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Research Article

Process Optimization and Mathematical Modeling of Cartridge Filter Cleanup Using Pulse Jet Air Ring (PJAR) Technology

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Abstract

Dust abatement is frequently performed using filters. The biggest challenge facing filter usage in different industries, is to sustainably clean and recycle them in order to reduce costs and increase filtration quality. A novel technology of Pulse Jet Air Ring (PJAR) has been invented in order to consume less time and energy, and to emit less pollutants into the air. In this method, a ring is installed around the filter body which is able to jet the air with a high speed in order to remove the dust around filter media. To get the best results, optimization of effective process parameters is necessary. Central composite design (CCD) of response surface methodology (RSM) is employed to optimize the cleanup process. Based on statistical analysis and optimization, the highest Pressure Difference percentage is accessible at the air pressure of 5.10 Bar, Velocity 43.00 m/s and Time 50.00 ms. The technique can be recommended as an economical as well as environmentally friendly technology.

Keywords: Cartridge filter, Gas purification, Filter recovery, RSM, PJAR.

Introduction

Cartridge filters, including the pleated filter cartridge and bag filter, have the characteristics of high efficiency and good economy, and they are generally being used for gas purification. Bag filters and cartridge filters are being used for controlling the emissions of industrial particulates to the atmosphere and industrial working environments, including dust abatement systems which is widely used in air suppliers, mine industry as well as gas power plants. In recent years, cartridge filters have attached a great deal of attention, due to the fact that the filter cartridge offer a larger filtration surface when compared to the filter bags (if both filters are used in housing of the same size) (Yuan et al., 2021). In a cartridge filter, gas permeates into the filter media with low pressure. As a result, dust will remain on the surface of the filter and forms filter cake. Filter cake will cause the pressure drop and as a result, filter fouling. In the past 5 years, waste management has become a challenge and filter recycling is not cost-effective (Ho et al., 2021; He et al., 2021). Thus, the filter cake has to be removed, and the key and challenging problem in applying filters is the dust-cleaning system's design. Several ways have been discovered to clean filters, e.g., air-washing

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cleaning (Cho et al., 2020), Pulse jet (Peterson et al., 2022) and multi-plug filtration cleanup (Song et al., 2022). Current technologies are not sufficient enough and the most applicable technique is Pulse Jet. However, incomplete cleaning is usually a challenging problem for the Pulse Jet System (Xie et al., 2022). Technically, the technology has several limiting factors, including energy consumption, it can be used only in short time and may cause cartridge filter media damage. A novel technique of Pulse Jet Air Ring (PJAR) is developed. PJAR technology can be widely used in different industries including Gas power plants, due to their high dust removal efficiency and easy operation (Dembiński et al., 2021). The gas power plant provides the power demand entirely through gas firing in a gas turbine (Rashid et al., 2019). There are many ways to increase the gas turbine output, e.g., controlling air filtration systems. Filter-effectiveness creates less fouling and deterioration, which is the key to maintaining higher efficiency and power (Gul et al., 2020).

Due to the complex and harsh environmental factors, the useful life of the filter in the gas turbine air intake system is usually less than its design life, and after filter degradation, the efficiency of the turbine will decrease noticeably as a result of the increase of inlet pressure loss (Jin et al., 2021). PJAR system has been designed in order to improve filters effectiveness and life, as a result of regenerating filter medium. In this process, pressure to the upper limit (ΔPmax) will be increased with short duration pulses of high pressure in the reverse direction. In this scenario, the air jet must generate a sufficiently powerful air-induced pulse to disintegrate the dust cake (Shim et al., 2017; Qian et al., 2015). Due to the Coanda effect, compressed air will push up the dust and peel it from the dirty surface of the filter. This sequence of filtration and cleaning is called a "cycle," and the new cycle begins when the pulse stops (Furumoto et al., 2021; Fukasawa et al., 2022). Previous researchers found that design and operating parameters such as nozzle diameter, nozzle type, jet distance, pulse duration, and filter material influence cleaning performance in filters (Li et al. 2018; Li et al., 2021a; Mukhopadhyay et al., 2021).

