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Determination of High Efficiency Standard Cyclone Performance Using Numerical Methods

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Abstract

The cyclones, one of the dust collection devices, are used to separate the particles or liquid from the carrier gas by centrifugal forces. They have been widely applied in gas-solid separation for an industrial air cleaning process. In addition to being economical, their simplicity of constructions, lack of moving parts, and adaptation to high pressure and temperature conditions make these devices durable and efficient. On the other hand, in the operation of cyclones, the effects of particle, carrier gas, cyclone dimensions, and other factors are very important operational requirements in determining the cyclone performance. In the cyclone design, the terms of pressure drop, and cut-off diameter determine the cyclone performance. In addition, cyclone geometry plays an important role on changes in pressure drop and cut-off diameter values. In this study, high efficiency standard cyclone geometric structure is studied, and this structure is modelled using Solidworks program. Computational Fluid Dynamics (CFD) was used to determine of cyclone separation performance. In the scope of the study, flow analysis is performed, and cut-off diameters are tried to be determined by using statistical learning methods from the results of the analysis.

Keywords: High-efficiency cyclone, Flow simulation, Cut-off diameter, Pressure drops, Particulate matter

Yüksek Verimli Standart Siklon Performansının Nümerik Yöntemler Kullanılarak Belirlenmesi

Öz

Siklonlar, santrifüj kuvvetler etkisiyle, katı ya da sıvı partikülleri gaz taşıyıcıdan ayırmaya yarayan toz toplama cihazlarıdır. Endüstriyel alanlarda hava toz temizleme proseslerinde çok yaygın olarak kullanılmaktadırlar. Ekonomik olmalarının yanı sıra çok fazla hareketli parça içermemeleri, yüksek basınç ve sıcaklık uygulamalarına uyum sağlayabilmeleri bu cihazları dayanıklı ve verimli kılmaktadır. Öte yandan siklonların çalışmasında, partikülün, taşıyıcı gazın, siklon boyutlarının ve diğer faktörlerin etkileri siklon performansı belirlemede oldukça önemlidir. Siklon dizaynında, basınç düşmesi ve kesme çapı değerleri siklon performansını belirleyen parametrelerdir. Bu anlamda siklon geometrisi basınç

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düşümü ve kesim çapı değerlerindeki değişiklikler üzerinde önemli bir rol oynamaktadır. Yapılan bu çalışmada yüksek verimli standart siklon geometrik yapısı üzerinde çalışılmıştır ve bu yapı Solidworks programı ile modellenmiştir. Bilgisayar destekli Akış Analizi (CFD), siklon performansını belirmek için kullanıldı. Çalışma kapsamında akış analizleri yapılmış, analiz sonuçlarından istatistiksel öğrenme yöntemleri kullanılarak kesme çapları belirlenmeye çalışılmıştır.

Anahtar Kelimeler: Yüksek verimli siklon, Akış simülasyonu, Kesme çapı, Basınç kayıpları, Partikül madde

