PREDICTION OF THE EFFECT OF DIMENSION, PARTICLE DENSITY, TEMPERATURE, AND INLET VELOCITY ON CYCLONE COLLECTION EFFICIENCY

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Abstract.   The collection efficiency of a cyclone separator depends on several factors including design parameters, such as dimensions of the cyclone separator, particle density, and operating temperature. The physical properties of fluid, namely the density and viscosity, and operating parameters such as the inlet velocity of the fluid into the cyclone and the outlet conditions also affect the cyclone efficiency. This paper compares the prediction accuracy of four cyclone collection models, namely Lapple [2], Koch and Licht [3], Li and Wang [4], and Iozia and Leith [5]. All the predictions proved to be satisfactory when compared with the presented experimental data. The Li and Wang model [4], predicts the cyclone collection efficiency much better than the other three models with a deviation of only 3% from the experimental data and therefore, it could be used in the evaluation of cyclone efficiency. The cyclone efficiency increases with decreasing cyclone body diameter, operating temperature, and cyclone inlet width. On the other hand, cyclone efficiency increases proportionally with inlet velocity and particle density.

Keywords: Cyclone efficiency, dimension, inlet velocity, temperature

Abstrak.   Kecekapan pengumpulan pemisah siklon bergantung kepada beberapa faktor seperti dimensinya, ketumpatan partikel dan suhu beroperasi. Sifat fizikal bendalir seperti ketumpatan dan kelikatan bendalir serta parameter operasi misalnya halaju masukan bendalir juga mempengaruhi kecekapan siklon. Artikel ini membandingkan ketepatan ramalan oleh empat model siklon iaitu Lapple [2], Koch dan Licht [3], Li dan Wang [4], dan Iozia dan Leith [5]. Kesemua ramalan terbukti memuaskan jika dibandingkan dengan data eksperimen yang sedia ada. Model Li dan Wang [4] menghasilkan ramalan yang lebih tepat berbanding tiga model lain dengan penyisihan hanya 3% dari pada data eksperimen. Oleh yang demikian, model tersebut sesuai digunakan untuk menilai kecekapan siklon. Kecekapan siklon meningkat dengan berkurangnya diameter siklon, suhu beroperasi dan lebar masukan siklon. Sebaliknya, kecekapan siklon di dapati meningkat secara berkadar terus dengan peningkatan halaju masukan dan ketumpatan partikel.

Kata kunci: Kecekapan siklon, dimensi, halaju masukan, suhu

1.0   INTRODUCTION

Cyclones are among the oldest types of industrial particulate control equipment and air sampling device. The primary advantages of cyclones are economy and simplicity

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in construction and design. Since there are no moving parts, cyclones are relatively maintenance-free. By using suitable materials and methods of construction, cyclones can be adapted for use in extreme operating conditions: high temperature, high pressure, and corrosive gases. Cyclone collection efficiencies can reach 99% for particles bigger than 5 μm [1] and can be operated at very high dust loading. Applications of cyclone in industry include the removal of saw dust, as a spray dryer, and for catalyst recovery in fluid bed reactor.

The performance of a cyclone separator depends on several factors including design parameters, such as scaling and dimensions of the cyclone separator, and particle parameters such as its density and shape factor. The physical properties of fluid such as density and viscosity, and operating parameters such as the inlet velocity of the fluid into the cyclone and the outlet conditions also affect the cyclone performance. An accurate prediction of cyclone efficiency is very important because an inaccurate prediction may result in an inefficient design of cyclone separators. This study compares the prediction accuracy of four different cyclone models, namely Lapple [2], Koch and Licht [3], Li and Wang [4], and Iozia and Leith [5]. The efficiency predictions of these models were compared with those of Kim and Lee [6], and Ray et al. [7]. The model with the best fit on experimental data was then used to investigate the effects of cyclone dimension, inlet velocity, particle density, and operating temperature on its collection efficiency.

