separators. It was obtained the clean coal with the minimum ash content at a centrifugal force of 30-40 G at a fluidized water flow rate of 4 L/min.

Sabah and Koltka (2014) obtained clean coal containing 30.51% ash content with a weight of 81.18% by enriching the material with 42.6% ash content in the -0.5+0.038 mm size group from the samples taken from the waste pond of ELİ Soma Plant with KC. They recovered coal tailings, which were pre-enriched by hydrocyclone and then beneficiated by using a KC. They investigated the effect of bowl speed, fluidization water pressure, solid ratio and sample collection time of KC on the ash of lignite tailings. It was determined that the fluidization water pressure and bowl speed, which form a fluidization particle bed within the tailings rings, play a critical role in achieving optimum results. They found that reducing the bowl speed below 1000 rpm increased the ash level of the clean coal as a result of the reduced centrifugal force. They concluded that separation was not successful at low or high fluidization water pressures and low gravitational speed. To improve the separation efficiency, the bowl speed should be higher, and the fluidization water pressure should be lower.

In similar study parameters, Majumder et al. (2007) reported that it can produce a clean coal product with 17% ash content at 40% combustible recovery from a feed with 36.13% ash content. In their study, where they enriched fine coal, they kept the rotational speed constant at 1000 rpm, increased the fluidization pressure from 3 to 15 psi and obtained these results at the lowest psi value. The change in fluidization pressure at other rotational speeds obtained similar results. At 3 psi fluidization pressure, when the rotational speed increased, the ash percentage in clean coal and coal yield increased.

