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The modelling of fine coal beneficiation with a water-only cyclone

Introduction

Fine coal beneficiation has become more important due to recent improvements in the mechanization of coal mining. Recent mechanization techniques have led to the production of large amounts of –1 mm fine coal. The beneficiation of –1 mm coal particles in a preparation plant is a great challenge because of near gravity materials, and it results in poor efficiencies in comparison to coarser sizes (Hore et al. 2012; Wei and Sun 2016). Nevertheless, there are various treatment methods for processing fine coals such as spirals, flotation, oil-agglomeration, and enhanced gravity separators

Because of the surface properties and oxidation of low-rank coals (Ateşok and Çelik 2000), flotation and oil-agglomeration processes cannot be effectively achieved. Spirals

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cannot achieve separation density lower than 1.65 g/cm^3; they usually have a d_{50} between 1.7 and 2.1 g/cm^3 and misplace a significant amount of ash fines into the clean coal. Even the application of wider-diameter spirals have been found not to solve this problem (Mohanta et al. 2017; Ye et al. 2021; Ramudzwagi et al. 2020). In some cases, enhanced gravity devices are also used, and effective separation results are obtained (Oluklulu and Koca 2018; Zhang et al. 2019; Tozsin et al. 2016). However, the industrial use of these devices has not yet been put into practice because of their capacities and operating-maintenance costs.

Under these circumstances, water-only cyclones (WOC) are a more effective and economical option for fine coal treatment. WOC have a wide conical bottom, and the separator can create its own dense medium by accumulating heavy particles in this wide conical portion of the cyclone. WOC has no moving parts and no external medium feed required. Thus, it is one of the best options for the cost-effective separation of fine coals (Suresh et al. 1996; Hacifazlioglu 2012; Kim and Klima 1998; Rao and Gouricharan 2006; Kalyani et al. 2008).

Many optimizations of parameters were performed to evaluate WOC's separation performance. Abbas and Muhammad (Abbas and Muhammad 2016), investigated the effects of the cyclone inclination, vortex finder diameter, and length, apex diameter, inlet pressure, and solid feed density on a WOC's separation performance. Research shows that yields of 61–80% and an ash reduction of 50% are attainable. Hembron and Suresh (Hembron and Suresh 2018), studied the effects of vortex finder length, vortex finder diameter and spigot diameter. Study shows that results obtained as maximum yield of 68.62% and ash reduction of 40.47%. Studies have shown that cone angle, spigot diameter, vortex finder diameter, and length play important roles in the operation of a WOC. Research shows that yields of 29–68.62% and ash reduction of 52% are attainable (Majumder and Barnwal 2011). The cone angle, feed density, vortex finder diameter, and length positively affect, while the apex diameter negatively affect the clean coal ash content and yield.

1. Materials and methods

1.1. Materials

The coal used in the study was supplied from Soma, Turkey and crushed to below 1 mm. A representative feed sample was taken to be used for proximate, size, and washability analyses. The results of the proximate analysis are given in Table 1, and the particle size distribution of the material is given in Table 2.

Table 3 shows the washability test results conducted using a zinc-chloride solution and 1–0.1 mm coal samples. The results represent the weight (wt.) and ash distributions of the density fractions of the coal sample.

Table 1. Proximate analysis of feed coal sample

Tabela 1. Analiza bezpośrednia próbki węgla wsadowego (nadawy)

Components	Value (%)
Ash	45.80
Volatile matter	34.91
Fixed carbon	19.29
Sulphur	0.54

Table 2. Particle size distribution of feed coal sample

Tabela 2. Rozkład uziarnienia próbki węgla wsadowego (nadawy)

Particle size (µm)	Weight (%)	Ash (%)
1,000–500	26.28	42.22
500–300	14.22	41.77
300–212	14.33	43.55
212–150	15.79	42.83
150–106	7.74	45.31
>106	21.64	56.63
Total	100	45.80