1. INTRODUCTION

Inertial dust collectors are generally divided into three main groups as deposition chambers, baffles, and cyclone dust collectors. The cyclone dust collectors or cyclone separators are one of the most efficient, important, and robust dust control devices in the field of both science and engineering [1]. Robustness is expressed by their higher ability to extreme operating conditions and lack of moving structures [1]. Cyclone Separators (CS) are widely used for aerosol sampling and industrial applications, in air pollution control and gas-solid separation [2]. The centrifugal force generated in cyclone separates solid particles from the air through the densities difference of gases and solids [3]. Significant advantages of cyclone separators as their simplicity to fabricate; low cost to operate, and maintenance; their capability of adaptation to extremely harsh conditions such as high temperature, high particulate matter (PM) loads, high corrosiveness (because of corrosive gases), high pressures were underlined for particulate control in air pollution control field [1,4-6]. However, their main disadvantages are pressure drop and low collection efficiency for fine particulate matter. Besides the advantages and disadvantages of cyclones, performance parameters are also very important. Pressure drop is the main part of cyclone performance. Performance and flow surfaces in cyclones can be considered as a function of cyclone dimensions, particulate properties, gas, and flow other parameters [1]. According to Demir [6], the cyclone pressure drop is the function of these parameters such as temperature, high solid loading; on other hand pressure drop related to collection efficiency. He showed that an increase in pressure drop increases collection efficiency [6]. As a result, the determination of pressure drop is a crucial application for design criteria. The performance usually described in cyclones is the sum of the pressure drop and collection efficiency [4]. Another important parameter for cyclones is cyclone geometry. Because the cyclone geometry also has significant effects on pressure losses and collection efficiency. In addition, experimental studies and simulations have revealed that the pressure drop and collection efficiency are a function of the cyclone geometry [4]. Cyclone inlet structures and configurations are among the geometric parameters by setting the cyclone options at the most [7]. In order to reveal the effects of cyclone geometry on cyclone efficiency, different approaches have been proposed: mathematical models, experimental measurements, computer aided flow dynamics, optimization methods, and artificial neural networks. For instance, Dirgo and Leith Stairmand [8] studied the collecting efficiency and pressure losses at various flow rates in the high-efficiency cyclone and wanted to empirically test the results. On the other hand, Griffiths and Boysan [17] examined the three cyclone samplers and calculated the pressure losses associated with CFD data very well. CFD provides the best possible flow dynamics in cyclone separators. Nowadays, optimal cyclone design is being used by using computer-aided methods in order to increase particle collection efficiency and reduce pressure drops [9,10]. However, the performance of the cyclone is greatly influenced by geometric design and operating conditions [11]. Pressure drops and partial collection efficiencies are defined as basic cyclone performance [11]. Particle removal or collection efficiency is a function of complex three dimensional and two-phase turbulent flow [12], the pressure drop is the sum of local and frictional losses [6] and fractional efficiency related to percent efficiency to the particle diameter [13]. The determination of an accurate cyclone pressure drop is concerning operating costs directly [14]. Considering these factors, flow regimes and various geometric designs in cyclones should be determined with the help of mathematical models [11]. In this sense, CFD applications can be seen as very useful tools. Recently, in order to improve cyclone performance, change in the geometric structure and properties of the cyclone have been made in the numerous studies. [15]. CFD use Reynolds Stress Model (RSM), Large Eddy Simulation (LES), e.g. in order to calculate velocities, pressures, particle moving, e.g. in turbulent flow.

In this study, High Efficiency Stairmand Cyclone structure is modeled by using the SolidWorks program and its performance is determined by numerical methods.

2. MATERIALS AND METHODS

In the present study the cyclone geometry was created by using Solidworks solid modeling and simulation program based on the High Efficiency Stairmand Standard Cyclone. The flow analysis were completed, and particle collection efficiencies obtained with uniform dispersed particulate matter using particle study tool. Based on the used statistical data obtained from particle study, it was found the cut-off diameter value according to the logistic regression method. The maximum likelihood method was used in the logistic regression. Maximization of the likelihood equation used to gradient ascent algorithm. The pressure drop value were also analyzed.

2.1. Cyclone Modelling

Based on the cyclone design and operation conditions, there are many types of cyclones to separate dust from the gas-particle mixture [16]. In this study, modeling and analysis were performed using high efficiency standard (Stairmand, 1951) cyclone sizes [17]. Basically, there are two types of standard cyclone, high throughput, and high efficiency, in terms of pressure drop and collection efficiency [17]. Since this study is efficiency based, the analyzes were carried out in high efficiency cyclone approach of Stairmand. The modeled cyclone is shown in Figure 1 and its geometrical dimensions such as inlet height (H), inlet width (W), vortex finder diameter (De), body height (Lb), cone height (Lc), vortex finder length (S), cone tip diameter (Dd) (proportional dimensions according to cyclone diameter) of the cyclone are given in in Table 1. In addition, the general structure of the cyclone is outlined as in Figure 2 and the cyclone diameter (D) is taken as $200\ mm$.