2.0   CYCLONE DESIGN

There are a number of different forms of cyclone, but the reverse flow cyclone (Figure 1) is the most common design used industrially. The cyclone consists of four main parts: the inlet, the separation chamber, the dust chamber, and the vortex finder. Tangential inlets are preferred for the separation of solid particles from gases [8]. In this study, the numerical simulation deals with the standard case of reverse flow cyclone with a tangential rectangular inlet with the dimensions given in Table 1.

Table 1   Cyclone geometry used in this simulations

Geometry	a/D	b/D	D_e/D	S/D	h/D	H/D	B/D
Stairmand high efficiency	0.5	0.2	0.5	0.5	1.5	4.0	0.375
Kim & Lee [6] cyclone 1	0.330	0.225	0.257	1.157	1.447	3.050	0.482
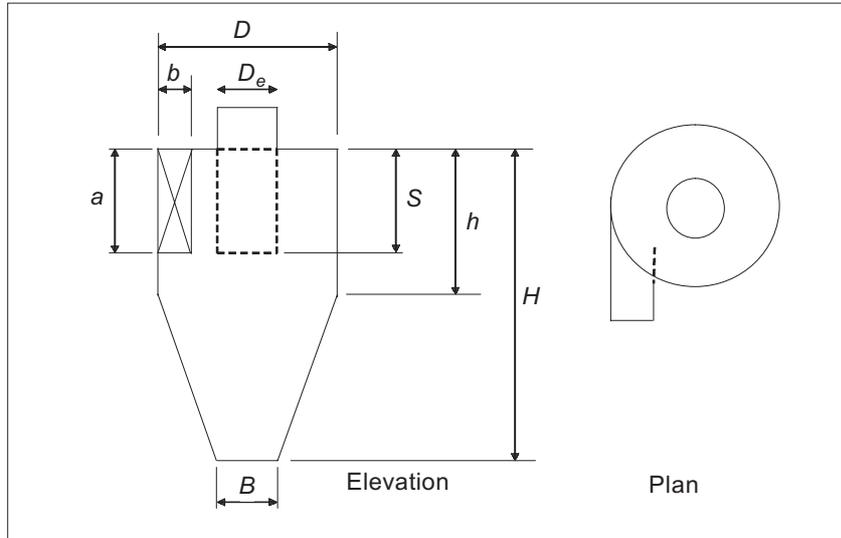
Figure 1 Tangential cyclone configuration

3.0 CYCLONE EFFICIENCY MODEL

3.1 Iozia and Leith Model

Iozia and Leith [5] logistic model, is a modified version of Barth [9] model which was developed based on force balance. The model assumes that a particle carried by the vortex endures the influence of two forces: a centrifugal force, Z, and a flow resistance, W.

The collection efficiency (η_i), of particle diameter (d_{pi}) can be calculated from:

$$\eta_i = \frac{1}{1+\left(d_{pc}/d_{pi}\right)^{\beta}} \tag{1}$$

where β is an expression for slope parameter derived based on the statistical analysis of experimental data of a cyclone with $D = 0.25$ m, given as:

$$\beta = 0.62 - 0.87\,ln\left(\frac{d_{pc}}{100}\right) + 5.21\,ln\left(\frac{ab}{D^2}\right) + 1.05\left[ln\left(\frac{ab}{D^2}\right)\right]^2 \tag{2}$$

and d_{pc} is the 50% cut size given by Barth [9]:

$$d_{pc} = \left[\frac{9\mu Q}{\pi\rho_p z_c v_{t\,max}^2}\right]^{0.5} \tag{3}$$

where core length (z_c) and core diameter (d_c) are given as:

$$z_c = (H - S) - \left[\frac{H - S}{(D / B) - 1}\right]\left[(d_c / B) - 1\right] \qquad \text{for } d_c > B \qquad (4a)$$

$$z_c = H - S \qquad \qquad \text{for } d_c > B \qquad (4b)$$

$$d_c = 0.47D\left(\frac{ab}{D^2}\right)^{-0.25}\left(\frac{D_e}{D}\right)^{1.4} \qquad (5)$$

3.2   Li and Wang Model

The Li and Wang [4] model includes particle bounce or re-entrainment and turbulent diffusion at the cyclone wall. A two-dimensional analytical expression of particle distribution in the cyclone is obtained. The Li and Wang [4] model was developed based on the following assumptions:

(1)   The radial particle velocity and radial concentration profile are not constant for uncollected particles within the cyclone.

