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# Optimization of Cyclone Design Parameters using Java in Netbeans Integrated Development Environment (IDE) Programme

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**Abstract** Cyclones are one of the most common means of separating particulate matters from gases in the process industry. They have no moving parts and are relatively easy to operate but its flow pattern is not well understood. Thus, a considerable number of experimental and theoretical studies have been carried out by different authors on various ways for improving cyclone collection efficiencies and reducing its pressure drops. In this work, the calculations were carried out using a developed Java in NetBeans Integrated Development Environment (IDE) program. Two test problems based on Shephard and Lapple and Stairmand high efficiency cyclone configurations were used to validate the program output. The maximum deviation between program output and corresponding literature values are less than 1.5% for collection efficiency and pressure drop. In addition, an attempt was also made to optimize the performance of Stairmand high efficiency cyclone using a $3^3$ factorial design. The factors considered were cyclone inlet height, inlet width and exit gas diameter while the other dimensions were kept constant. The optimisation results indicate that overall collection efficiency is dependent mainly on the cyclone inlet duct dimensions while pressure is dependent on inlet duct dimensions as well as exit gas diameter. The regression equations obtained for calculating pressure drop, collection efficiency and cut diameter fit their respective data very well.

**Keywords** Cyclone; Optimization; Design Parameters; NetBeans Java; Cyclone Collection Efficiency; Cut-Size diameter

## 1. Introduction

Cyclones are devices used for sizing, classification and removing of particulate matter from process fluids (gases or liquids) at low cost and low maintenance. When the fluid is liquid it is called hydro cyclones while when the fluid is air (gas) it is called air (gas) cyclones. Gas cyclones are used in a variety of industries including cement, agricultural processing, mineral processing, wood working, paper and textile industries. Cyclones have no moving parts.

A cyclone consists of two parts namely the upper portion called the barrel and the lower portion called the cone. The dust laden feed stream enters the barrel tangentially at the top and moves downwards into the cone forming an outer vortex (spiral flow). The centrifugal force on the particles in the vortex separates them from stream. The particles are collected at the bottom of the cone while the inner vortex created in the reverse direction at the bottom of the cone causes the clean gas to exit at the top of the cyclone through the exit gas pipe [1]. The gas exit pipe is also called the vortex finder. The cyclone geometries are usually expressed as ratios of the barrel diameter also referred to as the cyclone diameter. The important cyclone dimensions are cyclone diameter, inlet height, inlet width, vortex finder (or exit gas) diameter, vortex finder length, cylinder height, cyclone total height, cone tip diameter.

Cyclones are available in different geometries. Some of these are given by Kuye et al [2] and Utikar et al [3]. They are generally classified as high-efficiency, high-throughput or conventional cyclone designs. Irrespective of the design, three parameters (collection efficiency, pressure drop and cut diameter) are used to assess the performance of the cyclone. The cut diameter is defined as the diameter of the particle for which the collection efficiency is 50%.

Although the operation of a gas cyclone is relatively simple, it is however not completely understood, partly as a result of the complicated flow pattern within the cyclone. Consequently, a considerable number of experimental and theoretical studies have been performed on cyclone separators with the aim of improving collection efficiencies and reducing pressure drops. These efforts can be classified into two ways: one way is to optimize the configurations and geometric dimensions of the cyclone separators; and the other way is to add additional parts to the cyclone separators [4]. A number of models have been developed by researchers for predicting the performance of cyclones. Some of these were dedicated collection efficiencies these include [5-12] while the others were for pressure drops [13-19]. Despite these numerous studies, cyclone optimization studies are quite limited in literature and many of these studies are not very coherent [19]. Swamee et al [20] investigated the optimum values of the number of cyclones to be used in parallel. Ravi et al [21] and Safikhani et al [22] performed a multi-objective optimization of cycloneseparators. Pishbin and Moghiman [23] applied genetic algorithm for optimum cyclone design while Els ayed and Lacor [24] optimized cyclone for minimum pressure drop using the Nelder–Mead optimization technique.

Apart from cyclone configurations and geometries, the fluid properties such as density and viscosity of the gas stream as well as the particle size and distribution are required to solve the model equations. Some of these equations are either not very simple or require a lot of computational efforts. In this study, the calculations were carried out using a developed Java in NetBeans Integrated Development Environment (IDE) programme. Two test problems based on Shephard and Lapple and Stairmand high efficiency cyclone configurations were used to validate the programme output. In addition, an attempt was also made to optimize the performance of Stairmand high efficiency cyclone using a $3^3$ factorial design. The factors considered were cyclone inlet height, inlet width and exit gas diameter.

