International Review of Chemical Engineering (I.RE.CH.E.), Vol. 2, N. 6
November 2010

# Optimization of Cyclone Separators Using Genetic Algorithm

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**Abstract** – *Several classical approaches for designing cyclone separators have been presented till today. Although these approaches have worked well in certain circumstances, they may not always lead to the best possible designs. This paper presents a robust performance optimization method for cyclone separators using genetic algorithm. The effects of seven geometrical design parameters on efficiency and pressure drop are investigated simultaneously. For calculating these performance characteristics, a gas- solid multiphase flow simulation is used to model the two-phase flow inside the cyclone. The proposed computational fluid dynamic model is employed to formulate the objective functions, which are the pre-requisite of genetic algorithm. The simultaneous optimizing of cyclone parameters reveals the profound effects of the conical height and slope, on both efficiency and pressure drop of cyclone separators. The results also show that by increasing the efficiency over 85 percent, pressure drop will be increased significantly.*


***Keywords**: Cyclone, Efficiency, Genetic Algorithm, Pressure Drop, Weighting Coefficient*

## Nomenclature

| | |
|---|---|
| $a$ | Inlet height (-) |
| $B$ | Cone diameter (-) |
| $C_D$ | Drag coefficient (-) |
| $d_p$ | Particle size (m) |
| $D$ | Cyclone diameter (m) |
| $De$ | Vortex finder diameter (m) |
| $f_k(x)$ | Objective function (-) |
| $F_D$ | Dragging force (N) |
| $h$ | Cone height (m) |
| $H$ | Cyclone body height (m) |
| $M_{p,i}$ | is the conversion momentum between solid particle and gas fluid flow |
| $n_{in}$ | Number of particles with specific diameter in inlet (-) |
| $n_{out}$ | Number of separated particles with specific diameter in outlet (-) |
| $Re_p$ | Reynolds number of particles (-) |
| $S$ | Vortex finder height (m) |
| $u'$ | is the fluid fluctuation velocity axial direction (m/s) |
| $u_p$ | Particle velocity (m/s) |
| $v'$ | is the fluid fluctuation velocity radial direction (m/s) |
| $v_p$ | Particle velocity (m/s) |
| $V_p$ | Absolute velocity of particles (m/s) |
| $V_g$ | Absolute velocity of gas (m/s) |
| $w'$ | is the fluid fluctuation velocity tangential direction (m/s) |
| $w_p$ | Particle velocity (m/s) |
| $w_k$ | Weighting coefficient of objective function (-) |

*Greek Letter*

| | |
|---|---|
| $\alpha$ | Slope of conical part of the cyclone (-) |
| $\Delta p$ | Pressure drop (Pa) |
| $\eta(d)$ | Collection efficiency in the specific diameter (%) |
| $\mu$ | Viscosity (Pa s) |
| $\rho_g$ | Gas density (kg/m$^3$) |
| $\rho_p$ | Particle density (kg/m$^3$) |

## I. Introduction

Cyclone separators have been used widely during this century as a major gas-cleaning device. The standard designs available now, were perfected decades ago on the basis of practical experience and insight but often without quantitative application of the principles of engineering practice. Now, increasing demands and competition require the use of good mathematical models describing the operation of cyclones, as well as their use, with modern tools of optimization to give the best designs.

The complexity of the gas–solid flow pattern in cyclones has long been a matter of many experimental and theoretical works. Tangential entrance of fluid into the cyclone leads to a spiraling motion and a highly swirling particle flow is developed. The spiraling motion causes a strong centripetal acceleration proportional to the diameter and mass of particles, and if it is sufficiently large, then the particles drift towards the side wall and finally they are separated through the apex of the cyclone

Till today, several studies have been done in order to improve the performance of cyclone separators, i.e. increasing efficiency and decreasing the pressure drop.

*Manuscript received and revised October 2010, accepted November 2010*

Xiang *et al.* have analyzed the effects of the dimensions of the conical part of the cyclone and the input speed upon the performance of the cyclone separators [1]. In addition, Mi-Soo Shin *et al.* studied and analyzed the effects of the dimensions of the vortex finder on the performance of the device using numerical and experimental methods [2]. Also, Chuah *et al.* have studied the effects of conical part dimensions of the cyclone on its performance [3].