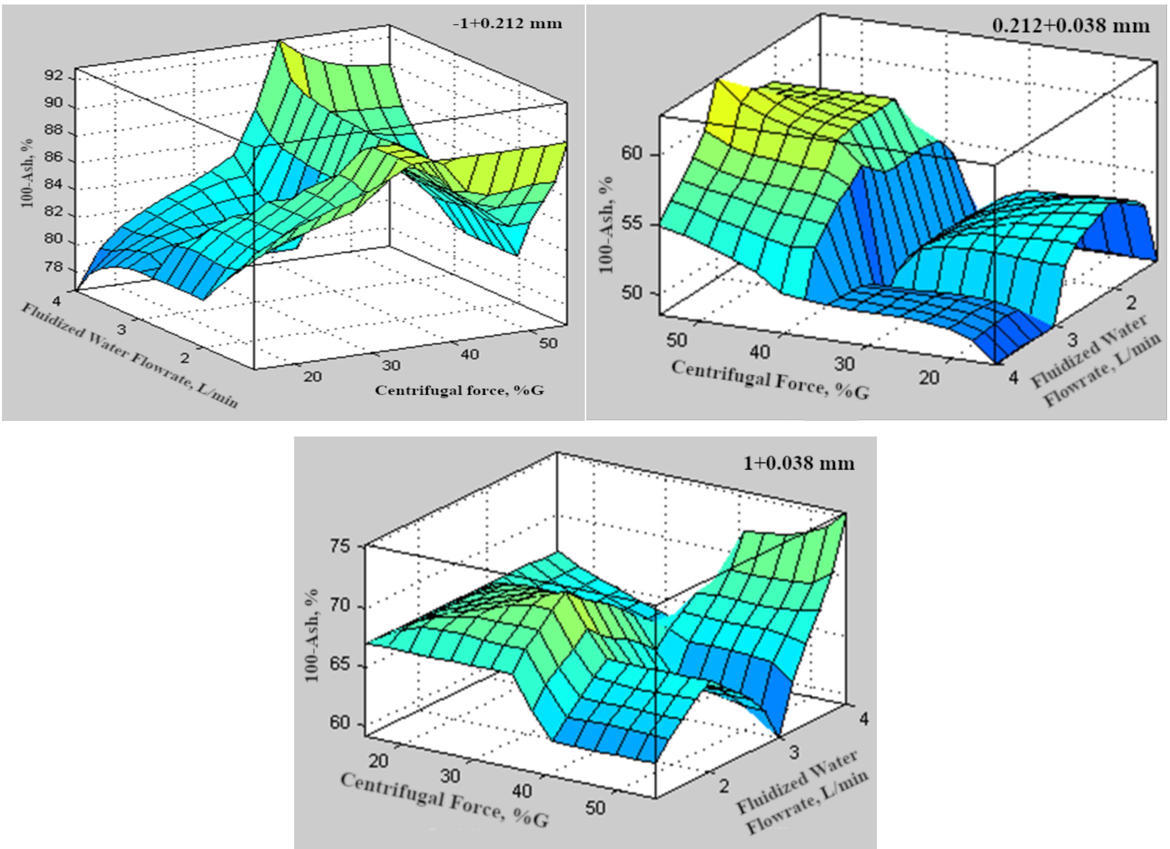

Fig. 7. 100-ash plots for experiments performed at (a) -1+0.212 mm, (b) -0.212+0.038 mm and (c) -1+0.038 mm

Fig 8 gives the effect of centrifugal force and fluidized water flow rate on the combustible recovery of clean coal in three size groups. For the -1+0.212 mm size group, the combustible recovery value rises with diminishing centrifugal force without affecting the fluidized water flow rate (Fig 8 (a)). However, ash is also mixed into the clean coal as I result of the low selectivity of the separation, which increases the combustible recovery. The combustible recovery is the highest value with reducing centrifugal force and increasing fluidized water flow rate in Fig 8 (b) and (c). Oney and Tanriverdi (2016) studied similar sizes using KC, enriched Amasra coal in the size range of -1+0.15 mm and obtained clean coal with 16.28% ash content from 34.30% ash content feed coal with 67.82% combustible recovery. Honaker and Das (2004) used pilot KC in a study on ultra-fine-sized coal (-0.150+0.044 mm). In their study, they enriched coal with 22% ash content and obtained clean coal with 8% ash content with 70% combustible recovery.

The relationship between experimental and fuzzy logic results for the output parameters of weight, 100-ash and combustible recovery is given in Fig 9 for all size groups. In the graphs, R^2 values representing the relationship between them are given above the graphs. The results in the -0.212+0.038 mm size group demonstrate that the experimental results are the best fitted to the fuzzy logic results. -1+0.038 mm is the size with the lowest matching.