## Materials and Methods

### Design Equations

A schematic diagram of a cyclone is shown in Figure 1. In this figure ‘a’ is inlet height and ‘b’ is inlet width while $D_e$ is the gas outlet diameter. For this work we have used the equations presented by Kuye et al [2] to calculate the cyclone pressure drop and efficiency. They used the Ogawa model for calculating the pressure drop and Lapple model for efficiency [25, 6]. These equations are valid for the following cyclone configurations:

1. Shephard and Lapple Conventional [26]
2. Stairmand High Efficiency [5]
3. Stairmand High Throughput [5]

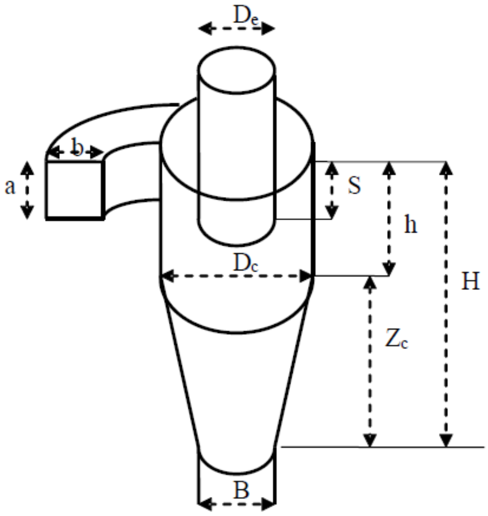

Figure 1: A Schematic Diagram of the Cyclone, where ‘a and b’ are the inlet height and width (in meters) respectively, which is the area where the dust goes into the cyclone. De is the gas outlet diameter where the

clean gas exit the cyclone while Dc is the cyclone body diameter which gives the ratio of each configuration. B is the dust outlet diameter, S is Gas outlet length, h is the cylindrical height of cyclone, Zc is conical height of the cylinder and H is the total height of the cylinder which is the sum of h and Zc all measured in meters.

Kuye et al [27] stated that, given the cyclone geometry and the operating conditions (operating temperature, operating pressure, particle density), there are 5 design parameters namely:

1. Feed rate, Q
2. Cyclone Diameter, Dc
3. Cut diameter, $d_{pc}$
4. Cyclone Efficiency, $\eta$
5. Cyclone Pressure Drop, $\Delta P$

Out of these five parameters, it is required to specify two or three and the others can be calculated. The 9 possible combinations are given by Kuye et al [27]. Also, the cut diameter can be calculated from:

$$d_{pc} = \left[\frac{9\mu b}{2\pi N_e v_i(\rho_p - \rho_g)}\right]^{1/2} \tag{1}$$

Where $\mu$ = gas viscosity; $N_e$ = number of turns the gas stream takes until it reaches the vortex finder; $\rho_p$ and $\rho_g$= respectively particle and gas density and $v_i$ = inlet velocity.

A computer program was developed to solve the design equations. It should be noted that Kuye et al [27] used visual basic 6.0 (VB6) as the programming language. VB6 is known to have some compatibility issues with Windows 7 or later versions. Also VB6 cannot be used for developing applications for mobiles or networks. Hence, the NetBeans integrated development environment (IDE) was used to perform the design computations. NetBeans IDE provides an array of user-friendly tools for developing Java desktop, mobile and web applications.

To validate the computer programme output, two problems from literature (one for air cyclones and the other for nitrogen gas) were used. For each, the nine different possible design combinations were computed. The test problems are summarized in Tables 1 and 2.

**Table 1**: Test Problems

| **Parameter** | **Problem1**[*] | **Problem 2**[**] |
|---|---|---|
| Configuration | Shephard and Lapple | Stairmand High Efficiency |
| Dimensions (Ratio to Dc) a | 0.500 | 0.500 |
| b | 0.250 | 0.200 |
| De | 0.500 | 0.500 |
| S | 0.625 | 0.500 |
| h | 2.000 | 1.500 |
| Zc | 2.000 | 2.500 |
| H | 4.000 | 4.000 |
| B | 0.250 | 0.375 |
| Flow rate ($m^3/s$) | 2.500 | 1.110 |
| Fluid | Air | Nitrogen |
| Particle Density ($Kg/m^3$) | 1600 | 2500 |
| Temperature (K) | 350 | 423 |
| Pressure (atm) | 1 | 1 |

Source: [*][28],[**][29]

**Table 2**: Particle size distribution

| **Problem 1** | | **Problem 2** | |
|---|---|---|---|
| **Particle Size Range (μm)** | **Mass (%)** | **Particle Size Range (μm)** | **% by Weight Less than** |
| 2 | 1 | 2 | 4 |
| 4 | 9 | 5 | 6 |

| | | | |
|---|---|---|---|
| 6 | 10 | 10 | 20 |
| 10 | 30 | 20 | 25 |
| 18 | 30 | 30 | 10 |
| 30 | 14 | 40 | 10 |
| 50 | 5 | 50 | 15 |
| 100 | 1 | 100 | 10 |