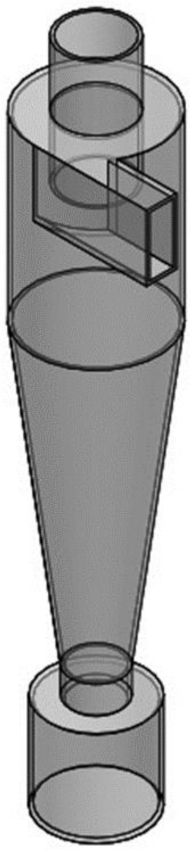

Figure 1. Isometric view of stairmand high efficiency standard cyclone

Table 1. Geometrical dimensions according to cyclone diameter

H/D	W/D	De/D	Lb/D	Lc/D	S/D	Dd/D
0.5	0.2	0.5	1.5	2.5	0.5	0.375

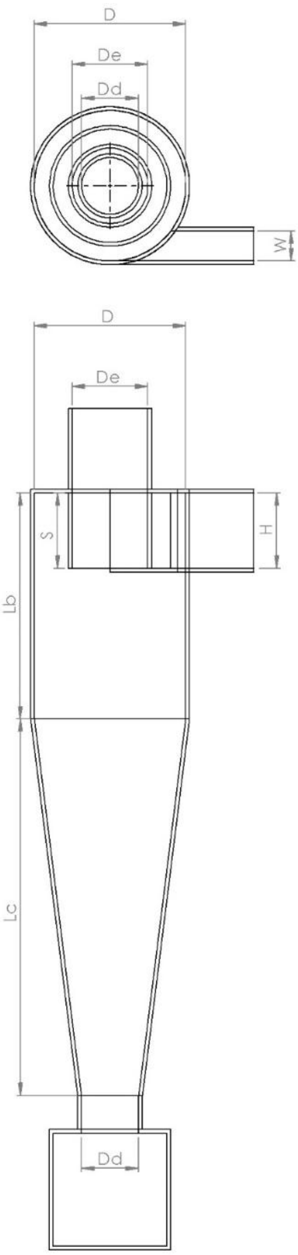

Figure 2. Schematic of studied cyclone separator

2.2. Flow Analysis with Computational Tools

Analysis of turbulent or laminar gas-particle flows in cyclone separators is carried out in computational tools. While making analysis, the most appropriate materials are selected. In the present study Talcum Powder is taken as the particulate matter. It has been studied by selecting suitable parameters for high efficiency cyclones. Hexahedral mesh structure was used to grid cyclone.

2.2.1. Flow Simulation

The gas flow in the cyclone is assumed to be turbulent flow regime for present study. The CFD approach, which has been widely used for simulation of gas cyclones, is applied to determine cut-off diameter and pressure drop.

In this section, for simulations temperature, pressure, relative humidity, gravitational acceleration, turbulence density, and turbulence length are 293.2 K, 101325 Pa, 50%, 9.81 m/s^2, 2%, and 2 mm, respectively. Air is selected as the fluid material and fluid dynamic viscosity, specific heat, and thermal conductivity graphs are given in Figures 3, 4, and 5.