Muschelknautz [4] used models [5], [6], [7] to obtain two geometrical ratios, ($H/De$) and ($D/De$), for the optimized cyclone, which resulted in the desired overall collection efficiency with minimum pressure drop. However, this analysis is not capable of determining all the optimized dimensions of the cyclone. Leith and Mehta [8] developed a procedure by which the designer determined the set of geometrical ratios that gave the highest possible efficiency for any combination of gas throughput, cyclone diameter, and pressure drop. Dirgo and Leith [9] varied the outlet diameter of the Stairmand cyclone and searched for compensating changes among other cyclone dimensions in order to increase the efficiency without changing the pressure drop. In both of these studies [8], [9] the pressure drop is fixed, and the cyclone dimensions are changed to achieve the maximum value of efficiency. However, all the previous studies which have been done till today have focused on the effects of one or two geometrical dimensions of the cyclone on performing aspects of the cyclone separators (efficiency and pressure drop).

In most of the earlier optimization studies, a single objective function was used. Nevertheless, optimization of cyclones really involves several conflicting objectives, namely, maximization of the overall collection efficiency and minimization of the pressure drop. Besides this, it is necessary to get into account all of the geometrical dimensions simultaneously. So in this study, the effects of seven geometrical parameters consist of: height and diameter of the cylindrical part of the cyclone, height and diameter of the conical part (dust outlet), height and diameter of the vortex finder and the diameter of the inlet pipe, as shown in Fig. 1, are investigated simultaneously on the performance of the cyclone.

In this study, optimization of cyclones (at the design stage) is carried out using coupled objective functions and the genetic algorithm method. Objective functions proposed for optimization of cyclones are nonlinear in nature, moreover, associated with the geometric constraints [10]. In these cases, genetic algorithm is the best tools for modeling and optimization of highly complicated and nonlinear systems without understanding the nature of phenomenon [11].

Optimization is the process of finding the maximum /minimum of the parameters called the objective function and must also satisfy a certain set of specified requirements within constraints. The optimization methodology adopted in this work was an artificial genetic approach proposed by Goldberg based on natural genetics.

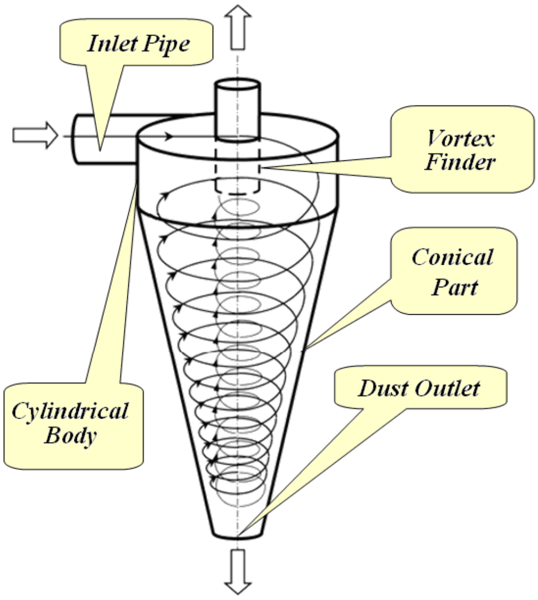


Fig. 1. Schematic diagram of the cyclone

Genetic algorithm efficiently exploits useful information contained in a population of solutions to generate new solutions with better performance [12].

## II. Theoretical Formulations and Methods of Solution for Fluid and Particles Flow Inside the Cyclone

The operation of cyclone separators are so that when the fluid, with the dispersed particles in suspension, is injected tangentially through the inlet pipe into the cyclone (Fig. 1), then due to the specially designed geometrical feature of the cyclone the fluid acquires a spiraling motion, which first descends along an outer spiral and then ascends through an inner spiral. Simultaneously, a highly swirling particle flow is developed inside the cyclone. The dispersed particles, which have a different density to that of their carrying fluid, are driven by the centripetal acceleration to move relative to the fluid motion. The relatively larger particles possess a larger inertia and therefore acquire a stronger centripetal acceleration. When the centripetal acceleration is sufficiently large, then the particles drift towards the side wall and finally they are separated through the apex of the cyclone. While the smaller particles, which are more dominated by the drag of the fluid flow, remain entrained in the fluid flow and finally they penetrate the cyclone [13].