(2)   Boundary conditions with the consideration of turbulent diffusion coefficient and particle bounce re-entrainment on the cyclone wall are:

$$c = c_0, \qquad \text{at } \theta = 0 \qquad (6)$$

$$D_r \frac{\partial c}{\partial r} = (1 - \alpha)wc, \qquad \text{at } r = D / 2 \qquad (7)$$

(3)   The tangential velocity is related to the radius of cyclone by uR^n = constant.

The concentration distribution in a cyclone is given as:

$$c(r, \theta) = \frac{c_0(r_w - r_n)\exp\left\{-\lambda\left[\frac{1}{K(1+n)}r^{1+n}\right]\right\}}{\int_n^w \exp\left\{\frac{1}{K(1+n)}r^{1+n}\right\}dr} \qquad (8)$$

where

$$K = \frac{(1 - n)(\rho_p - \rho_g)d^2Q}{18\mu b\left(r_w^{1-n} - r_n^{1-n}\right)} \qquad (9)$$

and

$$\lambda = \frac{(1 - \alpha)Kw_w}{D_r r_w^n} \qquad (10)$$

The resultant expression of the collection efficiency for particle of any size is given as:

$$\eta_i = 1 - \exp\{-\lambda\theta_1\} \tag{11}$$

where

$$\theta_1 = 2\pi\left(S + L\right)/a \tag{12}$$

3.3 Koch and Licht Model

Koch and Licht [3] collection theory recognized the inherently turbulent nature of cyclones and the distribution of gas residence times within the cyclone. Koch and Licht [3] described particle motion in the entry and collection regions with the additional following assumptions:

(1) The tangential velocity of a particle is equal to the tangential velocity of the gas flow. In other words, there is no slip in the tangential direction between the particle and the gas.
(2) The tangential velocity is related to the radius of cyclone by uR^n = constant.

A force balance and an equation on the particles collection yields the grade efficiency, η_i, where,

$$\eta_i = 1 - \exp\left\{-2\left[\frac{G\tau_i Q}{D^3}(n+1)\right]^{0.5/(n+1)}\right\} \tag{13}$$

where,

$$G = \frac{8K_c}{K_a^2 K_b^2} \tag{14}$$

$$n = 1 - \left\{1 - \frac{(12D)^{0.14}}{2.5}\right\}\left\{\frac{T + 460}{530}\right\}^{0.3} \tag{15}$$

$$\tau_i = \frac{\rho_p d_{pi}^2}{18\mu} \tag{16}$$

where G is a factor related to the configuration of the cyclone, n is related to the vortex, and τ is the relaxation term.

3.4 Lapple Model

Lapple [2] model was developed based on force balance without considering the flow resistance. Lapple [2] assumed that a particle entering the cyclone is evenly distributed

across the inlet opening. The particle that travels from inlet half width to the wall in the cyclone is collected with 50% efficiency. The semi empirical relationship developed by Lapple [2] to calculate a 50% cut diameter, d_{pc}, is:

$$d_{pc} = \left[\frac{9\mu b}{2\pi N_e v_i (\rho_p - \rho_g)}\right]^{0.5} \tag{17}$$

where Ne is the number of revolutions:

$$N_e = \frac{1}{a}\left[h + \frac{H-h}{2}\right] \tag{18}$$

The efficiency of collection of any size of particle is given by:

$$\eta_i = \frac{1}{1 + \left(d_{pc} / \overline{d}_{pi}\right)^2} \tag{19}$$

4.0   COLLECTION EFFICIENCY PREDICTION

Kim and Lee [6] and Ray *et al.* [7] presented experimental data of cyclone efficiency. Comparison between the calculated cyclone efficiency from the models and the experimental data are shown in Figures 2 and 3 respectively. Li and Wang [4] model's
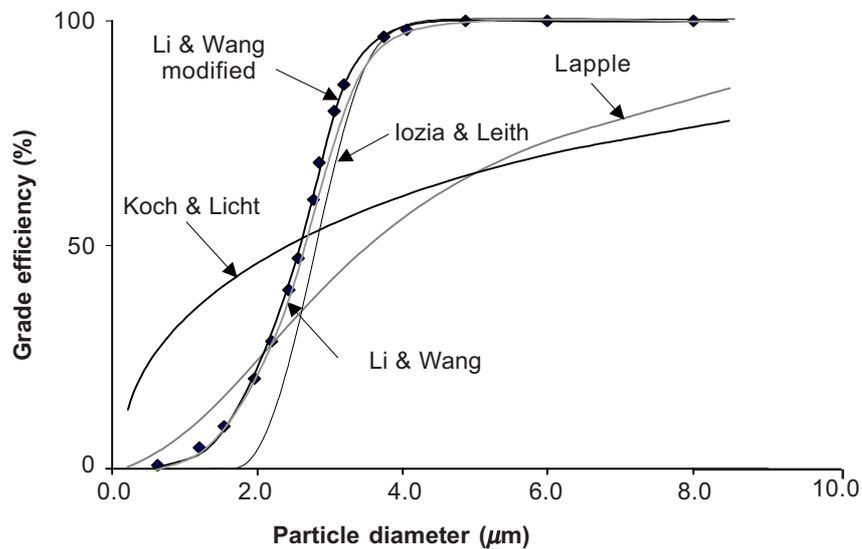
Figure 2   Comparison between data presented by Ray *et al.* [7] and predictions of four models (P = 1.7 Bar, T = 293 K, v_i = 11 m/s, D = 0.4 m, ρ_p = 2800 kg/m^3, Geometry Stairmand high efficiency) (from Gimbun *et al.*, [10])
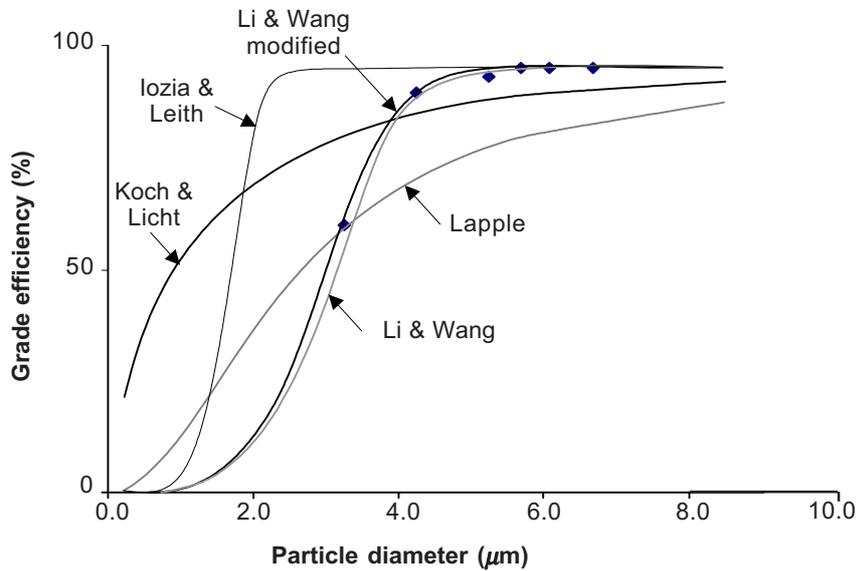
Figure 3   Comparison between data presented by Kim and Lee [6] and predictions of four models (T = 293 K, v_i = 4.25 m/s, ρ_p = 980 kg/m^3, D = 0.0311 m, geometry Kim & Lee [6] cyclone 1)

prediction on cyclone efficiency shows an excellent fitting under ambient condition. Lapple [2] and Koch and Licht [3] models considerably underestimate efficiency for large particles and overestimate efficiency for small particles to a lesser extent. Iozia and Leith [5] logistic model shows a good agreement with experimental data for the cyclone size range of D = 0.25 – 0.4 m. However, it is unable to predict the efficiency for small cyclone (D < 0.1 m) accurately. Iozia and Leith [5] model is found to be only suitable for efficiency prediction of cyclone diameter around 0.25 m.