In this study, the innovative method of PJAR was examined and optimized by central composite design (CCD) of response surface methodology (RSM). This study aims to optimize effective process parameters to achieve the highest efficiency for cartridge filter cleanup. Additionally, the synergistic effect between Velocity and Pressure was analyzed.

Material and Method

Cartridge Filter

The exact details of the cartridge filter used in this experiment are listed in table 1. The filters were purchased from Andishe Shomal Company, Rasht, Iran. The experiments were done under the American Society for Testing and Materials (ASTM) laboratory standards (F2704-17A).

Table1. Cartridge filter properties

OD	325 mm
ID	210 mm
Length	864 mm
Material	Synthetic Cellulose

Experiments

Experiments were carried out at research and development department zist filter company Tehran Iran and Montazer Ghaem power plant, Karaj Iran.

Based on literature and preliminary study, the range of data was selected. Three parameters of Velocity, Pressure and Time were examined as independent factors, and filter efficiency was monitored as a response. PJAR technology was employed using a steel ring (Diameter 32 cm).

Data Analysis

The experimental plan is made using central composite design (CCD) of response surface methodology (RSM), which is the most popular and purposive tool in different optimization reaction conditions, including biodiesel synthesis (Zahed et al., 2021) and material adsorption and production (Gul et al., 2021; Kowalczyk et al., 2021).

The main goal of this method is to determine the influence of these factors on the output result and consequently optimize these responses (Lafifi et al., 2019). The RSM mechanism involves understanding the topography of the response surface, including the local maximum, local, minimum, and ridgelines, and finding the region where the most appropriate response occurs (Chong et al., 2021). Several researchers used response surface methodology to optimize the process parameters in casting, welding, and machinability (Chelladurai et al., 2021). There are three significant steps for optimization by the RSM method. First, the experiment should be designed statistically. The designed experiments are introduced as Run Numbers. The next step is to estimate the coefficients in a mathematical model, and then the response should be predicted and checked (Pereira et al., 2021). These amounts are presented in table2.

Applying the RSM method in the optimization process has the potential to save time, as only a short period is required to test all of the variables pertaining to the consumer evaluation. In addition, parameters estimation can identify the variables that mainly affect the model, which helps the researcher focus on those particular variables that contribute to the product acceptance (Antony et al., 2020). Existing CCD studies can be classified into three major groups, based on the previous CCD applications, including optimizing the raw materials and preparation condition to achieve the optimal performance or the most economical mix design results, adding new components to investigate the performance range, and combining with other modeling techniques and then evaluating the feasibility (Li et al., 2021b).

The experimental data acquired by the mentioned procedure is analyzed statistically by response surface regression method using the following quadratic polynomial equation:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i \neq j=1}^{n} \beta_{ij} x_i x_{ij} + \varepsilon \tag{1}$$

Where Y shows the response percentage of Pressure Difference (PD), β_0 is the value of the fixed response at the central point of the design, β_i, β_{ii} and β_{ij} are the linear, quadratic and interaction-effect regression terms, respectively. x_i and x_j are the coded values of independent variables and ε is the random error.

Results and Discussion

The experimental measurements are analyzed mathematically by the 3-D regression model designed by CCD. This design is based on the independent variables in a frame of the regression equation. Analysis of variance (ANOVA) for the response surface quadratic models is performed to check the quality of the models and determine the major and minor influences of the machining factors considered in the present analysis along with their interaction terms on the formation of responses. In the experiment, performance after eliminating the insignificant coefficients (table 3) is as follows:

$$Yield\ (\%) = +72.73 + 3.90\,A + 4.68\,B - 10.24\,C - 4.98\,A^2 - 9.38\,B^2 + 8.12\,C^2 \tag{2}$$

Table 2. Test (experimental) Matrix Designed by CCD.