The prediction of the performance of the cyclone separators is a challenging problem for the designers owing to the complexity of internal aerodynamic process and dust particles. Hence, modern numerical simulations are needed to solve this problem. Fluid flows have long been mathematically described by a set of nonlinear, partial differential equations, namely the Navier-Stokes equations. We develop a CFD model for simulating the fluid flow in the cyclone using these equations. The use of an appropriate turbulence model in the numerical simulation is vital for a correct prediction of both the fluid flow and the particle separation in the cyclone. In this paper, the turbulence Algebraic Stress Model (ASM) is used for calculating the Reynolds stresses [14].

### *II.1. Gas-Phase Conservation Equations*

*Continuity:*

$$\frac{\partial U}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}(rV)=0 \tag{1}$$

*Momentum:*

$$\begin{aligned}&\frac{1}{r}\left[\frac{\partial}{\partial x}\left(\rho rU^2\right)+\frac{\partial}{\partial r}\left(\rho rUV\right)\right]=\\&-\frac{\partial P}{\partial x}-\frac{\partial}{\partial x}\left(\rho\overline{u'^2}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\rho\overline{u'v'}\right)+M_{p,x}\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{1}{r}\left[\frac{\partial}{\partial x}\left(\rho rUV\right)+\frac{\partial}{\partial r}\left(\rho rV^2\right)\right]=-\frac{\partial P}{\partial r}+\\&-\frac{1}{r}\frac{\partial}{\partial r}\left(\rho r\overline{v'^2}\right)-\frac{\partial}{\partial x}\left(\rho\overline{u'v'}\right)-\frac{1}{r}\rho\overline{w'^2}+M_{p,r}\end{aligned} \tag{3}$$

$$\begin{aligned}&\frac{1}{r}\left[\frac{\partial}{\partial r}\left(\rho rUW\right)+\frac{\partial}{\partial r}\left(\rho rVW\right)+\rho VW\right]=\\&=\frac{\partial}{\partial r}\left(\rho r\overline{v'w'}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\rho\overline{v'w'}\right)-\frac{1}{r}\rho\overline{v'w'}+M_{p,\theta}\end{aligned} \tag{4}$$

here $M_{p,i}$ is the conversion momentum between solid particle and gas fluid flow. The Eulerian approach is used to calculate gas-phase properties. The equations are solved by a control-volume based semi-implicit iterative procedure [15]:

$$\Delta M_{px}=-F\left(t-t_0\right)\left[0.5\left(u_p-u_{p,0}\right)-U-u'\right]\dot{m}_p \tag{5}$$

$$\Delta M_{pr}=-F\left(t-t_0\right)\left[0.5\left(v_p-v_{p,0}\right)-V-v'\right]\dot{m}_p \tag{6}$$

$$\Delta M_{p\theta}=-F\left(t-t_0\right)\left[0.5\left(w_p-w_{p,0}\right)-W-w'\right]\dot{m}_p \tag{7}$$

In the above equations, $\dot{m}_p$ is the mass flux of particles which is constant in all sizes and $u_{p,o}$ is the initial velocity of particle.

### *II.2. Solid-Phase Equations*

The Lagrangian approach is employed to compute the properties of each group of particles as it travels in the turbulent flow. The integration of particle motions equations which relate the drag and centrifugal forces and the particle to its resultant acceleration in cylindrical coordinates are [1]:

$$u_P=\left(u_{P,0}-U-u'+\frac{g}{F_D}\right)exp\left(-F_D\left(t-t_0\right)\right) \tag{8}$$

$$v_P=\left(v_{P,0}-V-v'+\frac{w_{P,0}^2}{F_D.r_{P,0}}\right)exp\left(-F_D\left(t-t_0\right)\right) \tag{9}$$

$$w_P=\left(w_{P,0}-W-w'+\frac{w_{P,0}v_{P,0}}{F_D.r_{P,0}}\right)exp\left(-F_D\left(t-t_0\right)\right) \tag{10}$$

These parameters can be achieved using Eqs.(11)-(14):

$$\mathrm{F_D}=\frac{18\mu}{\rho_p\cdot d_p^2}\cdot\frac{C_D\cdot Re_p}{24} \tag{11}$$

$$C_D=\begin{cases}24/Re_p & Re_p\le 1\\ \dfrac{24\left(1+0.15\,Re_p^{0.687}\right)}{Re_p} & 1<Re_p\le 10000\\ 0.44 & Re_p>1000\end{cases} \tag{12}$$

$$Re_p=\frac{d_p\rho_g V_r}{\mu_g} \tag{13}$$

$$V_r=\left|V_p-V_g\right| \tag{14}$$

In which, $C_D$ is the drag coefficient while $F_D$ is the dragging force [16]. $Re_p$ represents the Reynolds number of particle and $V_p$ and $V_g$ is the absolute velocity of particle and fluid.