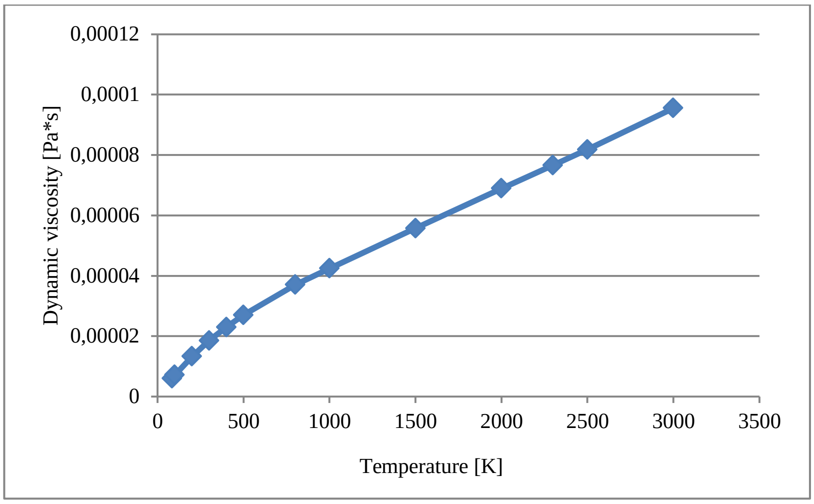

Figure 3. Dynamic viscosity of fluid

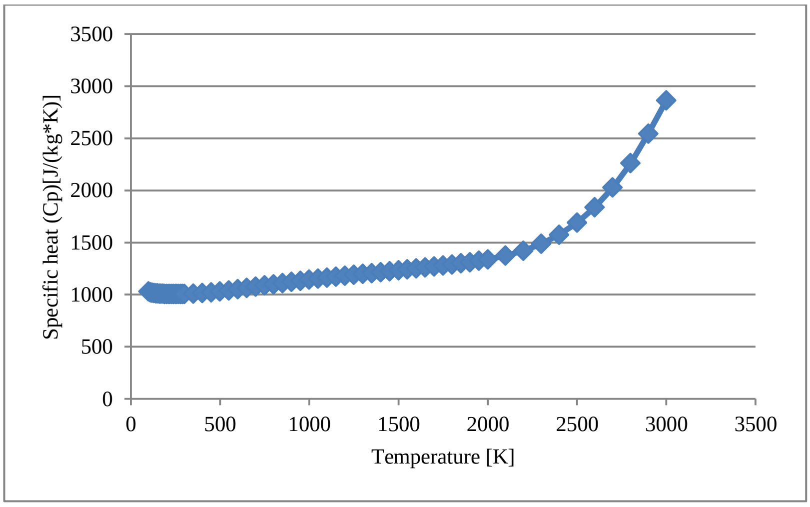

Figure 4. Specific heat of fluid

Adiabatic wall conditions were chosen as the cyclone wall conditions. In flow analysis, the inlet velocity of the fluid is 20 m/s; the cyclone outlet pressure is set to 101325 Pa and other boundaries was selected as wall.

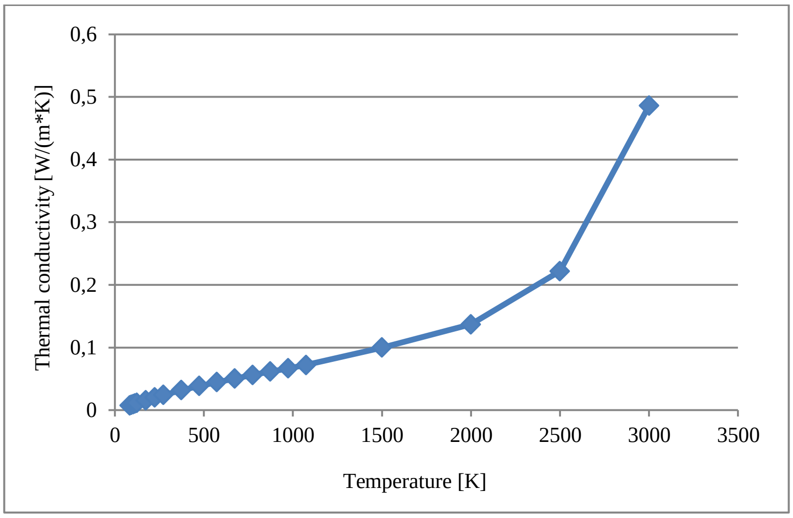

Figure 5. Thermal conductivity of fluid

2.2.2. Particle Study

In the current CFD study, the particle diameters were determined ranging from 1 micron to 10 microns with ten different classes and particles velocity equal to the fluid (air) velocity for inlet boundary. The relevant particle diameter range was determined in the particle study section of the CFD. The total particle concentration was 30 g/m^3 entering to this cyclone uniform distributed and concentration of 3 g/m^3 for each diameter. Because of the Talcum Powder widely used in cyclone separator, it was preferred in the current study. The Talcum Powder density, specific heat, thermal conductivity, and melting temperature are 2700 kg/m^3, 870.84 J/(kg.K), 7 W/(m.K), and 1073 K, respectively.

3. RESULTS AND DISCUSSION

3.1. Pressure Drops

The performance of the cyclones is expressed as the sum of the collection efficiency and the pressure drop. Figure 6 shows the contour plots of static pressure. However, the obtained pressure drop value was determined as 797.02 Pa.

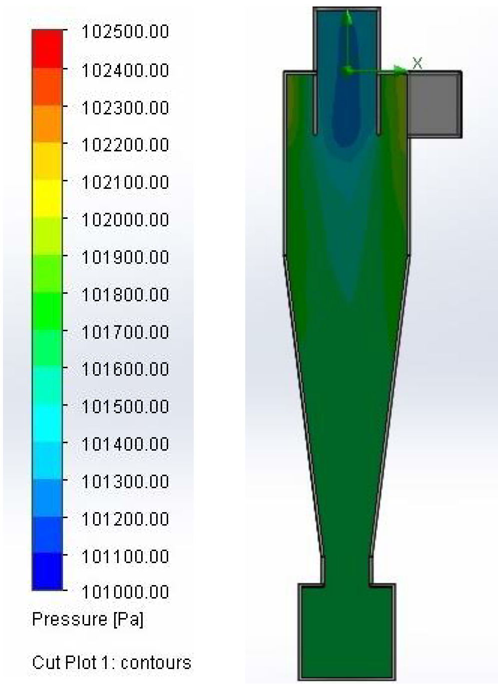

Figure 6. Pressure contour plot of working cyclone

3.2. Collection Efficiency

The Logistic Regression Method was used after obtaining particle collection efficiencies. The logistic regression equation is shown in Equation 1. Maximum likelihood approach was used to determine the coefficients. Likelihood function is defined by Equation 2. As underlined before, maximization of this function was performed gradient ascent algorithm.