Table 3. Float-Sink tests of 1–0.1 mm coal sample

Tabela 3. Testy typu *Float-Sink* próbki węgla o uziarnieniu 1–0,1 mm

Specific gravity (g/cm^3)	Wt. (%)	Ash (%)	Cumulative float		Cumulative sink	
			Wt. (%)	Ash (%)	Wt. (%)	Ash (%)
<1.3	5.75	3.17	5.75	3.17	100	42.21
1.3–1.4	25.06	5.88	30.82	5.37	94.25	44.59
1.4–1.5	5.53	13.62	36.35	6.63	69.18	58.61
1.5–1.6	1.88	40.5	38.23	8.3	63.65	62.52
1.6–1.7	3.2	52.3	41.43	11.7	61.77	63.19
1.7–1.8	12.03	62.58	53.46	23.15	58.57	63.79
>1.8	46.54	64.1	100	42.21	46.54	64.1

2. Methods

Experiments were conducted using a WOC (water-only-cyclone), the dimensions of which are given in Table 4. The WOC was operated in a closed-circuit test rig consisting of a slurry pump and a bypass line with which the clean coal and tailing were recycled back to the feed tank.

Table 4. Structural parameters of the WOC

Tabela 4. Parametry strukturalne hydrocyklonu

Diameter of cylinder	200 mm
Length of cylinder	270 mm
Diameter of apex	30 mm
Angle of cone	135°
Length of vortex finder	230 mm
Diameter of feed inlet	50 mm

The density-based separation tests with the WOC were conducted in accordance with the procedure given below.

- The feed coal (–1 mm) and water were mixed in the slurry tank at the pre-determined slurry concentration.
- The feed inlet pressure was adjusted with the bypass line.
- The system was then allowed to run for a few minutes to attain a steady state.
- The overflow and underflow streams were then collected simultaneously for a time of 6–7 s.

Table 5. Variables and levels for Box-Behnken design

Tabela 5. Zmienne i poziomy dla projektu Box-Behnken

	Symbol	Variables and range		
		–1	0	+1
Feed density (% wt.)	FD	10	20	30
Inlet pressure (kPa)	IP	25	35	45
Vortex finder diameter (cm)	VFD	6.5	7.5	8.5

–1 – factor at low level, 0 – factor at medium level, +1 – factor at a high level.

- The slurry and solid weights of the products were sieved through a 0.1 mm mesh to simulate dewatering screens.
- The products were subjected to ash analysis after drying.
- The effects of different parameters on the separation efficiency of the WOC were investigated using a three-level three-factor Box-Behnken experimental design. The list of the independent variables (feed density (FD), inlet pressure (IP), and vortex finder diameter (VFD)) with their coded and actual levels are presented in Table 5.

3. Results and discussion

3.1. Model equations and statistical analysis

In the study, a total of fifteen tests including three control experiments (center points) were conducted. The actual data collected from the tests were used to construct the empirical models representing clean coal ash and yield as process responses to the independent variables. The results obtained from the tests are presented in Table 6.

Table 6 also shows the predicted values of the process according to the variables. The actual model equations for ash and yield were as in Equations 1 and 2, respectively.

$$\begin{aligned} \text{Ash} = &-67.5 + 1.925\ \text{FD} + 1.075\ \text{IP} + 8.42\ \text{VFD} + \\ &+ 0.0038\ \text{FD} \cdot \text{FD} - 0.00361\ \text{IP} \cdot \text{IP} + 0.077\ \text{VFD} \cdot \text{VFD} - 0.0081\ \text{FD} \cdot \text{IP} - \\ &- 0.1727\ \text{FD} \cdot \text{VFD} - 0.0488\ \text{IP} \cdot \text{VFD} \end{aligned} \tag{1}$$

$$\begin{aligned} \text{Yield} = &-61.6 + 1.725\ \text{FD} + 1.85\ \text{IP} + 2.1\ \text{VFD} + \\ &+ 0.00691\ \text{FD} \cdot \text{FD} - 0.01107\ \text{IP} \cdot \text{IP} + 0.743\ \text{VFD} \cdot \text{VFD} - \\ &- 0.00315\ \text{FD} \cdot \text{IP} - 0.1531\ \text{FD} \cdot \text{VFD} - 0.0204\ \text{IP} \cdot \text{VFD} \end{aligned} \tag{2}$$