### *II.3. Efficiency Calculation*

The most important parameters in cyclone operation are pressure drop and collection efficiency. The pressure drop is given by the difference between the static pressure at the cyclone entry and the exit tube. The overall collection efficiency is defined as the ratio between the mass of solids collected by the cyclone in a time interval and the mass flow rate of incoming solids [17].

According to Eq. (15), collection efficiency is the ratio between the number of particles with specific diameter at input ($n_{in}$) and the number of separated particles with the same diameter in output ($n_{out}$) [18]:

$$\eta(d)=\frac{n_{out}(d)}{n_{in}(d)} \tag{15}$$

But Eq. (15) gives the collection efficiency of cyclone in a specific diameter ($d$), and the overall collection efficiency of cyclone is hence calculated by the following expression:

$$Overall\ efficiency = \frac{\sum_{d=1}^{d_{end}} n_{out}(d)}{\sum_{d=1}^{d_{end}} n_{in}(d)} \quad (16)$$

The particle sizes which containing in the airflow in this study are from 1 μm up to 20 μm, because the particles larger than 20 μm have been collected completely.

## III. Genetic Algorithm

Genetic Algorithm (GA) is a computerized search procedure based on the mechanics of natural genetics and natural selection that can be used to obtain global and robust solution to optimization problems [12]. GA combines survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm with some of the innovative flair of human search. In every generation, a new set of artificial strings is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure. This work concentrates on simple GA with reproduction, crossover and mutation operator.

There are many types of crossover operators like edge recombination, partially mapped crossover, ordered crossover, heuristic crossover, simulated binary crossover, etc. In this work, Heuristic crossover was used in which produces a linear extrapolation of the two individuals ($P_1$, $P_2$). This is the only operator that utilizes fitness information [19]. A new individual is created using Eq. (17), where $r$ is a random number between [0, 1]:

$$P_1' = r(P_1 - P_2) + P_1 \quad (17)$$

According to what kind of symbol is used as the alleles of a gene, the encoding methods can be classified as binary encoding, real number encoding, integer or literal permutation encoding and general data structure encoding. Out of these, real number encoding is best used for function optimization problems [12].

### *III.1. Steps of Genetic Algorithm Optimization*

Given the clearly defined problem to be solved and a bit string and the candidate solutions, a GA works as follows [12]. Start with a randomly generated population of '$n$' 1-bit chromosomes (candidate solutions to the problems):

(1) Calculate the fitness $F(x)$ of each of the chromosome '$x$' in the population.
(2) Create '$n$' offspring from current population using the three operators namely selection, crossover and mutation.
(3) Replace the current population with the new population.
(4) Repeat the above steps until the termination criterion is reached.

For this work, we use CFD code for calculating fitness function $F(x)$ and the chromosome '$x$' contains seven geometrical dimensions of cyclone separator.

### *III.2. Weighted-Sum Genetic Algorithm*

The classical approach to solve a multi-objective optimization problem is to assign a weight $w_k$ to each normalized objective function $f_k(x)$ so that the problem is converted to a single objective problem with a scalar objective function as follows:

$$f(X) = \sum_{k=1}^{n} w_k f_k(X) \quad (18)$$

$$\sum_{k=1}^{n} w_k = 1 \quad (19)$$

This approach is called the priori approach since the user is expected to provide the weights. In this method, by choosing different weightings for the objectives, the preference of the decision-maker is taken into account [20]. Solving a problem with the two objective function for a given weighting vectors, $w = \{w_1, w_2\}$, yields a single solution, and if multiple solutions are desired, the problem must be solved multiple times with different weight combinations ($w_k$).

### *III.3. Objective Functions*

In this paper, we used seven different group of weighting coefficients for two objective functions (efficiency and pressure drop). In Eq. (20), the $w_1$ varies from 0.1 to 0.9 and $w_2$ is equal to 1-$w_1$. Allotting different coefficients to the objectives will lead to different results. It means that, if the coefficient of efficiency in Eq. (20) is increased, GA searches for an optimized cyclone with more collection efficiency. So we use seven various group of coefficient to find multiple solutions and to compare the results between a cyclone with high efficiency ($w_1$=0.9) and a cyclone with low pressure drop ($w_2$=0.9):

$$\left.\begin{aligned} f_1 &= \eta \\ f_2 &= -\Delta p \end{aligned}\right\} \Rightarrow w_1 \cdot \eta - w_2 \cdot \Delta p \quad (20)$$

Without losses of generality, all objectives are of the minimization type - a minimization type objective can be converted to a maximization type by multiplying negative one [21]. So we multiply pressure drop with negative one, because genetic algorithm code searches for maximization and we need to minimize the pressure drop. Other specifications such as genetic operators and parameters which use in this procedure are presented in Table I.