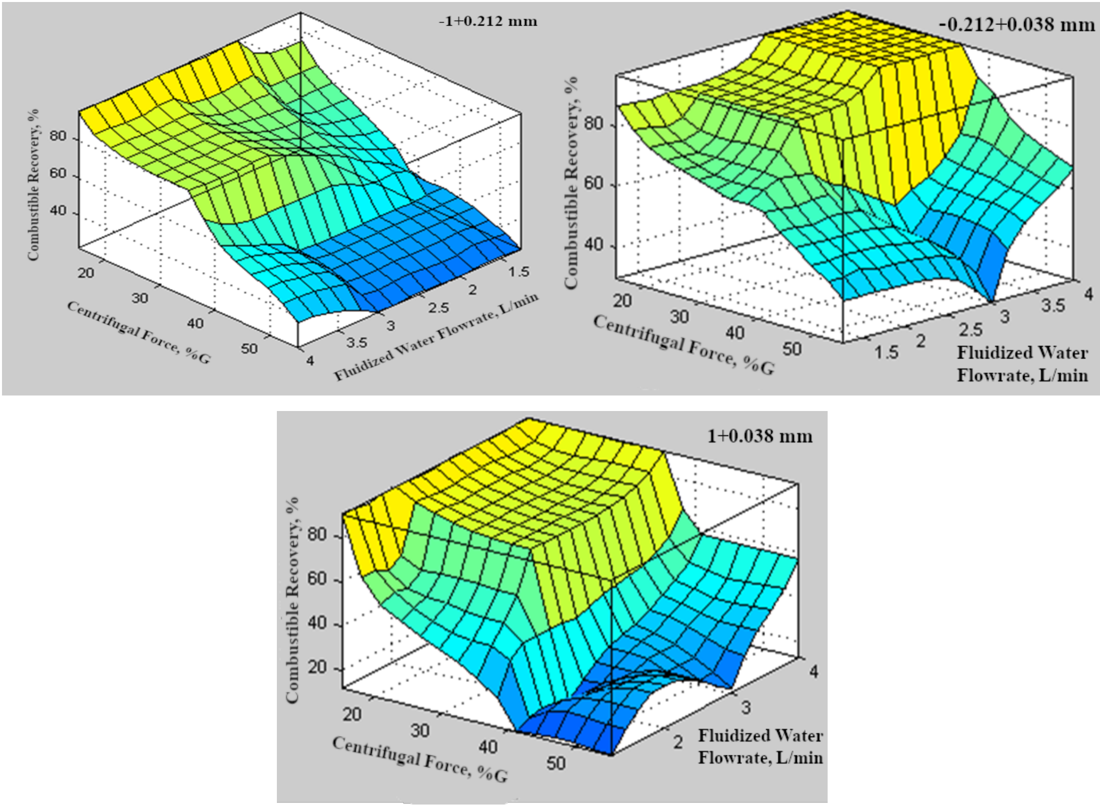

Fig. 8. Combustible recovery graphs for experiments performed at (a) -1+0.212 mm, (b) -0.212+0.038 mm and (c) -1+0.038 mm size

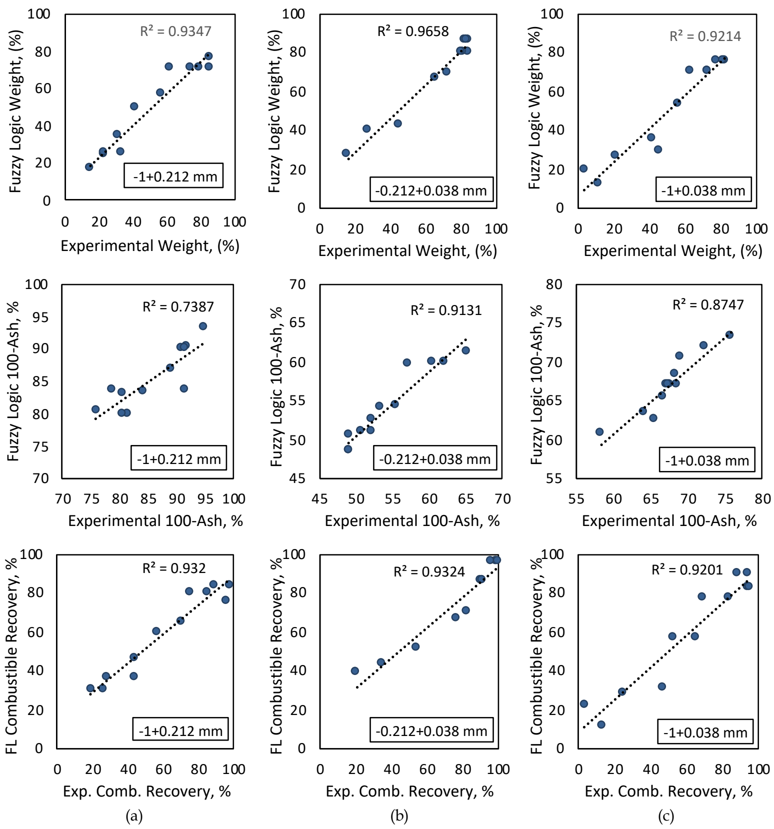

Fig. 9. Comparative distribution of experimental results and fuzzy results of experiments for weight, 100-ash, and combustible recovery from top to bottom, respectively ((a) -1+0.212 mm, (b) -0.212+0.038 mm and (c) -1+0.038 mm)