However, there remains a slight discrepancy between the calculation of Li and Wang's model [4] and Ray's [7] experimental data (Figures 2 and 3). In the our previous paper [9], we found that their agreement can be further improved if a modified form of the expression of vortex exponent, n, is used. In the model of Li and Wang [4], the expression of vortex exponent, n, is described as:

$$n = 1 - \left[\left(1 - 0.67 D^{0.14} \right) \left(T / 283 \right)^{0.3} \right] \tag{20}$$

However, Li and Wang's [4] prediction can be further improved by changing the constant of empirical expression, n:

$$n = 1 - \left[\left(1 - 0.5 D^{0.14} \right) \left(T / 283 \right)^{0.3} \right] \tag{21}$$

5.0   PREDICTION OF THE EFFECT OF DIMENSION, PARTICLE DENSITY, TEMPERATURE, AND INLET VELOCITY ON CYCLONE COLLECTION EFFICIENCY

Li and Wang [4] modified model has an excellent prediction on cyclone efficiency for different cyclone configurations (Figures 2 and 3). Therefore, this model can be used to investigate numerically the effect of cyclone dimensions, inlet velocity, particle density, and operating temperature on its collection efficiency. A study on the effect of variables such as temperature, inlet velocity, and particle density to cyclone performance is necessary to obtain the most suitable operating condition, while, the study on cyclone dimensions is necessary to investigate the effect of the critical dimensions such as cyclone diameter and inlet width to its performance. In this study, the constructed spreadsheet, based on Li and Wang [4] modified model was tested for various cyclone input parameters and dimensions in order to study the relationship between these parameters and cyclone efficiency. These input variables are the particle-air density difference, $(\rho_p - \rho_g)$, and gas inlet velocity, v_i, and temperature, T. Stairmand high efficiency cyclone with diameter of 0.4 m was used in this simulation.

5.1   Effect of Air-Particle Density Difference

Air-particle density difference $(\rho_p - \rho_g)$ is a key parameter in cyclone efficiency calculations. Efficiency prediction by Li and Wang [4] modified model for different particle density is shown in Figure 4. The numerical simulation result shows that the critical particle size, d_{pc}, for particle with density 3000 kg/m^3 is around 2.2 μm and is around 4.2 μm for 1000 kg/m^3 particle density. A bigger particle density tends to result in a larger air-particle density difference since the air density remains constant. Bigger air-particle density difference led to a higher resultant centrifugal force acting
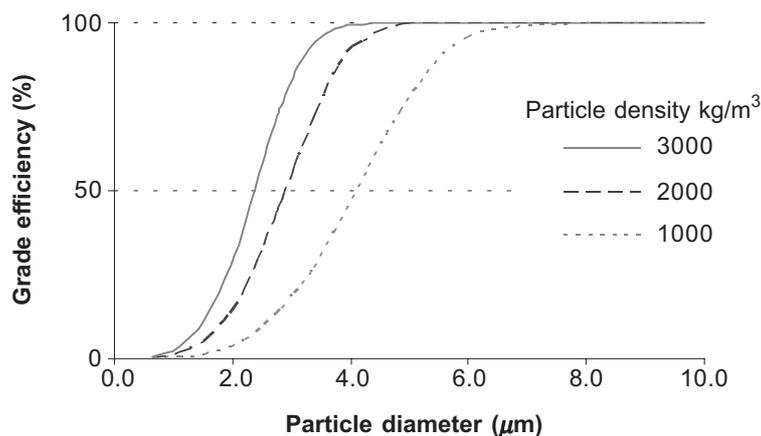
Figure 4   Li and Wang [4] modified model predictions for different particle density

on the particle, and the higher centrifugal force in cyclone has led to higher separation efficiency. It can be concluded from this finding that the bigger the particle density is, the smaller the critical particle size (d_{pc}) would be obtained, or by other means, the sharper the separations would be.