## Optimization of Cyclone Design Parameters

From Fig. 1, it can be seen that there are nine cyclone dimensions (a, b, De, Dc, S, h, Zc, B and H). A three-level, three-factor without replication full factorial design of experiment was employed to optimize three of these dimensions. The three factors considered were the inlet height (a), inlet width (b) and gas outlet diameter (De) while the remaining six dimensions were kept constant for a given configuration. The levels for each factor are as indicated in Table 3. It can be seen that the intermediate levels are the same as the one given in Table 1 and the lower/higher values are taken as ±5% of the corresponding base values. For each factor and level, the following parameters were computed using the developed programme: pressure drop ($\Delta P$, N/m$^2$), cut-size diameter ($d_{pc}$, m) and overall efficiency ($\eta$, %). Thus for each parameter, a total of twenty seven calculations were made [30].

**Table 3**: Values of Factors and levels for the different configurations

| | **Stairmand High Efficiency** | | | **Shephard and Lapple** | | |
|---|---|---|---|---|---|---|
| **Factor** / **Level** | **A** | **B** | **De** | **A** | **B** | **De** |
| Low | 0.475 | 0.190 | 0.475 | 0.475 | 0.2375 | 0.475 |
| Intermediate | 0.500 | 0.200 | 0.500 | 0.500 | 0.2500 | 0.500 |
| High | 0.525 | 0.210 | 0.525 | 0.525 | 0.2625 | 0.525 |

The Analysis of Variance (ANOVA) was used to analyse the effect of the different factors on each parameter. Each parameter was modelled by the regression equation:

$$y = \beta_0 + \beta_1 a + \beta_2 b + \beta_3 De + \beta_4 ab + \beta_5 aDe + \beta_6 abDe \qquad (2)$$

Where y is the parameter $\Delta P$, $d_{pc}$, or $\eta$ and $\beta_I$'s are the regression constants. The goodness of fit of Equation (2) was assessed by computing the regression coefficient and the residual plot [30].

## Results and Discussion

The nine possible combinations of the five design parameters that were used as inputs in the developed programme for solving Problems 1 and 2 are shown respectively in Tables 4 and 5. The program then calculated the unspecified parameters. For example, with Q and Dc specified, the programme calculated dpc, $\Delta P$ and $\eta_{overall}$. Tables 4 and 5 indicate that the maximum error in the calculation of any unspecified parameter is 3.64%. The error in calculating the pressure drop and overall collection efficiency is much lower (less than 1.5%). The slight differences between the calculated and literature values may be due to differences in the values of density and viscosity of the fluid used; the programme uses a correlation while the literature used just a single value. The error was calculated using:

$$\%\,Error = \frac{100\left|Calculated\,value - Literature\,value\right|}{Literature\,value} \qquad (3)$$

Thus we can say with reasonable confidence that the programme can be used for cyclone design and performance evaluation.

**Table 4**: Summary of Design Results for Problem 1

| **Specified** | **Q (m$^3$/s)** | **Dc (m)** | **dpc (cut size, µm)** | **$\Delta P$ (N/m$^2$)** | **$\eta_{overall}$(%)** |
|---|---|---|---|---|---|
| Q& $D_c$ | 2.5000 | 1.0000 | 6.2696 | 815.1300 | 68.4490 |
| Q&dpc | 2.5000 | 1.0020 | 6.3000 | 815.1400 | 68.4470 |
| Q& $\eta$ | 2.5000 | 1.0010 | 6.2694 | 815.1800 | 68.4480 |

| | | | | | |
|---|---|---|---|---|---|
| Q&ΔP | 2.5000 | 1.0090 | 6.2690 | 815.6000 | 68.4500 |
| $D_c$&dpc | 2.5010 | 1.0000 | 6.3000 | 815.1400 | 68.4600 |
| dpc& η | 2.5001 | 1.0010 | 6.3000 | 815.1400 | 68.4480 |
| $D_c$, Q&ΔP | 2.5000 | 1.0000 | 6.2900 | 815.6000 | 68.4000 |
| dpc&ΔP | 2.5012 | 1.0020 | 6.3000 | 815.6000 | 68.4500 |
| η, Q &ΔP | 2.5000 | 1.0040 | 6.2675 | 815.6000 | 68.4480 |
| Literature | 2.5000 | 1.0000 | 6.3000 | 815.6000 | 67.6000 |
| Max % Error | 0.0500 | 0.9000 | 0.5200 | 0.0600 | 1.2700 |