TABLE I
GENETIC OPERATORS AND PARAMETERS

| | |
|---|---|
| Crossover operation: | Heuristic crossover |
| Mutation operation: | Non-uniform mutation |
| Selection operation: | Normalized geometric ranking |
| Stopping criteria: | Last generation |
| Number of generations: | 300 |
| Number of initial population: | 40 |

The total airflow rate is $0.08 m^3/s$ and the release density is assumed $1.225\ kg/m^3$ and the viscosity $1.7894\times10^{-5}$ kg/m [22]. Fig. 2 has depicts the symbols which have been used to identify the geometrical dimensions of the cyclone.

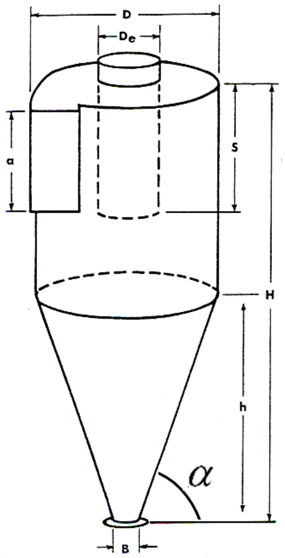


Fig. 2. Symbols of the cyclone geometrical dimensions

## IV. Results and Discussion

Computational Fluid Dynamics (CFD) code simulation with ASM turbulence provides a close agreement to experimental data [16], [22] as shown in Figs. 3(a),(b). The success of the CFD simulation may be attributed to the inclusion of a very fundamental fluid dynamics and a detailed description of turbulence model in the code [23]**.** The geometrical dimensions of Stairmand cyclone which have been studied in this paper are given in Table II.

Figs. 3(a) and (b) show the experimental and calculated axial and tangential velocities at two sections of the cyclone body. The simulation results are in good agreement with the experimental results. The diameter of upward flow is slightly larger than that of the vortex finder. Moreover, since much gas flows over into the vortex finder, the axial velocity reaches a peak value under the vortex finder. These results are also showing the same conclusions as B. Wang [16] and the value of the tangential velocity equals zero on the wall.

Fig. 4 shows the trajectories of particles with different sizes. Particles above 10 µm are settled down in the conical part of cyclone. Fig. 5 shows the velocity vectors inside the cyclone.

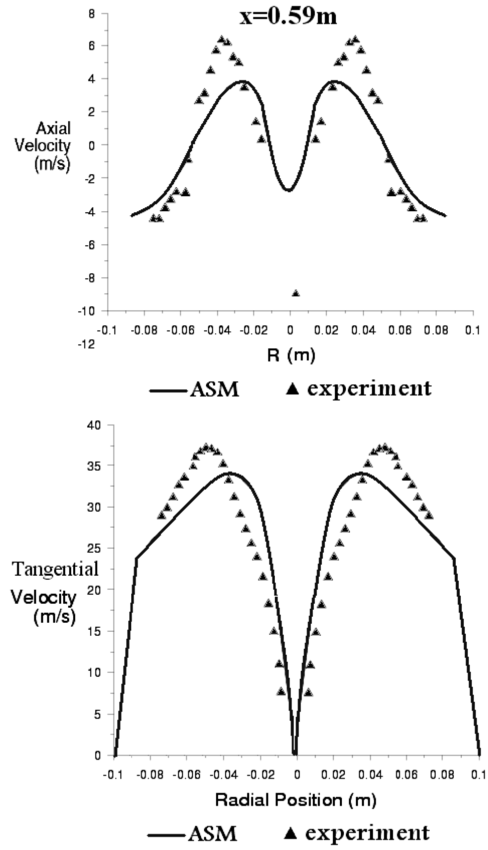


Fig. 3(a). Experimental vs. calculated tangential and axial velocities. Experimental data are obtained from [21]