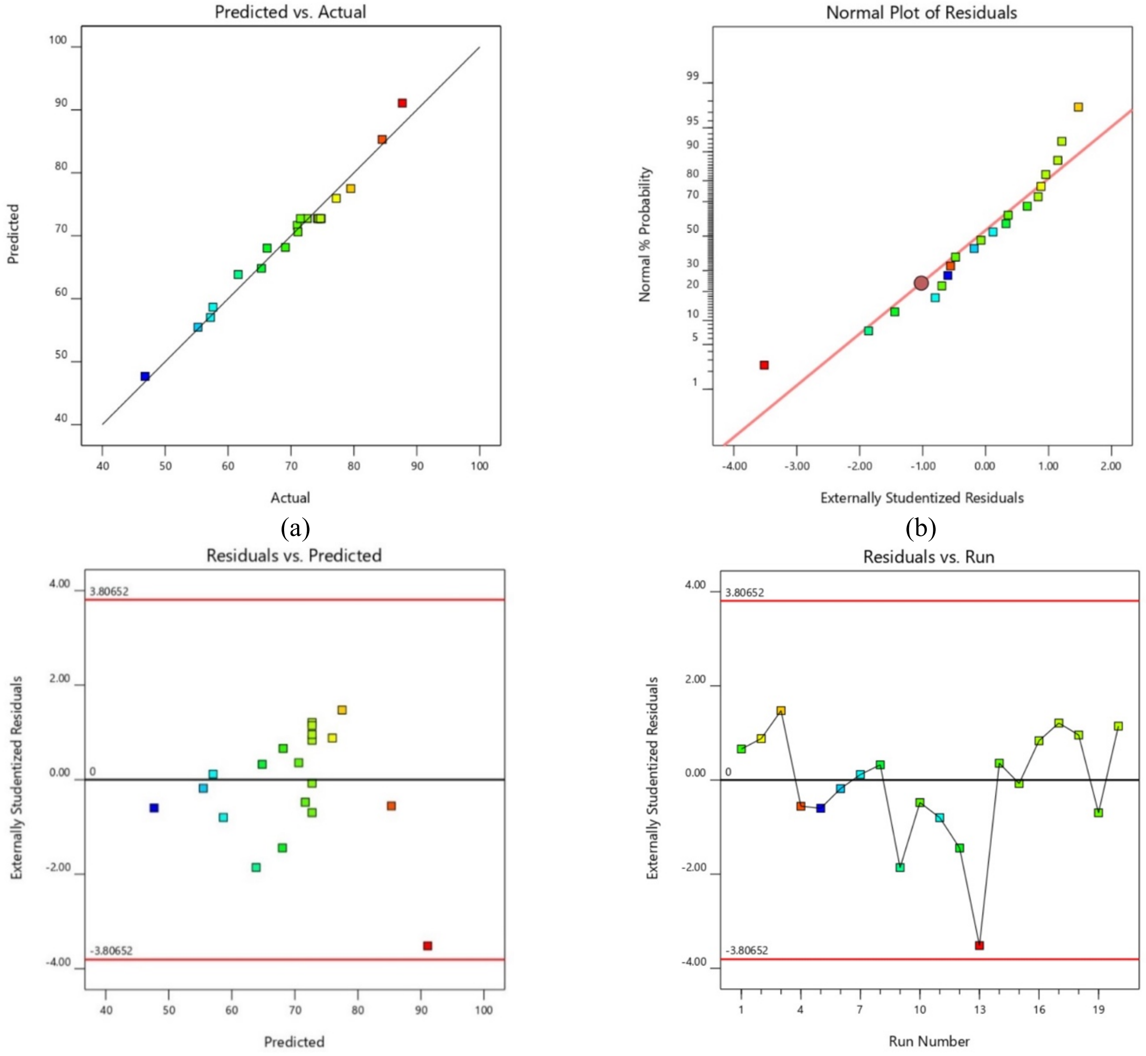
Run	Factor 1 A:Pressure Bar	Factor 2 B:V m/s	Factor 3 C:T Ms	Response 1 PD %
1	4	30	50	69.1
2	6	30	50	77.2
3	4	50	50	79.5
4	6	50	50	84.5
5	4	30	100	46.8
6	6	30	100	55.2
7	4	50	100	57.2
8	6	50	100	65.3
9	4	40	75	61.6
10	6	40	75	71
11	5	30	75	57.6
12	5	50	75	66.2
13	5	40	50	87.7
14	5	40	100	71.1
15	5	40	75	72.6
16	5	40	75	74.2
17	5	40	75	74.8
18	5	40	75	74.4
19	5	40	75	71.5
20	5	40	75	74.7