$$P(Y=1|X=x)=\frac{e^{\beta_0+\beta_1 x}}{1+e^{\beta_0+\beta_1 x}} \quad (1)$$

$$l(\beta_0,\beta_1)=\prod_{i:y_i=1} p(x_i) \prod_{i':y_{i'}=0} (1-p(x_{i'})) \quad (2)$$

The coefficients are calculated as $\widehat{\beta}_0$=-7.458 and $\widehat{\beta}_1$=2.632. The statistical R^2=0.9893 for this regression process. This value reveals that regression is successful. The regression curve is shown in Figure 7.

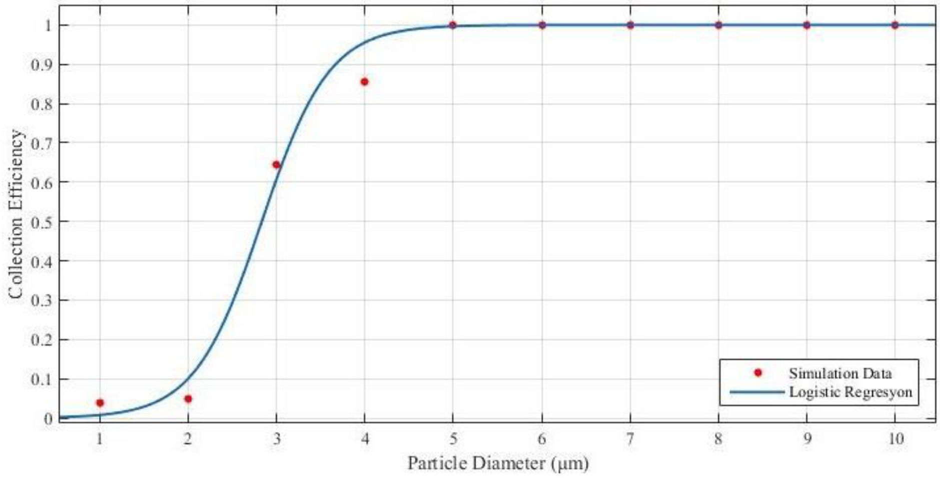

Figure 7. View of collection efficiency and logistic regression

Determination of the cut-off diameter $\widehat{d}_c$ value was made by substituting the $\widehat{\beta}_0$ and $\widehat{\beta}_1$ values in Equation 3. As a result, the cut-off diameter was found as $\widehat{d}_c$=2.834 μm.

In addition, tangential velocity, due to its effects on the particle separation process and pressure drops, it is an important component of gas flow in cyclones [4]. The tangential velocity increases with the increase of the inlet velocity. In cyclones separators, collecting efficiency increases with tangential velocity. Similarly, increasing the particle density increases the collection efficiency.

3.3. Model Validation

To validate the CFD analysis, the experimental cyclone study by Karadeniz [18] is simulated and the CFD results are compared with the corresponding measured data. The present model is capable of determining the collection efficiency and pressure drops in cyclones acceptable accuracy.

4. CONCLUSIONS

More recently the CFD techniques have been applied to design of cyclone separators and it predict performance parameters are governed by operational and geometrical elements. Furthermore, pressure drops, collection efficiencies of cyclone were easily predicted with CFD which is becoming most important component of processes. In contrast to experimental studies, CFD is cost and lead times effective methods. These features make CFD effective and preferred.

Improving the collection efficiency and pressure drop in cyclone separators is the most important step. The effects of geometric properties of cyclone on the cut-off diameter and pressure drop were determined for the Stairmand High Efficiency Cyclone Separator in present study. Cut-off diameter is important in determining the characteristic of cyclones. The cut-off diameter is the particle size where the cyclone collection efficiency is 50%. For the geometries and operating conditions of cyclones, it is important to know the cut-off diameter [11]. For that reason, many investigations carried out about cyclone purposed to understanding calculation of cut-off diameter.

In this study, the particle cut-off diameter was found to be 2.834 μm in the given working conditions based on the high-efficiency cyclone geometry, using the numerical and statistical learning methods. In addition, the resulting pressure drop value was determined as 797.02 Pa.

The statistical learning method used to determine the particle cut-off diameter successfully. This study also showed that, result of successful modeling, performance of high efficiency cyclone can be revealed upon the computational tools.

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