5.2 Effect of Inlet Velocity

Inlet gas velocity, v_i, is an important factor for cyclone sizing in order to achieve a desired separation efficiency. Inlet cyclone velocity is a result of dividing the inlet gas flow rate, Q, to the cyclone inlet area ($a \cdot b$). At a high flow rate, the inlet velocity becomes larger thus, the tangential velocity, v_i, also increases. The cut-off diameter varies inversely with the square root of the inlet velocity [11]. The effect of inlet velocity to the cyclone performance is shown in Figure 5. It shows that for the identical size and configuration of cyclone, the higher the gas inlet velocity is, the sharper the efficiency would be.
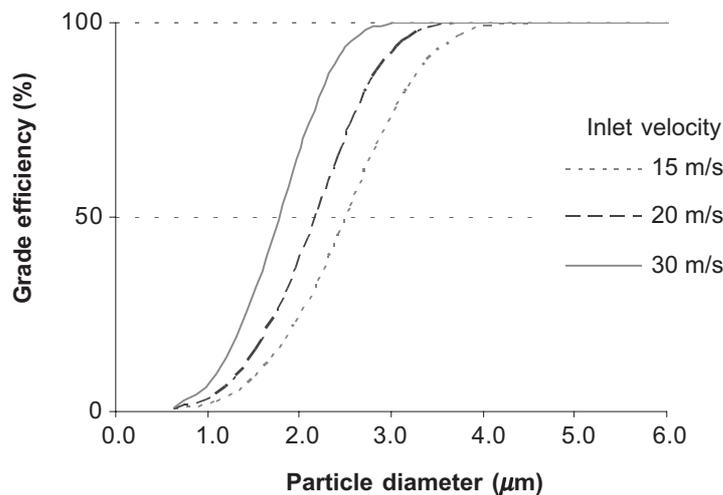
Figure 5   Effect of inlet gas velocity on cyclone performance

However, a very high inlet velocity would decrease the collection efficiency because of increased turbulence and saltation/re-entrainment of particles. Shepherd and Lapple [11] recommended that the optimum cyclone operating velocity is around 18 m/s. However, the range of practicable cyclone inlet velocity is around 15 – 30 m/s [12].

5.3 Effect of Temperature

Simulation of the effect of temperature on the cyclone performance is carried out using a Stairmand high efficiency cyclone ($D = 0.4$ m) at three different temperatures (293 K, 785 K, and 1221 K). Figure 6 shows that higher operating temperature would result in
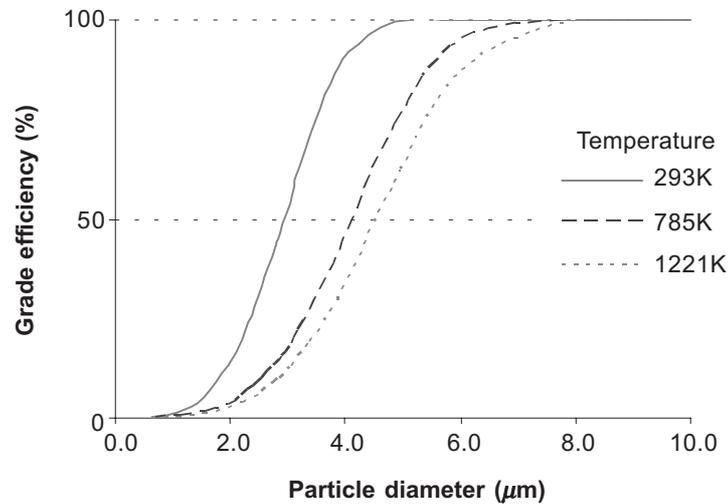
Figure 6   Effect of operating temperature on cyclone performance

lower separation efficiency. This result agrees with Parker *et al*. [13] findings at temperature 973 K which concluded that the efficiency decreased dramatically as the temperature increased. This is because the air viscosity increases with temperature.