The actual and predicted values obtained using the model equations (Equations 1 and 2) are presented in Figure 1. The predicted values were matched with the experimental data points. The coefficients of determination (R^2) obtained for ash and yield are 0.9884 and 0.9899, respectively, indicating that the regression was significant as illustrated in Figure 1.

The significance test of model fit for clean coal ash and yield were performed using an analysis of variance (ANOVA). The results showed that both models were significant as the F values were high and the Prob > F(p-value) were lower than 0.05 (Table 7–8). A "lack-of-fit p-value" of >0.05 implies that the lack of fit is not significant for the model (Ye et al. 2017).

Table 6. Box-Behnken experimental design matrix using three-levels and three-factors and their predicted results

Tabela 6. Macierz schematu eksperymentalnego Boxa-Behnkena z wykorzystaniem trzech poziomów i trzech czynników oraz ich przewidywane wyniki

Experiment	FD (%)	IP (kPa)	VFD (cm)	Actual values		Predicted values	
No				Ash (%)	Yield (%)	Ash (%)	Yield (%)
1	10	35	6.5	18.89	38.62	18.19	37.18
2	10	45	7.5	27.68	55.49	27.66	55.29
3	20	25	6.5	20.02	34.56	20.72	35.53
4	20	45	8.5	36.15	72.74	35.45	71.77
5	30	25	7.5	31.69	52.74	31.71	52.94
6	20	35	7.5	27.99	52.87	28.86	54.22
7	30	35	6.5	32.33	56.28	31.61	55.10
8	20	35	7.5	29.29	54.35	28.86	54.22
9	10	25	7.5	20.14	36.98	20.14	37.45
10	20	35	7.5	29.29	55.43	28.86	54.22
11	20	45	6.5	26.88	51.50	27.60	53.15
12	20	25	8.5	31.24	56.61	30.52	54.96
13	30	45	7.5	35.99	70.00	35.99	69.52
14	10	35	8.5	29.75	58.08	30.47	59.26
15	30	35	8.5	36.28	69.62	36.98	71.07

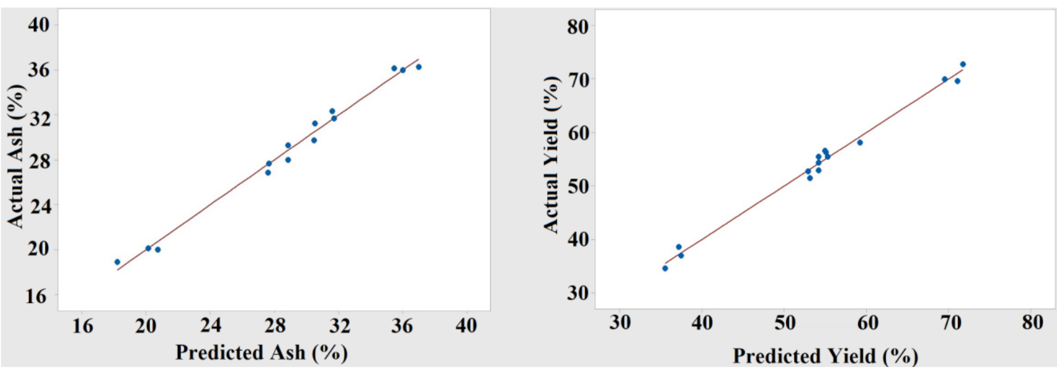

Fig. 1. Relationship between observed and predicted values

Rys. 1. Związek między wartościami obserwowanymi i przewidywanymi

Table 7. ANOVA table derived for the clean coal ash model

Tabela 7. Tabela ANOVA uzyskana dla modelu zawartości popiołu we wzbogaconym (czystym) węglu