**Table 5**: Summary of calculations for Problem 2

| **Specified** | **Q ($m^3/s$)** | **Dc (m)** | **dpc (cut size, µm)** | **ΔP ($N/m^2$)** | **$\eta_{overall}$(%)** |
|---|---|---|---|---|---|
| Q& $D_c$ | 1.1100 | 0.5328 | 6.5900 | 640.1210 | 88.4196 |
| Q&dpc | 1.1100 | 0.5343 | 6.5768 | 640.2301 | 88.4186 |
| Q& η | 1.1100 | 0.5300 | 6.5892 | 640.1780 | 88.4206 |
| Q&ΔP | 1.1100 | 0.5323 | 6.5902 | 640.0000 | 88.4156 |
| $D_c$&dpc | 1.1010 | 0.5328 | 6.5768 | 639.9811 | 88.4195 |
| dpc& η | 1.0901 | 0.5301 | 6.5768 | 641.0010 | 88.4206 |
| $D_c$, Q&ΔP | 1.1100 | 0.5328 | 6.5912 | 640.0000 | 88.4190 |
| dpc&ΔP | 1.1211 | 0.5306 | 6.5768 | 640.0000 | 88.4200 |
| η, Q &ΔP | 1.1100 | 0.5312 | 6.5893 | 640.0000 | 88.4206 |
| Literature | 1.1100 | 0.5200 | 6.8250 | 640.0000 | 88.7000 |
| Max % Error | 1.7900 | 2.7500 | 3.6400 | 0.1600 | 0.3200 |

The results for the Three-Level, Three-Factor Full Factorial design of experiments computations for pressure drop, cut diameter and collection efficiency for the Stairmand high efficiency cyclone configuration are shown in Table 6. Similar results were obtained for the Shephard and Lapple configuration and shown elsewhere [31]. Table 6 indicates that the maximum efficiency within the range considered is 95.64% and it occurred when a = 0.475 and b = 0.19. This value is affected by De values. However, the De values affected the pressure drop at the maximum efficiency; the higher the De value the lower the pressure drop. From these results, it would appear that overall collection efficiency is dependent mainly on the cyclone inlet duct dimensions while pressure drop is dependent on the three factors. Similar results were obtained by Elsayed and Lacor [18] who reported that the exit gas diameter of the cyclone is the most important parameter affecting its pressure drop.

**Table 6**: $3^3$-Full Factorial Design for Stairmand High Efficiency (HE) Configuration

| **Runs** | **Inlet Height (a)** | **Inlet Width (b)** | **Gas Exit (De)** | **ΔP ($N/m^2$)** | **dpc(µm)** | **$\eta_{overall}$(%)** |
|---|---|---|---|---|---|---|
| 1 | 0.475 | 0.19 | 0.475 | 781.6879 | 4.630125 | 95.63699 |
| 2 | 0.5 | 0.19 | 0.475 | 790.9039 | 4.750408 | 95.45968 |
| 3 | 0.525 | 0.19 | 0.475 | 800.5926 | 4.86772 | 95.28596 |
| 4 | 0.475 | 0.2 | 0.475 | 790.9039 | 4.750408 | 95.45968 |
| 5 | 0.5 | 0.2 | 0.475 | 801.1156 | 4.873816 | 95.27691 |
| 6 | 0.525 | 0.2 | 0.475 | 811.851 | 4.994175 | 95.09793 |
| 7 | 0.475 | 0.21 | 0.475 | 800.5926 | 4.86772 | 95.28596 |
| 8 | 0.5 | 0.21 | 0.475 | 811.851 | 4.994175 | 95.09793 |
| 9 | 0.525 | 0.21 | 0.475 | 823.6868 | 5.117506 | 94.91388 |
| 10 | 0.475 | 0.19 | 0.5 | 773.3704 | 4.630125 | 95.63699 |
| 11 | 0.5 | 0.19 | 0.5 | 781.6879 | 4.750408 | 95.45968 |
| 12 | 0.525 | 0.19 | 0.5 | 790.4319 | 4.86772 | 95.28596 |
| 13 | 0.475 | 0.2 | 0.5 | 781.6879 | 4.750408 | 95.45968 |
| 14 | 0.5 | 0.2 | 0.5 | 790.9039 | 4.873816 | 95.27691 |
| 15 | 0.525 | 0.2 | 0.5 | 800.5926 | 4.994175 | 95.09793 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 16 | 0.475 | 0.21 | 0.5 | 790.4319 | 4.86772 | 95.28596 |
| 17 | 0.5 | 0.21 | 0.5 | 800.5926 | 4.994175 | 95.09793 |
| 18 | 0.525 | 0.21 | 0.5 | 811.2744 | 5.117506 | 94.91388 |
| 19 | 0.475 | 0.19 | 0.525 | 766.2126 | 4.630125 | 95.63699 |
| 20 | 0.5 | 0.19 | 0.525 | 773.7568 | 4.750408 | 95.45968 |
| 21 | 0.525 | 0.19 | 0.525 | 781.6879 | 4.86772 | 95.28596 |
| 22 | 0.475 | 0.2 | 0.525 | 773.7568 | 4.750408 | 95.45968 |
| 23 | 0.5 | 0.2 | 0.5 | 790.9039 | 4.873816 | 95.27691 |
| 24 | 0.525 | 0.2 | 0.525 | 790.9039 | 4.994175 | 95.09793 |
| 25 | 0.475 | 0.21 | 0.525 | 781.6879 | 4.86772 | 95.28596 |
| 26 | 0.5 | 0.21 | 0.525 | 790.9039 | 4.994175 | 95.09793 |
| 27 | 0.525 | 0.21 | 0.525 | 800.5926 | 5.117506 | 94.91388 |