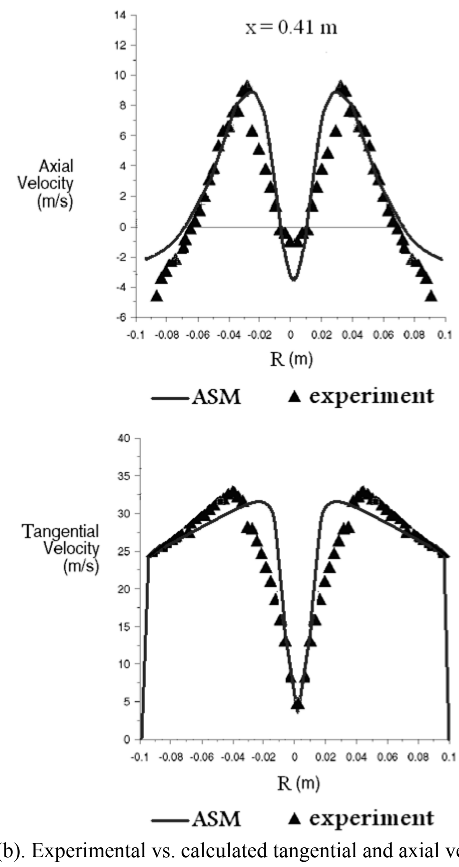


Fig. 3(b). Experimental vs. calculated tangential and axial velocities. Experimental data are obtained from [21]

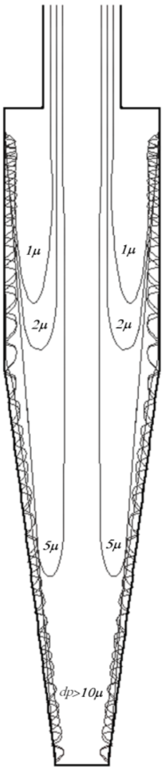


Fig. 4. The trajectories of particles with different sizes

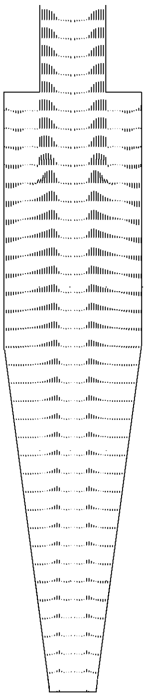


Fig. 5.Velocity Vectors in the cyclone at flow rates 0.08m$^3$/s

TABLE II
GEOMETRICAL DIMENSIONS (M) OF STAIRMAND CYCLONE STUDIED [21]

| | | | |
|---|---|---|---|
| B:Cone diameter | 0.074 | D: Cyclone diameter | 0.205 |
| h: Cone height | 0.512 | H: Cyclone body height | 0.82 |
| a: Inlet height | 0.1 | De: Vortex finder diameter | 0.103 |
| | | S: Vortex finder length | 0.103 |

## V. Optimization Results

As it can be seen in Fig. 6, by decreasing the cone diameter ratio (*B/De*), due to the change in flow field and increase of the tangential velocity in conical part, the collection efficiency of the particles and also pressure drop increases rapidly, this behavior continues until the range of: 0.6<*B/De*<1.2, when efficiency remains almost constant but pressure drop increases as well. And further decreasing cone diameter, will lead to further decrease in the efficiency. These results are in a great accordance with the analytical results of Avci and Karagoz in 2001 and also measurement results of their studies [24].

Xiang in 2001 [1] performed optimization analysis for increasing efficiency and decreasing pressure drop, for three small fabricated cyclones with following dimension ratios, *B/De*=0.74, 1, 1.25 و *De/D*=0.5. He came to the conclusion that the optimized performance is achieved for the dimension of *B/De*=1 (outlets ratio). These results are also in good accordance with the studies of this paper, as shown in Fig. 7. By omitting two margin results for $w_1$=0.9 and $w_1$=0.1, it can be seen that most of the results with high efficiency and appropriate pressure drop have been achieved to nearly the same ratio of *B/De*=1.0.