	Degree of freedom	Sum of square	Mean square	F-value	Prob > F
Model	9	440.37	48.93	47.39	<0.0001
FD	1	198.37	198.37	192.10	<0.0001
IP	1	69.62	69.62	67.43	<0.0001
VFD	1	155.75	155.75	150.84	<0.0001
FD*FD	1	0.532	0.532	0.52	0.505
IP*IP	1	0.48	0.48	0.46	0.526
VFD*VFD	1	0.02	0.02	0.022	0.058
FD*IP	1	2.624	2.624	2.54	0.172
FD*VFD	1	11.934	11.934	11.56	0.019
IP*VFD	1	0.95	0.95	0.92	0.381
Lack-of-fit	3	4.031	1,344	2.37	0.31
Pure error	2	1.132	0.566		

Table 8. ANOVA table derived for the clean coal yield model

Tabela 8. Tabela ANOVA uzyskana dla modelu uzysku wzbogaconego węgla

	Degree of freedom	Sum of square	Mean square	F-value	Prob > F
Model	9	1,777.15	197.46	54.53	<0.0001
FD	1	441.99	441.97	122.05	<0.0001
IP	1	592.44	592.44	163.6	<0.0001
VFD	1	723.81	723.81	199.88	<0.0001
FD*FD	1	1.76	1.76	0.49	0.517
IP*IP	1	4.52	4.52	1.25	0.315
VFD*VFD	1	2.04	2.04	0.56	0.487
FD*IP	1	0.4	0.4	0.11	0.754
FD*VFD	1	9.37	9.37	2.59	0.169
IP*VFD	1	0.17	0.17	0.05	0.839
Lack-of-fit	3	14.8	4.93	2.98	0.261
Pure error	2	3.31	1.65		

The lack-of-fit value was found as 0.310 and 0.261 for clean coal ash and yield, respectively. The predicted R^2 values of ash and yield models (0.8495 and 0.8640, respectively) show consistency with the adjusted R^2 values (0.9676 and 0.9718), the difference between these two values was lower than 0.2 for both models.

3.1.1. The effect of feed density and inlet pressure

The effect of feed density (%) and inlet pressure (kPa) on ash (%) of clean coal at the center level of the vortex finder diameter is shown in Figure 2. As can be seen, a lower ash content was obtained at lower levels of feed density and inlet pressure. This may be ex-

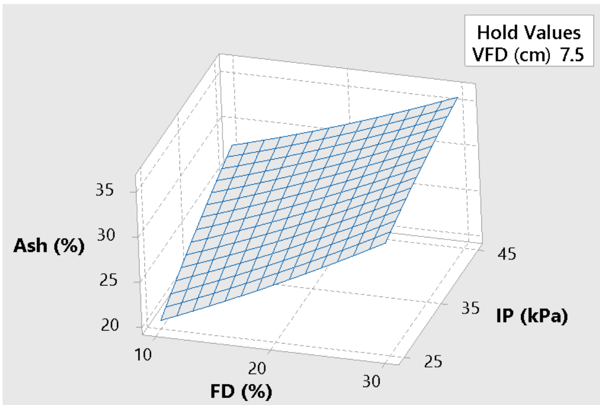

Fig. 2. Effect of FD and IP at the center level of VFD on ash content of clean coal

Rys. 2. Wpływ gęstości nadawy (FD) i ciśnienia wlotowego (IP) na środkowym poziomie wiru (VFD) na zawartość popiołu we wzbogaconym węglu