5.4   Cyclone Inlet Width

The bigger cyclone inlet width, b, $(b > (D - D_e)/2)$ causes the contraction of the vortex at the cyclone inlet thus resulting in poor vortex formation inside the cyclone and also lower separation efficiency (Figure 7). Poor vortex reduces the number of effective turns in cyclone and leads to lower separation efficiency [2]. Figure 8 shows the flow patterns of different cyclone inlet widths. Coker [14] recommended that for better design of cyclones, the inlet width should be smaller than $(D - D_e)/2$.

5.5   Cyclone Diameter

It is important to know the effects of cyclone size on the cut-off diameter under certain operational conditions and geometry. It is generally accepted that the cut-off diameter is proportional to the square root of cyclone body diameter [11]. For comparison purposes, the Stairmand high efficiency cyclone with the diameter of 0.3, 0.4, and 0.5 m at the mean inlet velocity of 11 m/s, was considered. Figure 9 shows Li and Wang [4] model predictions for different cyclone diameters. The result shows that bigger cyclone diameter would result in lower separation efficiency due to lower generated centrifugal forces as revealed by [11].
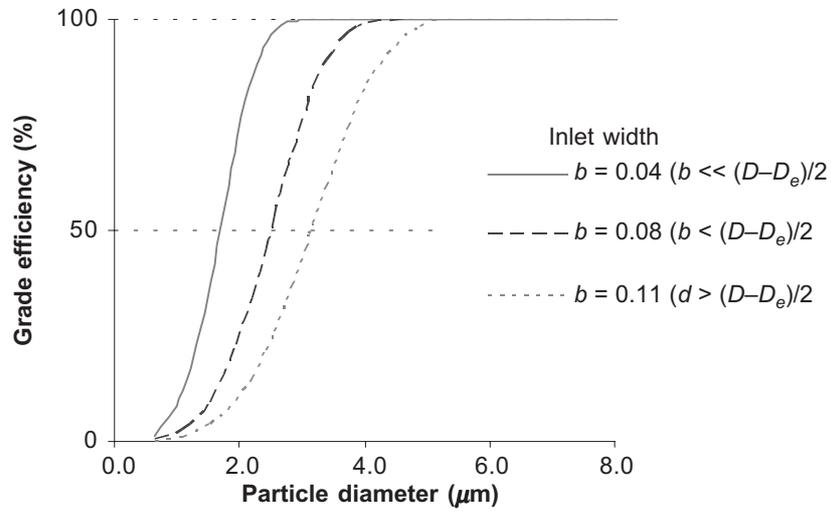
Figure 7 Li and Wang [4] modified model predictions for different inlet widths
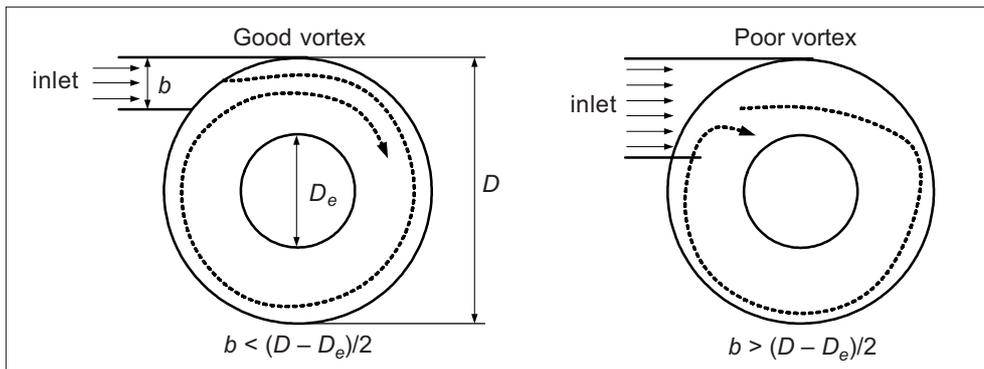
Figure 8 Flow pattern of different cyclone inlet widths
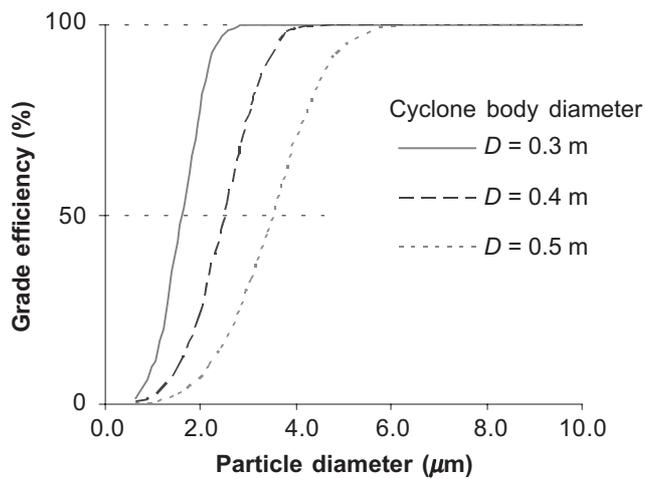
Figure 9 Li and Wang [4] modified model efficiency prediction of different cyclone diameters