The value of Lack of fit for the model is non-significant, suggesting that the quadratic model is valid for this cleanup process. The lack of fit F-value of 2.47 indicates the lack of fit is not significant relative to the pure error. This standard deviation and mean are 1.85 and 69.61, respectively, and the coefficient of variation (CV) is 2.66. R-squared is 0.9770. The predicted R-squared is 0.9346 and it is a reasonable agreement with the adjusted R-squared of 0.9664. The predicted error sum of squares (PRESS) provides useful residual scaling and it is 126.78 for this model.

Adequate precision statistic, which is a signal-to-noise ratio comparing the range of the predicted values at the design points to the average prediction error, is 39.6644. Ratios greater than 4 indicate adequate model discrimination. Diagnostics plots were generated to ensure quality of modeling. As presented in figure 1, plots of predicted versus actual, normal plot of residual, residual versus predicted and residual versus run showed the model is adequate.

Table 3. Analysis of variance for the quadratic model

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	p-value	
Model	1894.20	6	315.70	92.19	< 0.0001	significant
A-Pressure	152.10	1	152.10	44.42	< 0.0001	
B-V	219.02	1	219.02	63.96	< 0.0001	
C-T	1048.58	1	1048.58	306.21	< 0.0001	
A^2	68.25	1	68.25	19.93	0.0006	
B^2	242.05	1	242.05	70.68	< 0.0001	
C^2	181.24	1	181.24	52.93	< 0.0001	
Residual	44.52	13	3.42			
Lack of Fit	35.52	8	4.44	2.47	0.1675	not significant
Pure Error	9.00	5	1.80			
Cor Total	1938.72	19				



(a) (b)

(c) (d)

Figure 1. Statistical plots of testing design: (a) predicted versus actual; (b) normal plot of residual; (c) residual versus predicted; (d) residual versus run

As presented in figure 2, the synergetic effect between Velocity and Pressure is notable. When the PJAR cleaning is initiated, the injector nozzle blows a high-velocity primary jet to the bag. Air injection raises the pressure inside the bag. Thus, the air will flow opposite to normal operating flow. These mechanisms are important and essential to achieving cleaning efficiency (Dutta et al., 2021). Several parameters affect the dust-cleaning performance, including tank pressure, nozzle diameter, number and type, and jet distance (Huang et al., 2021). However, further researches will clarify the application of venturi, built-in baffles, or cones in the filter cartridge has achieved an excellent pressure-equalizing effect (Lin et al., 2021; Yuan et al., 2021).At the pressure of 74, the highest cleanup efficiency is acceptable, as shown in figure 3.