A comparative presentation of the statistical parameters of the models is given Fig 10. Similarly, R^2, RMA and MAPE values for all sizes are in detail in Table 2. Factors such as coefficient of determination (R^2) and error variance criteria (RMS and MAPE) were taken into consideration in determining the best-fit particle size. In the evaluation of the results, the model with a high R^2 value and low RMS and MAPE values shows the best fit. In addition, a MAPE <10% was considered a very good agreement, 10-20% as a good agreement, and 20-50% as an acceptable agreement. The results revealed that high R^2 values for weight and combustible recovery were generally recorded for all particle sizes. It was found, but the R^2 values of 100-ash were low.

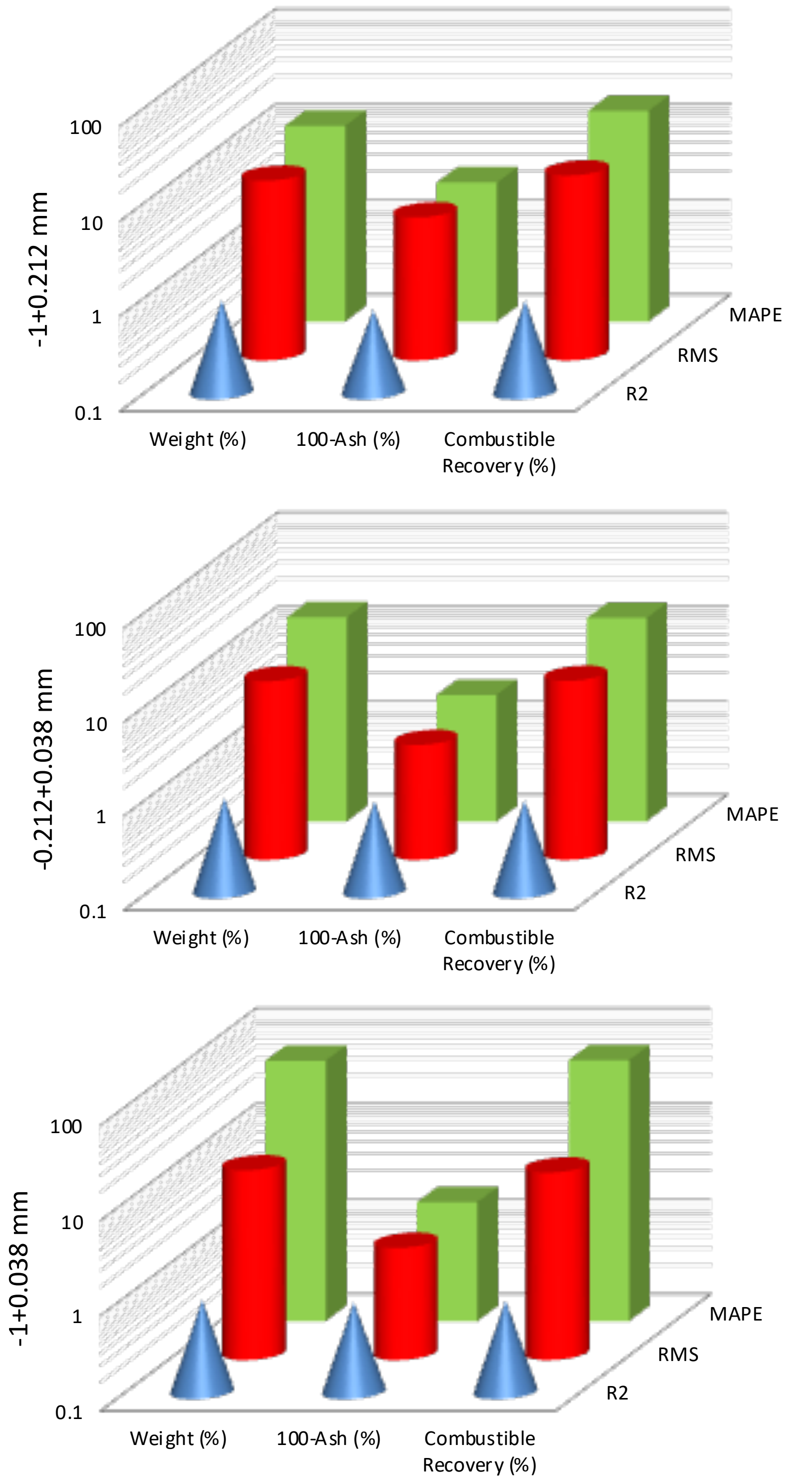

Fig 10. Comparison of output parameters for (a) -1+0.212 mm, (b) -0.212+0.038 mm and (c) -1+0.038 mm size groups according to R^2, RMS and MAPE assessment criteria

Table 2. Determining the agreement between the actual value and the model prediction

Outputs	-1+0.212			-0.212+0.038			-1+0.038		
	Weight (%)	100-Ash (%)	Combustible Recovery (%)	Weight (%)	100-Ash (%)	Combustible Recovery (%)	Weight (%)	100-Ash (%)	Combustible Recovery (%)
R^2	0.9347	0.7387	0.9320	0.9658	0.9131	0.9324	0.9214	0.8747	0.9201
RMS	7.0149	3.2159	8.8860	5.4583	1.6758	8.0691	7.7490	1.5149	9.3900
MAPE	11.0467	2.9007	16.5312	12.4416	2.2288	14.6385	51.9848	1.7821	55.4473

In the study, the highest R^2 value was observed for the size group of -0.212+0.038 mm. The R^2 value of clean coal weight at this size is 0.9658. It was found that the lowest R^2 value was 0.9131 for the 100-ash value. In 100-ash value, the MAPE and RMS values are 2.2288 and 1.6758, respectively, demonstrating that the estimation outcomes are highly accurate.