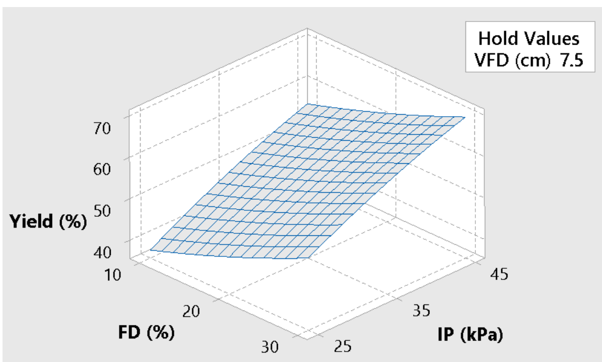

Fig. 3. Effect of FD and IP at the center level of VFD on yield of clean coal

Rys. 3. Wpływ gęstości nadawy (FD) i ciśnienia wlotowego (IP) na centralnym poziomie wiru (VFD) na uzysk wzbogaconego węgla plained by that at the higher solids concentration, the separation medium density increases; thus, a part of heavier and higher ash fractions reports to the overflow stream and results in an increase in the ash content of clean coal.

Figure 3 represents the effect of the feed density (%) and inlet pressure (kPa) on clean coal yield (%) at the center level of the vortex finder diameter. It can be observed in Figure 3 that the maximum yield was found at the maximum levels of feed density and inlet pressure. This may be attributed to the fact that separation medium density in the cyclone is increased and higher proportion of clean coal reports to the overflow. These effects were consistent with the results obtained in some previous studies (Wang et al. 2020; Abbas and Muhammad 2016).

3.1.2. The effect of inlet pressure and vortex finder diameter

Figure 4 illustrates the effect of inlet pressure and vortex finder diameter on the ash content of the clean coal at the center level of feed density. The higher feed pressure resulted in an increased flow rate and reduced the retention time of the particles. This led to heavy particles short-circuiting to the overflow without separation and increasing the ash content of the product.

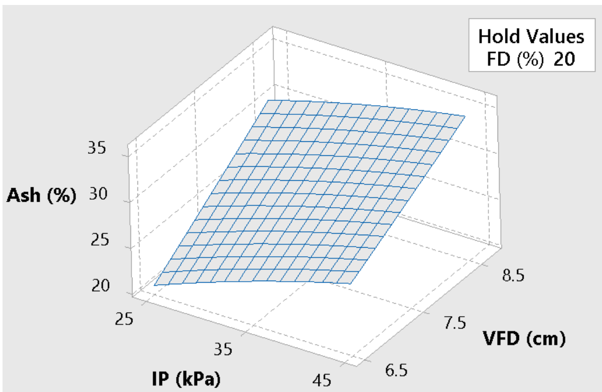

Fig. 4. Effect of IP and VFD at the center level of FD on ash of clean coal

Rys. 4. Wpływ ciśnienia wlotowego (IP) i wiru (VFD) na środkowym poziomie gęstości nadawy (FD) na zawartość popiołu we wzbogaconym węglu

Figure 5 shows the effect of inlet pressure and vortex finder diameter on the yield of clean coal in the WOC at the center level of feed density. Increasing the inlet pressure led to a higher yield due to the increased number of particles transported to the overflow. At higher feed pressure levels, the pressure drop between the spigot and cylindrical region increases exponentially and this leads to volumetric slurry split to overflow will increase (Majumder and Barnwall 2011).

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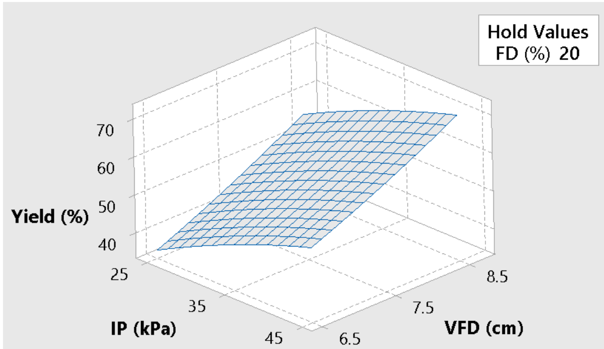