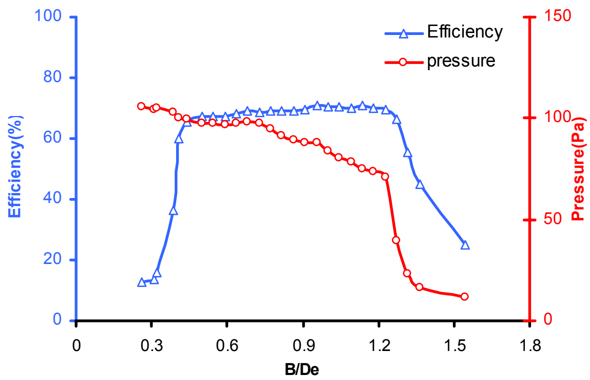


Fig. 6. The variation of pressure drop and efficiency by changing the cone diameter

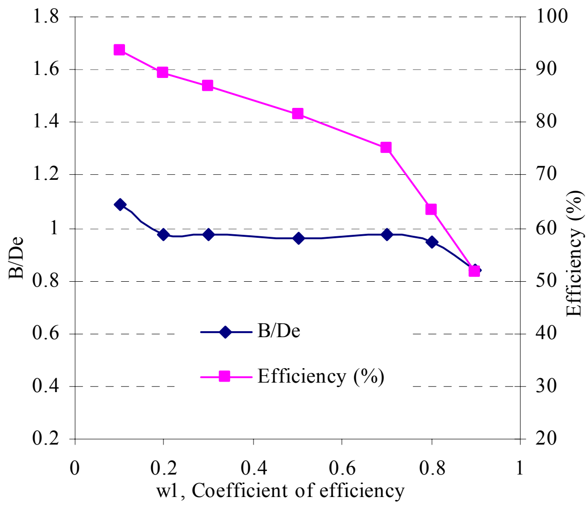


Fig. 7. The effect of cone diameter ratio on performance of cyclone

Fig. 8 illustrates the alterations of the dimensionless diameter of the vortex finder (*De/D*) and its effects on pressure drop. It shows that, proportionally, by increasing the drop pressure coefficient ($w_2$) in Eq. (20), the diameter of the vortex finder will be increased as well. This is due to the fact that with increasing the vortex finder diameter, the fluid flows over into the vortex finder easier, resulting to the decrease in the pressure drop of the cyclone. However, this will lead to departure of more particles with fluid from the vortex finder and decrease the efficiency. There is another reason for this phenomenon, tangential velocity in the inner region of cyclones decreases when the cyclone vortex finder diameter is increased, and this would lead to the lower separation efficiency observed in cyclones with bigger vortex finder. This conclusion is in a good agreement with previous studies presented by A. Raoufi *et al*, and K. Pant *et al,* in [25] , [26] respectively.

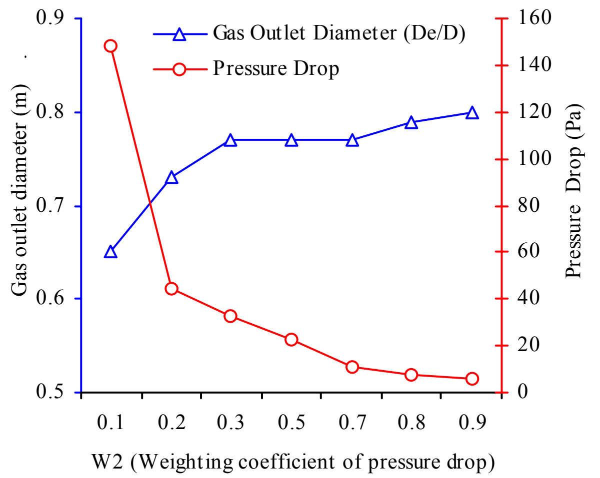


Fig. 8. Variation of the pressure drop with alteration of the vortex finder diameter

Fig. 9 illustrates the relation between the variation of the height of the cyclone and height of the conical part of it on the efficiency.

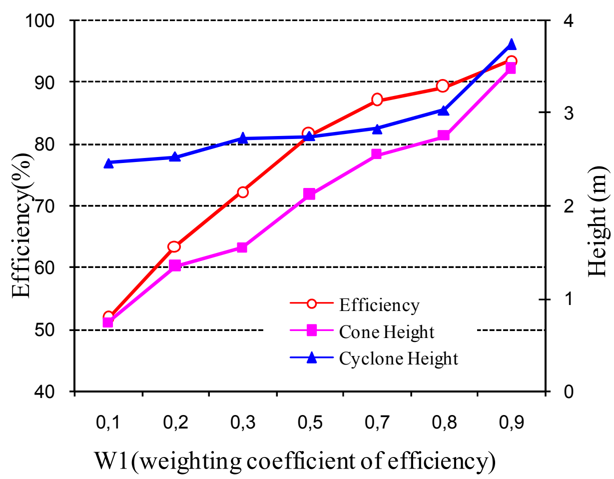


Fig. 9. The cyclone and conical height effect on the efficiency

Results demonstrate that with increasing the weighting coefficient of the efficiency ($w_1$), the height of the cyclone have been increased, leading to the increment of the efficiency. In other words, in Fig. 9, by declining the portion of conical height of the cyclone, the efficiency of the cyclone has been decreased significantly.