From a practical point of view, cyclones are normally designed for maximum particulate collection efficiency at the lowest possible pressure drop. Higher efficiency means more particulates are removed from the feed stream while lower pressure drop implies a reduction in the operating cost. Thus for the results shown in Table 6, the optimum cyclone configuration is run 19, that is, a = 0.475, b = 0.19 and De = 0.525. This suggests that the Stairmand high efficiency cyclone configuration can be modified to improve its performance. A plot of overall collection efficiency versus pressure drop is shown in Fig. 2 for the different De’s. Fig. 2 confirms the earlier assertion that De affects the pressure drop of cyclones.

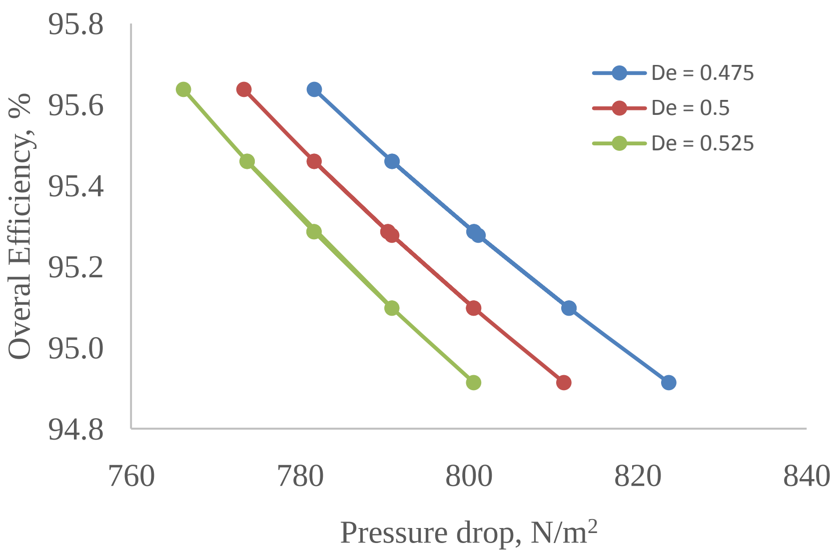

Figure 2: Collection efficiency versus pressure drop for different gas exit diameters. Green, red and blue curves indicate trends of the plot of overall efficiency versus pressure drop at 0.525, 0.5 and 0.475 values of gas outlet diameter (De) respectively. These plots show that, De values affected the pressure drop at the maximum efficiency; the higher the De value the lower the pressure drop.

The regression equations for the results presented in Table 6 respectively for pressure drop, cut diameter, and collection efficiency are shown in Equations 4 to 6 and the relevant statistic are shown in Table 7. It should be noted that the relative deviation was also calculated using Equation 3.

$$\Delta P = 980.484 - 1138.307a - 2845.768b - 378.892De + 11400.967ab + 1517.88aDe + 3794.7bDe - 15202abDe \quad (4)$$

$$dpc = 1.219 + 2.436a + 6.09b - 0.005De + 12.191ab \quad (5)$$

$$\eta_{overall} = 100.404 - 3.022a - 7.556b + 0.006De - 21.05ab \quad (6)$$

**Table 7**: Statistic for the regression equations

| | $\eta_{overall}$, % | dpc, µm | ΔP, $N/m^2$ |
|---|---|---|---|
| Average Relative Deviation | 0.001 | 0.019 | 0.046 |
| Maximum Relative Deviation | 0.003 | 0.045 | 0.097 |
| Correlation Coefficient | 1.0000 | 0.9999 | 0.9991 |

From Table 7, it is apparent that Equations 4 to 6 fit their respective data very well. This is further confirmed by the random nature of the residual plots shown in Figures 3 to 5. Equations 5 and 6 also indicate that cut diameter and collection efficiency are weakly dependent on exit gas diameter; the coefficients for De are much smaller than that for a and b.