Fig. 5. Effect of IP and VFD at the center level of FD on yield of clean coal

Rys. 5. Wpływ ciśnienia wlotowego (IP) i wiru (VFD) na środkowym poziomie gęstości nadawy (FD) na uzysk wzbogaconego węgla

3.1.3. The effect of vortex finder diameter and feed density

Figure 6 shows the ash content of clean coal against the vortex finder diameter and feed density. The ash content of clean coal increased with increasing feed density and vortex finder diameter. With an increase in VFD, the volumetric slurry split to the overflow of the WOC increases because of the higher degree of passage for the flow of slurry through the vortex finder carrying a larger proportion of the feed water (Hembron and Suresh 2018). As the volumetric stream of the overflow increases, heavier particles tend to report overflow and this results in an increase in the ash content of clean coal.

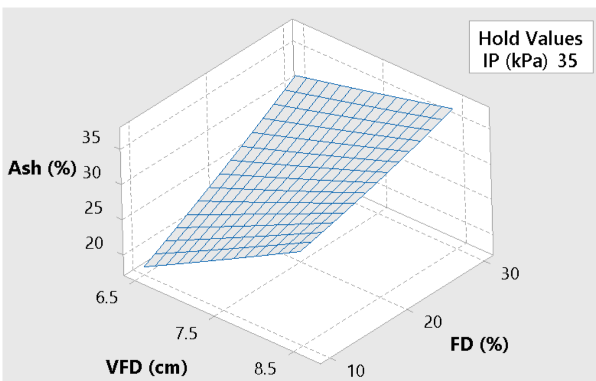

Fig. 6. Effect of VFD and FD at the center level of IP on ash of clean coal

Rys. 6. Wpływ wiru (VFD) i gęstości nadawy (FD) na środkowym poziomie ciśnienia wlotowego (IP) na zawartość popiołu we wzbogaconym węglu

Figure 7 demonstrates the effect of vortex finder diameter and feed density on the yield of clean coal at the center level of inlet pressure. The highest yield value was obtained by increasing both vortex finder diameter and feed density. This may be explained by the fact that at higher levels of vortex finder diameter, the amount of solids that were carried to the overflow increased and resulted in an increase in the yield of clean coal. Similar results were reported for the effect of VFD on ash and yield (Maharana and Suresh 2020; Majumder and Barnwall 2011).

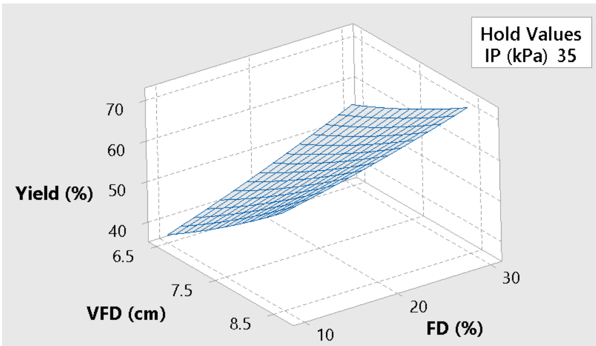

Fig. 7. Effect of VFD and FD at the center level of IP on yield of clean coal

Rys. 7. Wpływ wiru (VFD) i gęstości nadawy (FD) na środkowym poziomie ciśnienia wlotowego (IP) na uzysk wzbogaconego węgla

Conclusions

In this study, the effects of vortex finder diameter, feed pressure and feed density on the coal washing process by water-only-cyclone was investigated. Box-Behnken design and response surface methods were used to develop mathematical models for both ash content and yield of clean coal. Mathematical model equations were derived using experimental data and mathematical software package Minitab 17. The ANOVA results indicated that feed density and vortex finder diameter were more effective independent variables on the ash content and yield of the clean coal. The results of the numerical optimization in the range of the experimental data showed that it is possible to reduce the ash content of clean coal from 42.21% to 18.89%, with yield values of 72.74% and 38.62%, respectively.