The R^2 values at -1+0.038 mm in fuzzy logic are 0.9214, 0.8747 and 0.9201 for weight, 100-ash and combustible recovery, respectively. Despite the fact that the R^2 values determined are not low, the high MAPE and RMS values observed for weight and combustible recovery in this size experiment reveal that the prediction is of low accuracy. MAPE is the mean absolute percentage error. It is the average multiplicative effect between the predicted average value and the actual results. MAPE is higher when the predicted value exceeds the actual value. It is explained by the fact that the percentage error cannot exceed 100% for very low estimates, whereas there is no upper limit for high estimates. That is, MAPE selects models with low predictions. Therefore, the reason for the high MAPE value for this dimension is that the predicted weight and combustible recovery values are higher than the values obtained from the experiments. This situation may be interpreted as the results obtained from KC experiments are much dispersed. The reason for this can be the wider size scale.

In the -1+0.212 mm size group, as in the other size groups, the R^2 value of the 100-ash is low and has the lowest value (0.7787). However, MAPE and RMS are low, indicating that the actual values are in good agreement with the predicted values. The R^2 values are 0.9347 and 0.9320 for weight and combustible recovery, respectively. The MAPE values of both output parameters are in the range of 10-20%.

4. Conclusions

In this study, MATLAB software was used to perform fuzzy logic prediction to validate the experimental results of three different size group of waste coal concentrated using KC. The fuzzy prediction method applied for the two critical factors for the KC, which are centrifugal force and fluidized water flow rate.

The results of the evaluations show that, in general, high R^2 values were recorded for all size groups. In addition, it is seen that the -0.212+0.038 mm size group gives higher R^2 values and lower error values than the -1+0.038 mm size group. Experimental and fuzzy logic results are most similar in the -0.212+0.038 mm size group. It is also seen with R^2, RMS and MAPE statistical values.

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