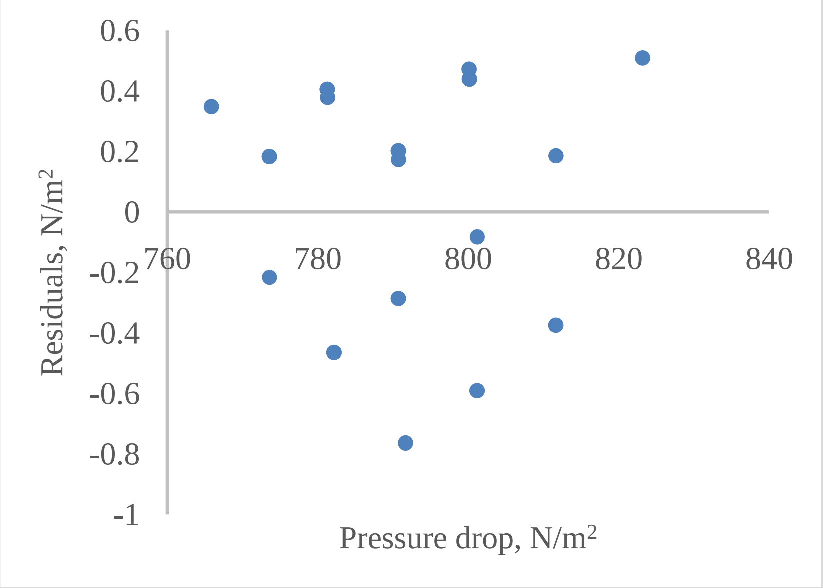

Figure 3: Plot of residuals versus Predicted Pressure Drop. The random nature of this plot is an indication that the regression equation (Equation 4) fit the data very well. It also indicates that pressure drop is strongly dependent on exit gas diameter because of high coefficient for De in equation 4 when compared to that of Equations 5 and 6.

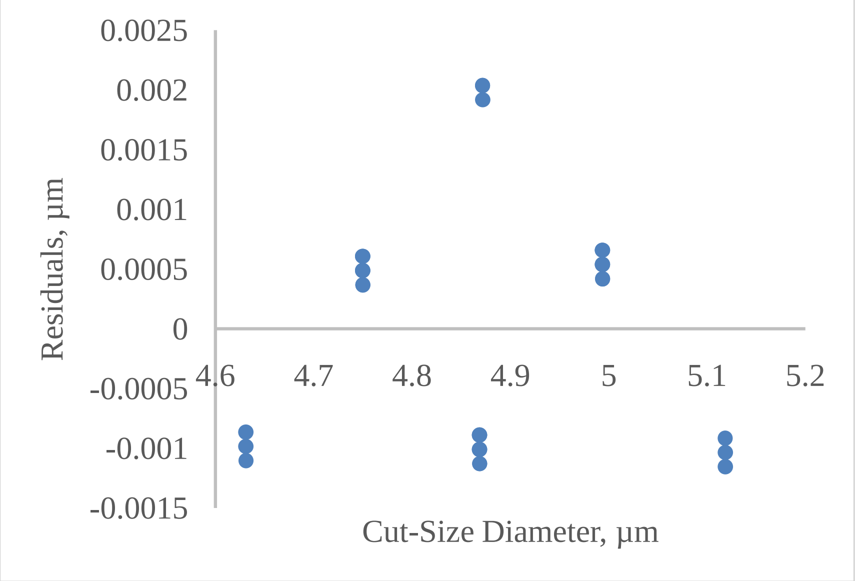

Figure 4: Plot of residuals versus Predicted Cut-Size Diameter. The random nature of this plot is an indication that the regression equation (Equation 5) fit the data very well. It also indicates that cut-size diameter is weakly dependent on exit gas diameter because of negligible coefficient for De in equation 5.