Another important factor which has a remarkable influence on efficiency and pressure drop is the slope of the conical part of the cyclone. This non-dimensional parameter is a new suggestion which propose by authors. According to Eq. (21), this parameter indicates the compound effect of three dimensions of the cyclone as well; hence it can be an effective parameter in optimization design of the cyclone:

$$\alpha = \frac{h}{\left[(D-B)/2\right]} \tag{21}$$

Fig. 10 illustrates that by ever-increasing $\alpha$, efficiency and pressure drop rise up too. So for attaining the maximum efficiency, one must be select the correct ratio between *h* (the height of the conical part), *D* (the cyclone body diameter) and *B* (the cone diameter).

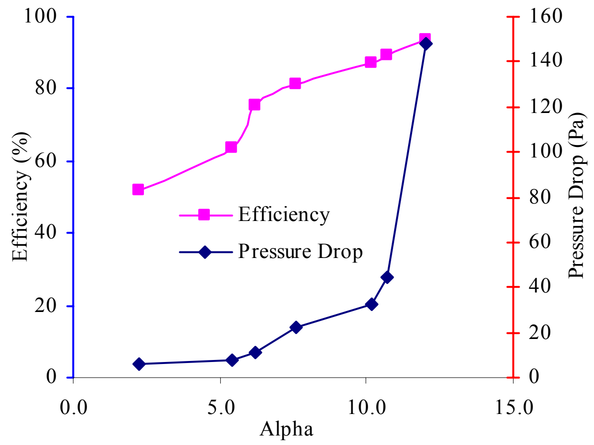


Fig. 10. The effect of the conical part slope on the overall efficiency

Fig. 11 demonstrates the alterations of efficiency versus the alterations of the pressure drop.

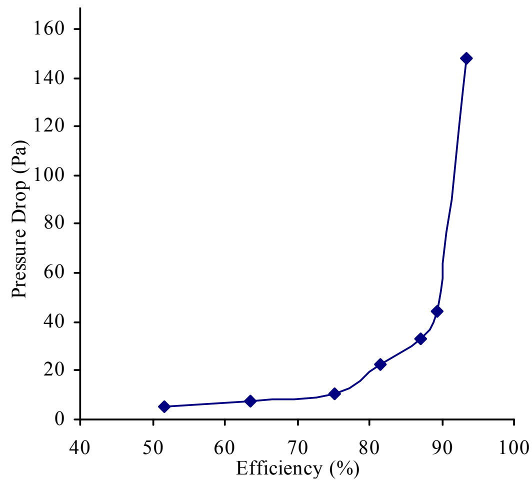


Fig. 11. The optimized cyclones results for seven groups of weighting coefficients

By increasing $w_1$ in Eq. (21), efficiency has increased while simultaneously pressure drop has strongly increased as well, demonstrating its negative effect in the industrial systems. This figure also shows that with ever-increasing the efficiency over 85 percent, pressure drop will be increased significantly.

## VI. Conclusion

In this paper, the performance of a cyclone has been optimized using the genetic algorithm. Results obtained from the computer modeling have demonstrated that CFD is an effective method for modeling the effect of cyclone dimensions on its performance.

The following conclusions can be drawn from the present study:

- By comparing the results of seven solutions with seven different coefficients shown in Fig. 11 it was observed that with increasing efficiency over 85%, the pressure will drop significantly. So the decision-makers must be aware of making a balance between desired efficiency and pressure drop in the cyclones and their combination and simultaneity effects on the system.
- Results indicate that the collection efficiency increases significantly as height and slope of conical part of cyclone are increased. These dimensions also play a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows.
- Increasing the diameter of vortex finder will lead to the decrease of the pressure drop but the collection efficiency will be decline too.
- By comparing the efficiency curve in Fig. 6, it was observed that the collection efficiency increases significantly as cone bottom size is reduced. If the cone bottom diameter is not reduced to be smaller than the gas exit tube diameter, the change in pressure drop will not be significant when cone size is varied; this conclusion is in a good accordance with Xiang *et al* studies [1].

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