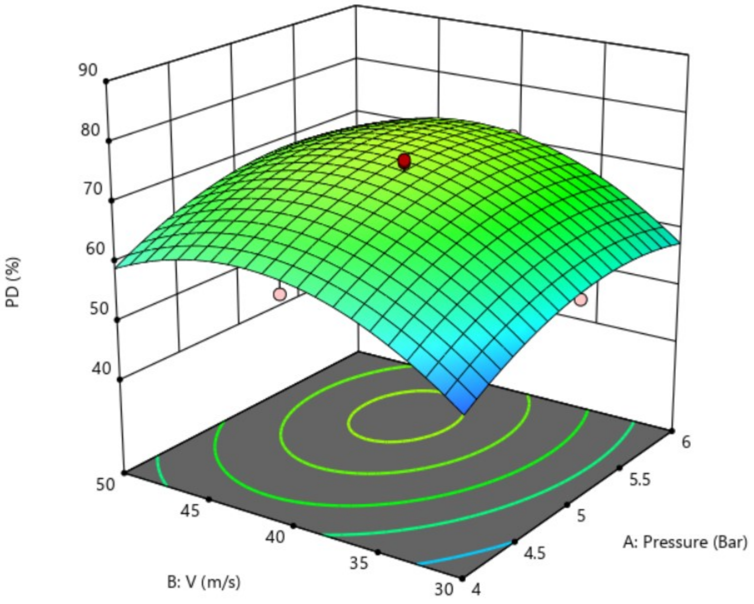


Figure 2. Three-dimensional (3D) plot between V and P against PD

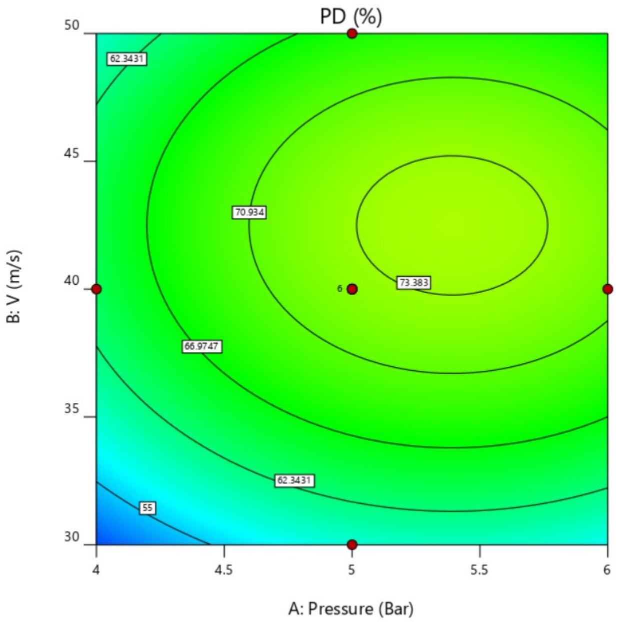


Figure 3. Showing the synergistic effect of Velocity and Pressure

Optimization

RSM-provided suggestions carried out optimization. The goal was to achieve maximum PD percentage. The numerical optimization criteria were set due to each factor's characteristics, as mentioned in table 4. The time factor was set equal to 50, as it is hard to change. The highest PD percentage was achieved at the levels mentioned in table 5. Optimization result by RSM illustrated in figure 4.

Table 4. Numerical optimization criteria

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Pressure	is in range	4	6	1	1	3
B:V	is in range	30	50	1	1	3
C:T	is equal to 50	50	100	1	1	3
PD	maximize	46.8	87.7	1	1	5