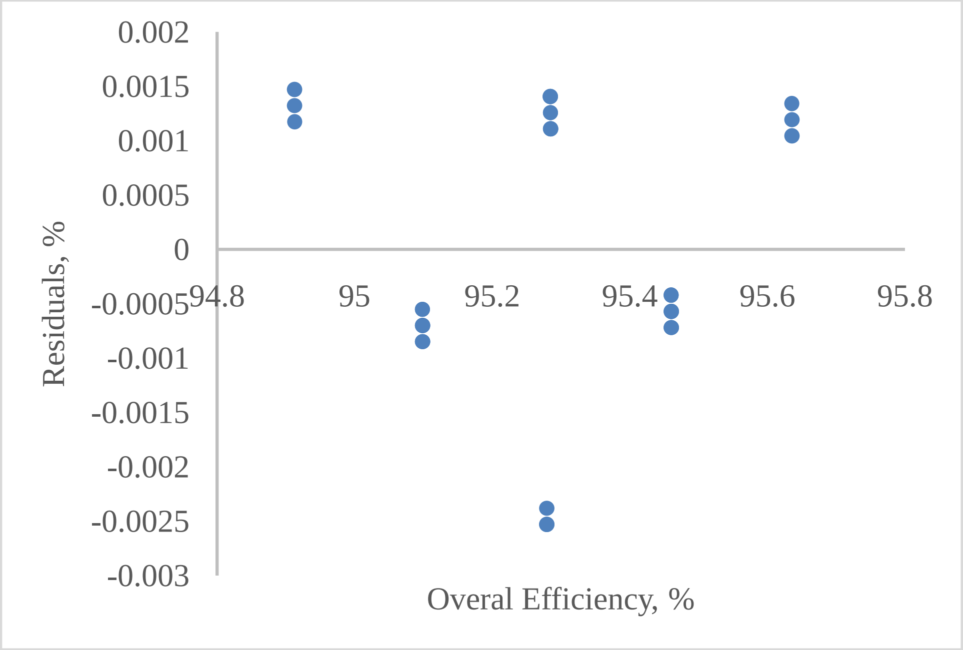

Figure 5: Plot of residuals versus Predicted Collection Efficiency. The random nature of this plot is an indication that the regression equation (Equation 6) fit the data very well. It also shows (like in Figure 4) that collection efficiency is weakly dependent on exit gas diameter because of negligible coefficient for De in Equation 6.

## Conclusion

A programme developed using java in Netbeans IDE has been used to solve eighteen different problems derived from two test problems obtained from literature. The maximum deviation between programme output and corresponding literature values are less than 1.5% for collection efficiency and pressure drop. There are nine dimensions that must be specified to design a cyclone. With the other six dimensions kept constant, the Three-Level, Three-Factor Full Factorial design of experiments indicate that overall collection efficiency is dependent mainly on the cyclone inlet duct dimensions while pressure is dependent on inlet duct dimensions as well as exit gas diameter. Furthermore, the results suggest that the Stairmand high efficiency cyclone configuration can be modified to improve its performance. Finally, regression equations were presented for calculating pressure drop, collection efficiency and cut diameter.

## NOMENCLATURE

| | |
|---|---|
| a | Inlet height, m |
| b | Inlet width, m |
| B | Dust outlet diameter, m |
| d | Particle diameter, m |
| $d_n$ | Diameter of core where vortex turns, m |
| $d_{pc}$ | Cut size (critical diameter at 50% efficiency), microns ($d_{50}$) |
| $D_C$ | Cyclone diameter, m (D) |
| De | Gas outlet diameter, m |
| h | Cylindrical height of cyclone, m |
| H | Total height of cyclone (h+Zc), m |
| Q | Feed rate, $m^3/s$ |
| S | Gas outlet length, m |
| Zc | Conical height of cyclone, m |

| | |
|---|---|
| $\Delta P$ | Pressure drop, $N/m^2$ |
| $\eta$ | Collection efficiency, % |

**References**

[1]. Wang, L. (2004) Theoretical study of cyclone design. PhD Dissertation, Texas A&M University, College Station, USA

[2]. Kuye, A.O, D. B. Ayo, K.O Okpala, T.O. Folami, F. O. Chukwuma, A. S. Ahmed, S. N. Mumah, I. I. Ismail, M.O. Ayoola, C. Hamilton, A. I. Okereke, I. O. Ejuya, and U. M. Mansur(2006): Design of air cyclones: Part I - A review of applicable models, Journal of Raw Materials Research, 3(2): 104 - 117,

[3]. Utikar, R., Darmawan, N., Tade, M., Li, Q., Evans, G., Glenny, M. And Pareek, V., (2010): Hydrodynamic simulation of cyclone separators, in Computational Fluid Dynamics by Hyoung Woo Oh (ed.), Intech, Croatia.

[4]. Xiong, Z., Z. Ji and X. Wub (2014) Development of a cyclone separator with high efficiency and lowpressure drop in axial inlet cyclones. Powder Technology 253: 644–649

[5]. Stairmand, C. J. (1951). The Design and Performance of Cyclone Separators. Transactions of Industrial Chemical Engineers 29: 356-383.

[6]. Lapple, C.E., (1951). Processes use many collector types. Chemical Engineering 58: 144-151.

[7]. Leith, D. and Licht, W. (1972). Collection efficiency of cyclone type particle collector: A new theoretical approach. American Institute of Chemical Engineers Symposium Series (Air-1971) 68:196-206.

[8]. Dietz, P.W. (1981). Collection efficiency of cyclone separators. Journal of American Institute of Chemical Engineers 27: 888 – 894.