6.0 CONCLUSION

The cyclone efficiency increases with decreasing cyclone body diameter. This is due to the fact that a higher centrifugal force is created in a smaller cyclone diameter. The cyclone efficiency decreases with increasing cyclone inlet width due to the poor vortex formation inside the cyclone. The increase of other variables like air-particle density difference and inlet velocity will result in higher separation efficiencies because of higher resultant centrifugal force. However, cyclone efficiency decreases dramatically as temperature increases from 293 to 993 K as a result to the increase in air viscosity.

NOMENCLATURE

L	=	natural length (m)
a	=	cyclone inlet height (m)
b	=	cyclone inlet width (m)
D	=	cyclone body diameter (m)
D_e	=	cyclone gas outlet diameter (m)
H	=	cyclone height (m)
h	=	cyclone cylinder height (m)
S	=	cyclone gas outlet duct length (m)
B	=	cyclone dust outlet diameter (m)
c_0, c_1	=	particle inlet and outlet concentration (kg/m^3)
d	=	particle diameter (m)
D_r	=	radial turbulent diffusion coefficient
d_{pc}	=	cut particle diameter collected with 50% efficiency (m)
n	=	cyclone vortex exponent $(0.5 < n < 1)$
Q	=	volumetric gas flow rate (m^3/s)
r	=	radial dimension, $r_w = D/2$ and $r_n = D_e/2$ (m)
R	=	radius (m)
T	=	absolute temperature (K)
w	=	radial particle velocity (rad/s)
w_n, w_w	=	radial particle velocity at $r = r_n$ and $r = r_w$ (rad/s)
α	=	particle bounce or re-entrainment coefficient
λ	=	characteristic value
η	=	grade efficiency (%)
ρ_g	=	gas density (kg/m^3)
ρ_p	=	particle mass density (kg/m^3)
μ	=	gas viscosity (m^2/s)
θ	=	angular coordinate
d_{pi}	=	diameter of particle in size range i (m)
g	=	gravity acceleration (m/s^2)
G	=	cyclone configuration factor

τ = relaxation time (s)

η_i = grade efficiency of particle size at mid-point of internal i (%)

i = subscript denotes interval n particles size range

K_a = a/D

K_b = b/D

K_c = cyclone volume constant

N_e = number of revolutions N_e of gas spins through a in the outer vortex

v_i = inlet velocity (m/s)

K = cyclone configuration and operating condition constant

β = slope parameter

z_c = core length (m)

d_c = core diameter (m)

$v_{t\,max}$ = maximum tangential velocity (m/s)

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