Table 5. Optimized condition provided by RSM

Number	Pressure	V	T	PD	Desirability
9	5.10	4300	50.00	91.99	1.00

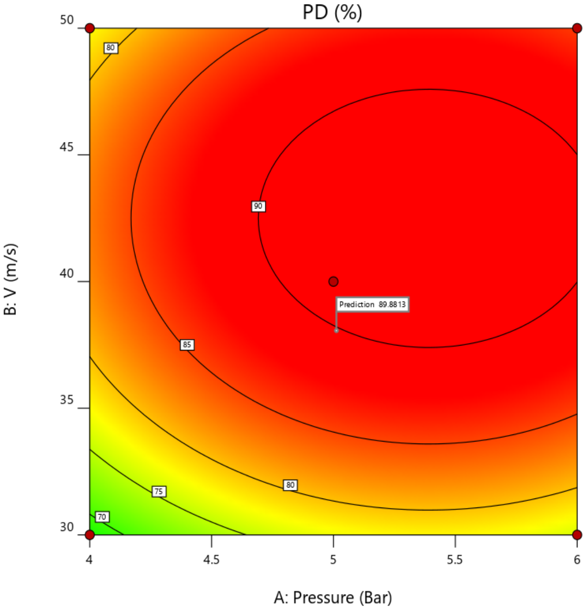


Figure 4. Optimization result by RSM

PJAR is an innovative and novel method that has been successfully used in recent experiments. The PJAR has more minor disadvantages and more profits than other similar methods. Cartridge filters are mainly hard to clean in the bottom of the long filter bag. It can show the cartridge filter's problematic cleaning and uneven cleaning in its general applications, which puts forward higher requirements for the PJAR cleaning system (Jin et al., 2021; Ren et al., 2022). Cleaning is crucial to optimize the utilization of PJAR filters. Still, it is at the origin of continuous energy consumption, as it is usually carried out by changing the flow direction in the filter, regardless of the clogging of the filter. This will cause about 80% of the dust accumulated on the filter bags to fall into the silo floor where the filter bags are located with the effect of gravity, while the remaining part sticks to the filter bags around (Çankaya and Özcan, 2019). However, these filters must be replaced regularly, as they are vulnerable to damage. Optimization of dust cartridge filter cleanup systems are important and critical. Recent published data related to cartridge filter cleanups are presented in table 6.

Table 6. Study results of researches about the cartridge filter cleanup optimization.

Study Result	Reference
an optimum nozzle diameter and jet distance could achieve improved pulse jet cleaning effectiveness	Li et al. 2019 c
supersonic nozzles can improve static pressure uniformity on the inner wall of the cartridge	Yan et al. 2013
A novel time-differenced colliding pulse jet method is put forward and tested. The results show that the non-time-differenced colliding pulse jet mode increased the pulse jet intensity obviously compared with the one-way pulse jet mode.	Li et al. 2019 a
The optimum jet distance and the peak pressure along the length of the filter cartridge was introduced.	Qian et al. 2018
A built-in rotator was developed to clean the pleated filter cartridge	Li et al. 2019 b
The effects of diversion device types on the pulsejet cleaning were researched.	Yuan et al. 2021
the parameters of the pulse jet cleaning system were optimized by observing the influence of cleaning order and pulse interval on the cleaning performance of the cartridge filter	Jin et al. 2021

The quality of the cleaning may be reduced when the filter cartridges are applied to collect particles in humid air (Schwarz et al., 2021). However, the effect of air humidity on filtration performance of filtering media is not entirely understood, as it depends on several parameters such as the hydroscopicity of the particles, their size, the nature and size of the fibers, and their ability to sorb water, or the loaded mass of particles on the filter (Boudhan et al., 2019; He et al., 2021). It should be mentioned that the performance of the filters can be improved using different types of surface treatments, and this method is used to overcome the disadvantages. For example, fibrous filters modified with microporous membranes and smooth anti-adhesive thermally-bonded surfaces are employed to achieve high efficiency in the collection of fine particles (Cirqueira et al.; 2019, Boudhan et al., 2018).

Conclusion

There are several ways to clean a filter from dust and pollutions. This step is crucial for all filtration methods, as it can reduce costs and save energy. The PJAR mechanism is one of the most promising filter cleaning methods that can be investigated through different procedures. Comparing to other available cleaning methods, PJAR technology consumes less time and energy. Besides, unlike other available methods, PJAR system will not reduce filter's lifespan, as in this method the air is not pulsed into the filter directly. In summary, the present work contains an innovative work using CCD of RSM, by which there is a mathematical equation presented to optimize the factors affecting the process. The final optimization results indicate that the best PD percentage occurs at the Pressure 5.10 Bar, Velocity 43.00 m/s and Time 50.00 ms.

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