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MODELLING OF FINE COAL BENEFICIATION WITH WATER-ONLY CYCLONE

Keywords

coal fines, water only cyclone, BBD-RSM, modelling

Abstract

In this study, a three-level Box-Behnken design of experiments combined with response surface methodology used to investigate the effects of the feed density, feed pressure and vortex finder diameter on the separation results (ash content and yield of the overflow) of a water-only cyclone. The coal used in the study was supplied from Soma, Turkey and crushed to below 1 mm. Experiments were conducted using a watter-only cyclone (WOC) which was operated in a closed-circuit test rig, overflow and underflow streams were collected and were sieved through 0.1 mm to simulate dewatering screens.The actual data collected from the tests were used to construct the empirical models representing clean coal ash and yield as process responses to the independent variables. The significance test of model fit for clean coal ash and yield were performed using analysis of variance (ANOVA). The results showed that ash content and yield of the clean coal models were significant.The results showed that with an increase in vortex finder diameter (VFD), feed density (FD) and inlet pressure (IP), ash content and yield of the clean coal increases. The results suggested that all main parameters affected the ash content and yield of the clean coal to some degree. The significance order of the effect of the variables on the ash content and yield was found as FD > VFD > IP and VFD > IP > FD respectively. The results of the numerical optimization in the range of the experimental data showed that it is possible to reduce the ash content of clean coal from 42.21 to 18.89.

MODELOWANIE WZBOGACANIA MIAŁU WĘGLOWEGO ZA POMOCĄ HYDROCYKLONU

Słowa kluczowe

miał, cyklon wodny, BBD-RSM, modelowanie

Streszczenie

W tym badaniu zastosowano trzypoziomowy projekt Box-Behnken eksperymentów w połączeniu z metodologią powierzchni odpowiedzi wykorzystaną do zbadania wpływu gęstości nadawy, ciśnienia nadawy i średnicy wiru na wyniki wzbogacania (zawartość popiołu i uzysk przelewu) w hydrocyklonie. Węgiel użyty w badaniach był dostarczany z Somy w Turcji i rozdrobniony poniżej 1 mm. Eksperymenty przeprowadzono przy użyciu hydrocyklonu (WOC – *Water-Only-Cyclone*), który pracował na stanowisku badawczym w obiegu zamkniętym, odbierano strumienie z przelewu i wylewu, które przesiewano przez sito o oczku 0,1 mm w celu symulacji procesów odwadniających. Rzeczywiste dane zebrane z testów zostały wykorzystane do budowy modeli empirycznych przedstawiających zawartość popiołu we wzbogaconym w węglu i uzysk tego węgla jako zmienne niezależne. Test istotności dopasowania modelu dla zawartości popiołu we wzbogaconym węglu i uzysku węgla przeprowadzono za pomocą analizy wariancji (ANOVA). Wyniki w modelach wykazały, że zawartość popiołu i uzysk wzbogaconego węgla były znaczące; wraz ze wzrostem średnicy wiru (VFD – *Vortex Finder Dimeter*), gęstości nadawy (FD – *Feed Density*) i ciśnienia wlotowego (IP – *Inlet Pressure*), zawartość popiołu i uzysk wzbogaconego węgla wzrasta. Wyniki sugerowały, że wszystkie główne parametry w pewnym stopniu wpływają na zawartość popiołu i uzysk wzbogaconego węgla. Kolejność istotności wpływu zmiennych na zawartość popiołu i uzysk określono odpowiednio jako FD > VFD > IP i VFD > IP > FD. Wyniki optymalizacji numerycznej w zakresie danych eksperymentalnych wykazały, że możliwe jest zmniejszenie zawartości popiołu we wzbogaconym węglu z 42,21 do 18,89%.