[9]. Saltzman, B., (1984): Generalized performance characteristics of miniature cyclone for atmospheric particulate sampling. American Industrial Hygiene Association Journal 45:671-680.

[10]. Dirgo, J. and Leith, D. (1985). Cyclone collection efficiency: Comparison of experimental results with theoretical predictions. Aerosol Science Technology, 4, 401.

[11]. Wang, L. C. B. Parnell, B. W. Shaw and R. E Lacey. (2003) Analysis of Cyclone Collection Efficiency. ASAE Paper No. 034114. St. Joseph, Mich.: ASAE.

[12]. Lim, K.S., Kim, H.S. and Lee, K.W. (2004): Characteristics of the collection efficiency fora cyclone with different vortex finder shapes. Journal of Aerosol Science, 35(6):743–754.

[13]. Casal, J. and Martinez-Benet, J. (1983): “A better way to calculate cyclone pressure drop”, Chem. Eng., 90, 99

[14]. Coker, A.K. (1993) “Understand Cyclone Design”, Chemical Engineering Progress, 89, pp 51-55.

[15]. Wang, B., Xu, D.L., Chu, K.W. and Yu, A.B.(2006): Numerical study of gas-solid flow in a cyclone separator. Mathematical Modelling 30: 1326 – 1342.

[16]. Cortes, C. and Gil, A. (2007). Modelling the gas and particle flow inside cyclone separators. Progress in Energy and Combustion Science 33: 409-452.

[17]. Raoufi, A., Shams, M., Farzaneh, M. and Ebrahimi, R. (2008): Numerical simulation and optimization of fluid flow in cyclone vortex finder. Chemical Engineering and Processing 47:128-137.

[18]. Elsayed, K. And Lacor, C., (2010). The effect of vortex finder diameter on cyclone separator performance and flow field. V European Conference on Computational Fluid Dynamics, 14-17 June, 2010, Lisbon.

[19]. Elsayed K. (2011) Analysis and Optimization of Cyclone Separators Geometry Using RANS and LES Methodologies, Doctor in Engineering Thesis, VrijeUniversiteit Brussel, October.

[20]. Swamee, P. K., Aggarwal, N and Bhobhiya, K.(2009): Optimum design ofcyclone separator. American Institute of Chemical Engineers J, 55(9):2279–2283.

[21]. Ravi, G., Santosh K. Gupta, and Ray, M. B.(2000): Multiobjective optimization of cyclone separators using genetic algorithm. Ind. Eng. Chem. Res., 39:4272–4286.

[22]. Safikhani, H., Hajiloo, A; Ranjbar, M. A. and Nariman-Zadeh, N. (2011) Modeling and multi-objective optimization of cyclone separators usingCFD and genetic algorithms. Computers & Chemical Engineering, 35(6):1064–1071,.

[23]. Pishbin, S. I. and M. Moghiman. (2010): Optimization of cyclone separatorsusing genetic algorithm. International Review of Chemical Engineering, 2(6):683–690.

[24]. Elsayed, K and Lacor, C (2011) 'Modeling, analysis and optimization of aircyclones using artificial neural network, response surface methodology and CFD simulation approaches' Powder Technology, 212: 115-133.

[25]. Ogawa, A. (1997). Mechanical Separation Process and Flow Patterns of Cyclone Dust Collectors. Applied Mechanics Reviews, vol 50, no 3, pp 97-130

[26]. Shepherd, C.B. and Lapple, C. E. (1939), Flow pattern and pressure drop in cyclone dust collectors. Industrial and Engineering Chemistry 31(8): 972-984.

[27]. Kuye A. O, D. B. Ayo, K.O. Okpala, T.O. Folami, F.O. Chukwuma, A.S Ahmed, S. N Mumah, I. I. Ismail, M. O. Ayoola, C. Hamilton, A. I. Okereke, I. O. Ejuya, U. M. Mansur(2011): Design of air cyclones: Part II – Software Development, Journal of Raw Materials Research, 6(1): 62 - 72

[28]. Cooper, C. D., Alley, F. C. (2004), “Cyclones”, Adapted from air Pollution Control, 1986; http://engineering.dartmouth.edu/~cushman/courses/engs37/cyclone.htm

[29]. Coulson, J. M., Richardson, J. F., Sinnot, R. K. (2005) Chemical Engineering, Volume 6, 4th edition, Chapter 10, pp446-455, Pergamon Press.

[30]. Montgomery, D.C. (2013): Design and Analysis of Experiments.8th ed, John Wiley and Sons Publishers, Arizona State University, Canada

[31]. Enujekwu, F. M. (2016) Optimization of Cyclone Design Parameters Using Java in Netbeans Integrated Development Environment (IDE), unpublished M. Eng Thesis, University of Port Harcourt, Port Harcourt, Nigeria